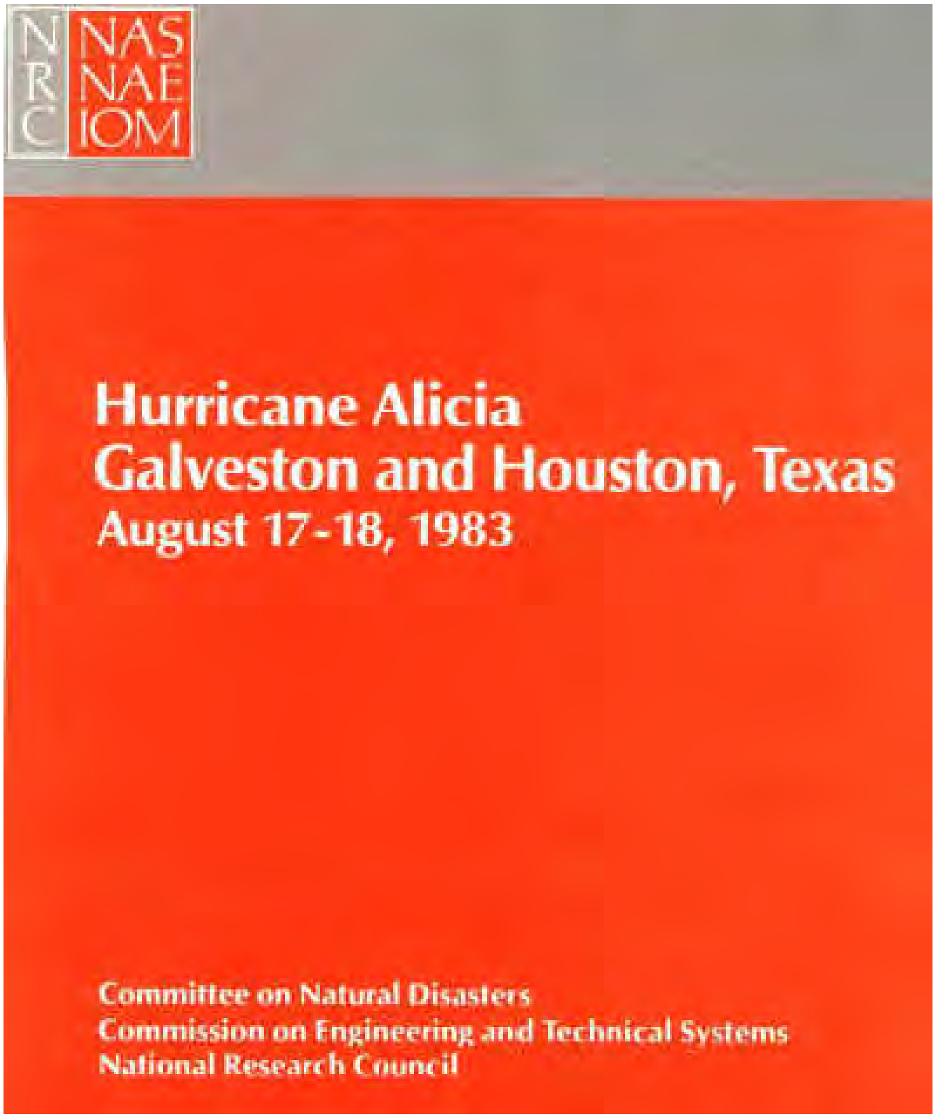

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INTRODUCTION AND OVERVIEW

Hurricane Alicia, which came ashore near Galveston, Texas, during the night of August 17-18, 1983, was the first tropical cyclone of full hurricane intensity to strike the U.S. mainland in over three years. It will be recorded as the second most costly storm ever to strike the United States, if Hurricane Agnes, which in 1972 caused inland flooding over a large part of the U.S. East Coast, is excluded. Alicia's coastal property damage was exceeded only by that of Hurricane Frederic, which came ashore near Mobile, Alabama, in 1979.

Though Alicia was not a strong hurricane, the area of maximum winds in the storm crossed a large metropolitan area--the Galveston-Houston area of Texas (see Figure I.l)--placing that area's network of expensive structures, buildings, and lifeline facilities at risk. Wind damage was extensive throughout the area, and rain and storm surges caused flooding damage in some areas bordering the Gulf of Mexico and Galveston Bay. A unique effect of the storm was concentrated damage to the glass of a cluster of high-rise buildings in downtown Houston. "It was a hypnotic thing to watch," said a spokesman from the city's Public Works Department who observed damage in downtown Houston from a police squad car. "A panel would break out, but it wouldn't fall directly to the ground. It would get whipped around in the wind, hit another panel, maybe in the building across the street, and then there would be more broken glass flying around. It seemed to be feeding on itself."

Other residents of the area reported being scared, lying in the dark listening to the wind roar, glass breaking, and flying debris hitting around them. For some, the storm was fatal. Tallies of the death toll from Alicia vary from 10 to 20, depending on the extent to which deaths indirectly attributable to the storm are included.

The purposes of this report are to document the storm's characteristics and effects, to call attention to specific characteristics, effects, and storm-related conditions that could be studied further with beneficial results, and to examine the warnings, responses, and recovery occasioned by the storm. The report is based on a four-day survey by team members on August 23-26 of the conditions after the storm and on oral and written follow-up.

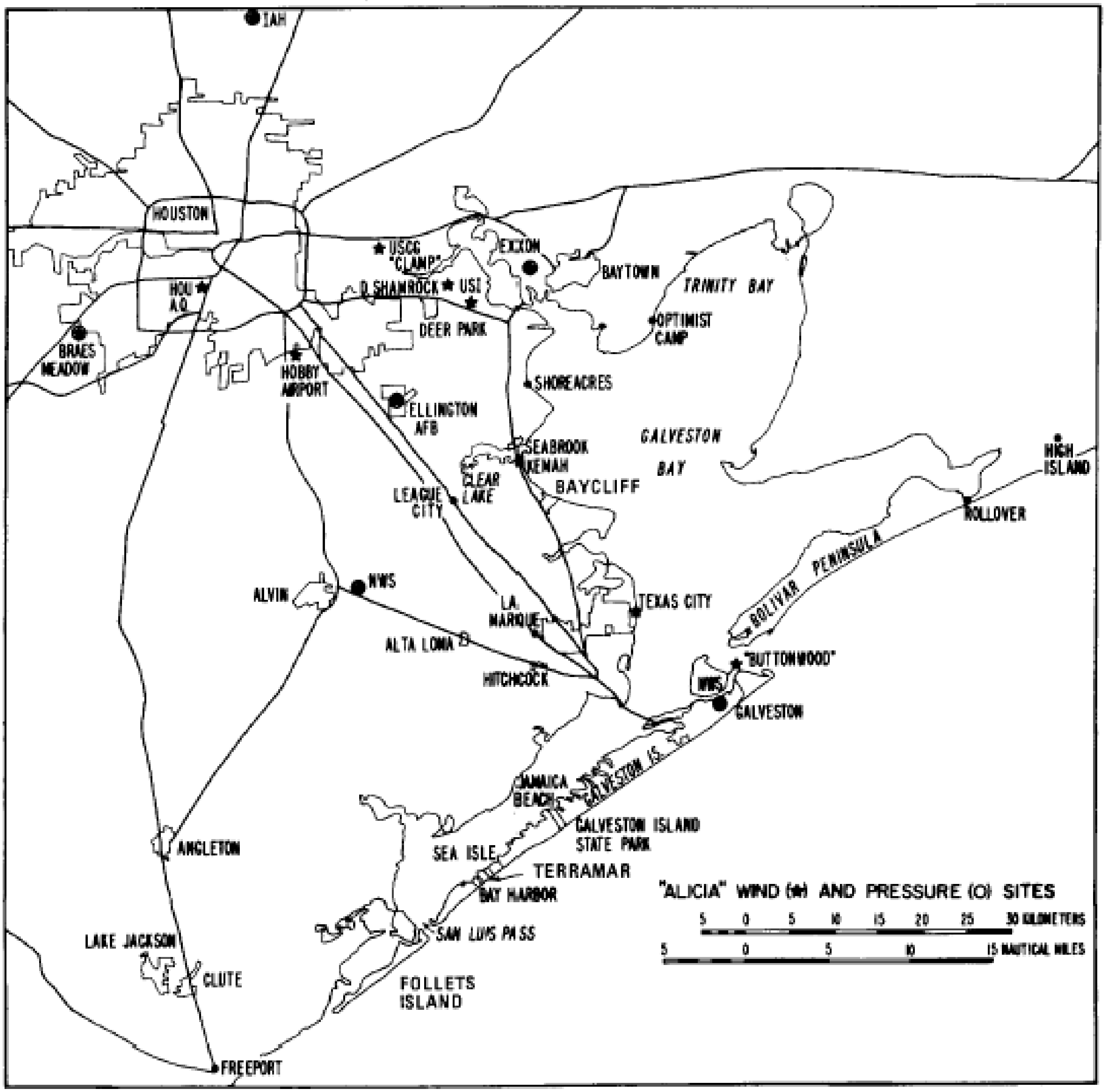


FIGURE 1.1 Layout of the Galveston-Houston area.

METEOROLOGY

Hurricane Alicia was the first tropical cyclone of the 1983 Atlantic hurricane season. It was also the first hurricane to strike the continental United States since Hurricane Allen made landfall near Brownsville, Texas, on August 10, 1980. The period of slightly over three years between these hurricane strikes is the longest time the mainland of the united States has gone without a hurricane landfall in recorded history. The next longest hurricane-free period was from September 28, 1929, to August 14, 1932.

Hurricane Alicia made landfall on the extreme western tip of Galveston Island during the predawn hours of Thursday, August 18, 1983. The storm had developed rapidly over the north-central Gulf of Mexico during the previous 24 hours. When it made landfall, it was slightly above average in terms of size and intensity. Research aircraft of the National Oceanic and Atmospheric Administration (NOAA) made measurements in the storm until it came ashore. In addition, the storm made landfall near several major weather offices and radar facilities. As a result, Alicia is one of the best documented hurricanes ever to affect the United States.

Some unusual aspects of Hurricane Alicia that are documented in this report include its rapid strengthening in the 12 to 18 hours prior to landfall, its rather sharp turn to the right (toward the northnorthwest) during the afternoon of August 17, and the double concentric eyewalls of the hurricane during the few hours prior to and just after landfall. Also, Hurricane Alicia was the first storm for which a new "probability" system of predicting hurricane landfall was used. Under this system, the probabilities of a hurricane's landfall are given and updated in each advisory issued for the storm, as described in Chapter 6.

Twenty-three tornadoes were reported to the National Weather Service (NWS) Severe Storms Forecast Center in Kansas City in association with Hurricane Alicia (National Climatic Data Center, 1983). However, subsequent damage surveys have not corroborated this number of tornadoes. Preliminary reports indicate rainfall totals for the storm of 10 to 11 in., which is below average for Gulf Coast hurricanes that make landfall (average peak values are roughly 10 to 15 in. for other hurricanes in the Gulf of Mexico; see, for example, Parrish et al., 1982, and Miller, 1958).

STORM SURGES AND SHORE PROCESSES

More than two days before Alicia crossed the Texas coast, water levels along the east Texas coast began to rise above normal levels. By midnight on August 16, the water level in front of Galveston Island was about 2 ft above normal tide level. The disparity had increased to more than 3 ft by 6 p.m. on August 17. Shortly after this time the main winds of the storm began to move into the area just seaward of Galveston Island, and Gulf water levels began a steep rise to almost 7-1/2 ft above the normal tide in front of the seawall at Pleasure Pier. Since the normal high tide would have been about 1.7 ft above the local national geodetic vertical datum (NGVD), the total water depth at the peak of the storm surge was just over 9 ft above NGVD (NGVD is about 0.3 ft below the local mean sea level datum).

During the two-day period when water levels in the Gulf were above normal, water flowed through the Galveston and Freeport Inlet navigation channels and through Rollover Pass into the bay complex behind Galveston and Follets islands and Bolivar Peninsula (see Figure 1.1). When the strongest winds of the hurricane reached shore, they drove the accumulated waters in these shallow areas to exceptionally high levels (more than 10 ft above NGVD) in the area behind Follets Island and in the northwest corner of Galveston Bay.

Wind waves from the storm began to affect the beaches of the Gulf shore long before the early winds of the storm reached shore. During the two-day period that the Gulf water level was rising, the beaches were continually responding to unusual waves and water levels. The waves, fresh from their generation areas in the nearby storm, were short and steep. Moving ashore on the high water level, they eroded the beaches and dunes behind the beaches, cutting further into the dunes as time passed and water levels rose. Along most of western Galveston Island and some of western Bolivar Peninsula, Gulf water levels eventually rose so high that waves began to overtop low areas in the dunes, usually at street ends. Water carrying sand then began to flow across the highway behind the beach and down the back of the island into the bays. As the Gulf water levels increased further and the dunes behind the beach continued to erode, water overtopped most of western Galveston Island, flowing across the highway and the island. Water depths on the island were from 1 to 3 ft, and overwash fans of sand up to 3 ft deep were created extending inland from the beach.

The front and western end of Bolivar Peninsula were also overtopped. However, a relic dune ridge on the body of the western part of the peninsula kept water from flowing into the bay, causing the overtopping water to pond between the dune ridge and the dunes behind the beach. As water levels in the Gulf rapidly receded after the peak of the storm surge, the ponded water flowed back into the Gulf through low places in the frontal dunes, cutting three large channels across the dunes and beach. During the same period the water in the bays behind Follets Island flowed gulfward through low places in the dunes, cutting more than 30 channels across the dunes and beach seaward of the highway. In several places these cuts reached the highway and began to undercut the pavement.

BUILDINGS AND STRUCTURES

Alicia's winds caused most of the property damage in the affected areas. The estimated costs of Alicia's damage ranged from about $750 million to as much as $1.65 billion. Overall, more than 2,000 homes and apartments were reported totally destroyed and over 16,000 other homes and apartments were damaged.

Beachfront houses along West Beach in Galveston were the first man-made objects on the coast to be affected by Alicia's winds. Many of them were destroyed. The 19-mile stretch of Galveston Island west of the seawall to San Luis Pass experienced major damage. The subdivisions most damaged include Terramar, Bay Harbor, Sea Isle, and Jamaica Beach. The Galveston seawall area, with its cluster of apartments and condominiums, suffered wind damage ranging from superficial cladding damage of roofs and walls to total loss of structural systems. The portion of Galveston Island protected by the seawall had only wind damage and minor flooding on the rear side. Communities like Surfside, near Freeport in Brazoria County, also experienced significant structural damage.

The practice of building structures on pilings above the ground level and the presence of the Galveston seawall reduced the wave damage to only a small fraction of what it otherwise would have been. Nevertheless, in many waterfront communities, especially on western Galveston Island, more than half of the buildings were severely damaged by winds and, in a few cases, by waves. Two high-rise "condo-type' buildings on East Beach in front of the seawall were an exception to this general rule. These buildings were about 500 ft behind the beach in an area where the strongest winds, highest surge, and largest wave action would be expected. Yet because they were well constructed they had no major damage.

In Seabrook, which is located on Galveston Bay east of Houston, there was heavy damage to houses, restaurants, and marinas fronting the bay. In some buildings along the waterfront, structural damage was initiated by storm surge and waves. Strong wind gusts acting on already weakened structures led to progressive failure.

There were no reports of damage to major coastal structures or to the coastal flood protection projects at Texas City and Freeport. Neither the Galveston seawall nor its toe protection was damaged, and the groins in front of the seawall had only minor damage. There was little or no damage to the Galveston entrance jetties.

In the Houston area the storm tore up signs, downed trees, and ripped away parts of buildings. In a localized area of Houston's central business district, Alicia smashed hundreds of windows in a cluster of high-rise buildings. Damage to these buildings was limited to the glass cladding; structurally, the buildings performed satisfactorily.

Damage to glass was not limited to the central business district. There were a few other locations around the city that also experienced some glass damage.

The wind-induced damage from Alicia in the Houston-Galveston area was caused by a lack of hurricane-resistant construction rather than by the storm. Adequate fastening and anchor of houses in Galveston and control of the availability of windborne missiles in the Houston area would have substantially reduced the damage caused by Alicia.

LIFELINE FACILITIES

The effect of Hurricane Alicia on lifelines was most severe on those lifelines dependent on electric power. Many overhead utility lines were downed by the wind, water erosion, and impact from flying debris. Telephone service was either partially or completely lost in many areas because of downed lines. Radio and TV generally continued to operate with standby power. However, TV broadcasts could not be received in many cases because of the loss of electric power.

Transportation was at a standstill during the storm. Many streets and roads were obstructed by fallen trees, signs, and other debris. Bridges generally were not affected. If they were impassable, it was due to debris on the bridge or a blocked roadway approach. Airports and railroads were closed during the hurricane and for most of August 18.

Water supply and sewage disposal systems were affected primarily by loss of power. Sewer lines west of the seawall in Galveston filled with sand and water as the result of the storm surge. In most cases, hospitals had standby power and they were able to continue operation during the storm. The primary effect of the storm on these facilities was to reduce water pressure.

All lifelines except highway and rail transportation were affected by the loss of electric power. Each lifeline resumed its normal function shortly after power was restored.

WARNINGS, RESPONSES, STORM EFFECTS, AND RECOVERY

The warning/response system has become increasingly complex over the past decade. The primary charge of the National Hurricane Center (NHC) in Miami is still to forecast a storm's movement and intensity and to communicate that forecast to the public, government, and commerce. The importance of the responsibility has become more salient as recent studies have revealed just how difficult it would be to evacuate many U.S. coastal areas. A regional evacuation study for the Galveston region (Ruch, 1981) calculated that 26 hours would be required to evacuate Galveston to ensure residents' safety should the area be threatened by a storm comparable to the 1900 hurricane that killed 6,000 people.

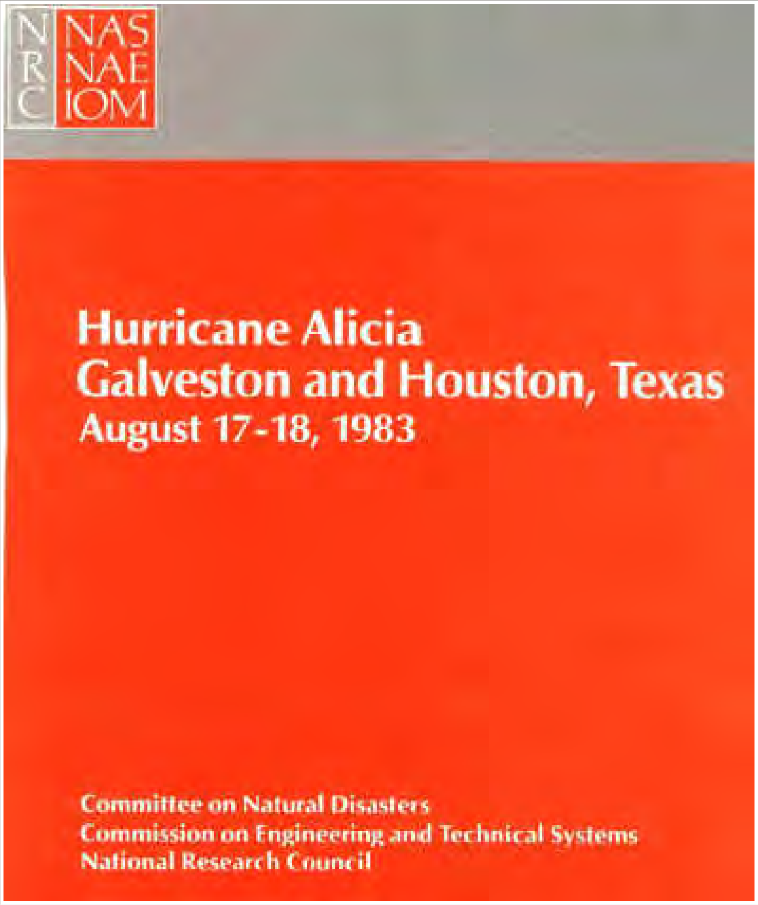
However, 26 hours before landfall it is not possible to predict with a great deal of accuracy where a storm is going to hit or how severe it is going to be. The average forecast error for the 24-hour position of a storm is about 125 miles, compared with 150 miles 30 years ago (Neumann, 1981). This 20 percent or so improvement in landfall forecasts must be compared with the population needing evacuation, which has grown far more rapidly. In the single decade of the 1960s, the population along the Atlantic and Gulf coasts within about a mile of the beachfront grew by more than 40 percent (Baker, 1979). The main change over the past 10 years, however, is not that there are now 40 percent more people to evacuate than in 1973, but that the seriousness of the problem is now recognized.

In response to the increased need for information upon which to base decisions about evacuation and other responses, the NHC developed a statistical model and in 1983 began including probabilities in its tropical storm and hurricane advisories. The number indicates the probability that the storm will "hit" (i.e., pass within 65 miles of) various coastal locations. Many meteorologists, emergency preparedness officials, and other people emphatically expressed their concern that the probabilities would confuse the public and keep people from evacuating as early as public officials would advise. The highest probability that any location would have of being "hit" when the storm is an expected 24 hours away is 45 percent; when it is 36 hours away, the highest possible probability is 25 percent (Carter, 1983). Alicia was the first hurricane for which probabilities were issued to the public, as described in Chapter 6.

The probabilities say nothing about the intensity of a storm when it does make landfall. A nightmare shared by many preparedness professionals is that they will make a decision not to evacuate when a storm is relatively weak and then the storm will rapidly intensify, leaving no time to evacuate. Alicia almost proved to be such a nightmare-come-true.

One reason for officials not ordering or urging evacuation very early, just to be safe, is belief in the "cry wolf" syndrome. This is the concern that if people leave at officials' behest during one threat and the hurricane does not hit their area, people will lose confidence in those officials' judgment and refuse to evacuate the next time they are urged to by officials. Although there is more systematic evidence to allay this concern than to support it, officials widely believe it. In 1980 Galveston was on the eastern edge of the watch area for Hurricane Allen, and 65 percent of the residents evacuated early when urged to do so by officials. A number of evacuees complained about the "unnecessary" evacuation, and the sensitivity of public officials to those complaints was significant in their handling of the Alicia threat. The City of Galveston was not formally evacuated, although most of western Galveston Island and Bolivar Peninsula were evacuated.

While Alicia was one of the nation's most costly storms for property damage, loss of life was far lower than would have been expected had evacuation been less successful. Cleanup and recovery followed the script of many disasters, but had their peculiarities as well, partly because such a large metropolitan area was affected by a fairly strong hurricane for the first time in many years. A number of long-term hazard mitigation policies resulted from the experience, including the public purchase of a housing development in a flood-prone area.



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Alicia Assessment

BUILDINGS AND STRUCTURES

CAUSES AND CHARACTERISTICS OF HURRICANE DAMAGE

There are two major sources of loads during a hurricane: wind-induced forces and water-induced forces. The water-induced forces are caused by storm surge, wave action, and subsequent flooding.

The wind flow field, on encountering an obstruction such as a building, exerts positive pressure on the windward face. At the corners of the building the flow separates, producing accelerated flows in the separation region and therefore negative pressure (suction) on the building surface in the separated flow regions. There are three distinct pressure regions on a building exposed to wind:

- 1. The windward, which is a region of positive pressure.
- 2. The side faces and roof regions of separated flow, which are generally characterized by negative pressure.
- 3. The leeward face, which is a region of negative pressure.

The distribution of negative or positive pressure is far from uniform, either in space or time. The most severe negative pressures are created near the edges, the corners, and at discontinuities in surfaces. Strong negative pressures initiate local structural damage, such as cladding failure. Any opening in the windward region of the structure, either by design or as a consequence of local failure, produces an increase in the internal pressure. Such an increase, coupled with existing negative pressure on the leeward and side surfaces of a structure, intensifies the combined pressure across these surfaces. Conversely, an opening in the region of negative pressure leads to a decrease in the internal pressure, which alleviates net pressure on these surfaces but enhances the net force on the windward face.

Failures of the structural system are triggered by the failure of one or more of the system's components. For example, poor connection or anchorage of the roof system to the walls, or failure of perimeter fasteners of the roof, can lead to the lifting of the roof, since storm winds create lifting forces on the roof. When wooden-frame structures such as single- and multifamily residences lose their roofs, the walls are left with no support at the top and usually collapse because of the surrounding wind pressures. Such a failure is often misinterpreted as tornado damage. Similarly, failure of the entire windward wall increases the internal pressure, promoting damage to the roof and side walls, which are already loaded by outward forces because of negative pressures acting outside.

Aerodynamic loads can be accentuated by nearby structures, which can channel the flow and heighten wind-induced loads. Similarly, in some locations other structures can block winds, thereby lowering wind effects. This is often referred to as the shielding effect. Windborne debris, such as gravel from roofs of buildings or from neighboring construction sites, act as missiles and contribute to glass damage.

Flooding and storm surges can either totally or partially submerge structures, inducing buoyant forces. In addition to these forces, lateral forces are produced by water flow. If breaking waves are present, impact forces are produced. Hydrostatic forces are also induced as a result of differential water pressure on opposite sides of walls or other structural components that block wave action. Finally, waterborne debris such as floating logs or loose timbers can cause impact forces when they strike structures.

To analyze the damage inflicted by hurricanes, all structures are subjectively classified into groups based on the level of engineering effort involved in their design. These categories are:

- 1. Fully engineered. These are buildings and structures that receive individual attention from professional architects and engineers. Examples are high-rise buildings, hospitals, and public buildings.
- 2. Preengineered. These are buildings and structures that are engineered as a general structural system and marketed in similar units. Examples are manufactured housing, mobile homes, prefabricated construction, and metal buildings.
- 3. Marginally engineered. These are buildings and structures that receive marginal engineering attention. Examples may include motels, apartments, billboards, commercial buildings, and light industrial buildings.
- 4. Nonengineered. These are buildings and structures that receive no specific engineering attention. Examples are most single- and multiple-family residences and small commercial buildings.

Fully engineered buildings rarely experience major damage from hurricanes. If damage does occur, it is usually to nonstructural (cladding) components. The quality of preengineered buildings varies considerably. Some of them, particularly mobile homes, are usually damaged during hurricanes. Damage to marginally engineered and nonengineered buildings is highly variable and depends largely on the methods, care, and control exercised in the design and construction of individual buildings.

OVERVIEW

Beachfront houses along western Galveston Island were the first structures to be affected by Alicia's landfalling winds. Many of them were destroyed as the 19-mile stretch of Galveston Island west of the seawall to San Luis Pass experienced major damage. The subdivisions most damaged include Terramar, Bay Harbor, Sea Isle, and Jamaica Beach (see Figure 1.1). The Galveston seawall area, with its cluster of apartments and condominiums, suffered damage ranging from cosmetic to total loss of structural systems. Communities like Surfside in Brazoria County experienced significant damage. Either because of differences in the quality of construction or the complexity of the hurricane wind field (which was further complicated by flow patterns generated around nearby structures), some buildings sustained only cosmetic damage while structures right next to them were severely damaged or destroyed by Alicia's winds.

In the Houston area the storm tore up signs, downed trees, and ripped away parts of buildings. In a localized area of Houston's central business district (CBD), Alicia smashed hundreds of windows in a cluster of high-rise buildings. Damage to high-rise buildings was limited to the glass cladding; structurally, the buildings performed satisfactorily. Damage to glass cladding was not limited to the CBD. There was minor wind-induced glass damage to buildings in Greenway Plaza (southwest of the

CBD) and the Westchase area (west of the CBD). In the CBD there was major glass damage to the glass-clad Allied Bank Building and InterFirst Tower (see Figure 4.1). After the storm the intersection of Louisiana and Lamar streets was littered with sheet metal, broken pieces of pink, annealed glass from the InterFirst Tower, and shards of emerald, tempered glass from the Allied Tower.

The Hyatt Regency Hotel, the Milam and Entex buildings, and the Sheraton-Houston Hotel also suffered glass damage. The Hyatt Regency, besides losing about 100 windowpanes, lost a number of skylights that opened above the cavernous 30-story atrium, allowing water and wind from the hurricane to swirl inside. There were cracked panes of glass in the walkway connecting the Four Seasons Hotel to the Houston Center, and a few windows were smashed in the elevated walkway of the Dresser Tower by winds whipping between Houston's skyscrapers. There was no reported injury from the falling glass in the CBD because the storm struck at dawn, with plenty of advance warning.

In Seabrook, which is located on Galveston Bay east of Houston, there was heavy damage to houses, restaurants, and marinas fronting the bay. In some waterfront structures, structural damage was initiated by storm surge and waves. Strong gusty winds enhanced the structural loads, leading to progressive failure.

The following sections give an account of structural damage and of the principal sources and mechanisms of damage in the Houston-Galveston area.

HOUSTON CENTRAL BUSINESS DISTRICT

The area of the Houston central business district in which substantial windowpane and glass cladding breakage occurred is bounded by McKinney Street on the northeast, Polk Street on the southwest, and Smith and Milam streets on the northwest and southeast respectively (Figure 4.1). The high-rise buildings in this area are the Allied Bank Plaza, the InterFirst Plaza, the Hyatt Regency Hotel, the Tenneco, Milam, and Entex buildings, and the Sheraton-Houston Hotel. All are fully engineered buildings. Figure 4.2 is an aerial photograph of this block. There was substantial glass breakage on at least one face of all these buildings except the Tenneco Building. Faces with regions of intense glass breakage are identified in Figure 4.1 by bold lines. Damage to these buildings is described in the following sections.

Allied Bank Building

The 71-story, glass-skinned Allied Bank Building at 1000 Louisiana suffered serious glass damage on its southeast and southwest faces up to approximately the fortieth floor. The building has emerald-colored, tempered, double-pane, insulating vision glass and tempered spandrel glass (Figure 4.3). Approximately 300 to 400 windowpanes were damaged. However, a closer inspection of the curtain wall by a curtain wall design and consulting company indicated that more than 1,100 to 1,200 lights were broken and more than 3,000 pieces of glass would have to be replaced, along with most of the metal strips and gaskets (Engineering News-Record, 1983).

A majority of the glass damage was to the outer vision glass of view-panel and single-pane spandrel glass (Figure 4.4). It is important to note that damage was more prevalent in the spandrel glass. The building showed very little evidence of damage to window frames. Broken glass still in place after the storm indicated fracture patterns similar to those induced by impact by small missiles. The building motion was monitored during the hurricane using a pair of accelerometers on the top floor. Wind velocity measurements were not made during the hurricane.

InterFirst Tower

The 51-story InterFirst Plaza at 1100 Louisiana suffered heavy glass damage on the northeast and southeast faces, losing approximately 630 glass panels (16 percent of the total). In addition, a number of glass panels were damaged during cleanup operations when workers knocked out the broken glass remaining in frames, letting it fall to the street below. Falling glass hit other glass panels, producing further damage. Figure 4.5 shows the lower part of the northeast face of the InterFirst Building. The InterFirst Plaza has pink, double-pane, annealed glass on the exterior that does not shatter like tempered glass but instead breaks into large chunks. A closer view of broken glass in the Inter- First Plaza is shown in Figure 4.6. Some window blinds from this building were found near the Houston Library, a couple of blocks to the northwest of the building. Large amounts of paperwork and other office contents were reportedly sucked from this building during the storm. Windowpane damage was largely limited to loss of outer panes. The study team's observations inside the building on many floors showed little water damage. The motion of this building was not monitored. Motion was perceived, however, by the building maintenance crew, who stayed inside the building during the storm. Elevators squeaked during the hurricane, and the building's motion was quite noticeable to occupants.

Hyatt Regency Hotel

The Hyatt Regency Hotel at 1200 Louisiana lost 80 to 100 glass windows, including a few large panels at the plaza level. Most of the breakage was concentrated on the northeast and southwest faces (Figure 4.7). The hotel also lost several plastic skylights, which left its cavernous 30-story atrium open to swirling wind and water. The revolving restaurant at the top of the building also lost a couple of large windowpanes.

Milam Building

Breakage on the Milam building was concentrated on the northeast face around the level of the top of the Tenneco Building. Figure 4.8 shows the bell-shaped damage pattern. Laminated sloped glazing at the plaza level of the Milam Building developed many cracks but stayed in place.

Entex Building

There was general glass breakage on the Entex Building, but damage was concentrated along the east corner of the northeast face (Figure 4.9). The breakage was more prevalent in the tempered spandrel glass. It should be noted that this building has a history of occasionally losing a glass panel.

Sheraton-Houston

Hotel Figure 4.10 shows the nature of glass damage to the Sheraton-Houston Hotel. The damage was more significant on the northeast face of the building.

Other Buildings

The Republic Bank Center, then under construction at Smith and Capital streets, the walkway connecting the Four Seasons Hotel to the Houston Center, and the elevated walkway of the Dresser Tower suffered cracks and smashed windows. The Pennzoil Place experienced a few broken panels of glass on the eastern exposure. The United Bank Building, then under construction, also experienced some glass damage near the plaza level and on its east exposure.

Damage Analysis

Before analyzing the extensive glass damage in a localized region of the central business district, it is expedient to review the behavior of structural glass under wind loading. Three types of glass are generally used in high-rise cladding: annealed, heat strengthened, and tempered. To increase glass strength for resisting wind loads, thicker plates, dual panes, and/or heat-strengthened or fully tempered glass are used. Tempered glass resists high thermal stresses, which makes it the ideal choice for spandrel glass applications. Its resistance to impact depends on the type of missile. Double glazing in large panels increases the strength of a single plate by transferring some of the load through the sealed air space to the adjoining plate. A greater increase in strength would be expected with positive loads (loads from outside the building), which stress the protected surface in the sealed space. Negative loads would stress the outdoor surface, which is subjected to abrasion damage during construction and to flying debris in a windstorm, resulting in a higher probability of glass damage. Dualwindow units seldom fail in a windstorm. The outer plate can break and the central area is sucked out due to negative pressure.

Generally, tempered glass or heat-strengthened glass is not weakened by surface scratches or rubs to the same degree as annealed glass, but if a powerful impact initiates fissures deep into the glass, failure may result. The surface of glass has numerous minute flaws of varying geometries and orientations, which result from the manufacturing process and subsequent exposure. Wind loads on the surface of glass produce tensile stresses that interact with surface flaws and introduce large local concentrations of stress. Glass failure occurs as a result of local stress associated with one of the surface flaws reaching a level sufficient to initiate fracture.

The degradation of glass strength with time poses a difficult problem due to the random nature, size, and orientation of surface flaws. In certain instances a storm can cause significant degradation of strength without causing failure. The weakened panel could then break under the action of subsequent, less intense storms.

Glass design charts advanced by manufacturers specify a nominal 1-minute uniform load purported to be representative of fluctuating loads. Typical frequencies of the fluctuating pressure field around a building are much lower than the resonant frequencies of cladding glass in most high-rise buildings. This precludes dynamic amplification of glass panel response. Nevertheless, dynamic excitation can occur for very large expanses of glass with low frequency and damping.

Design charts also advance the concept of a "design factor," which implies that a design factor of 2.5 makes the probability of failure for a given glass plate at the first design load equal to 0.008, assuming a normal distribution. The performance of windowpanes can be evaluated rationally by including the facts that (1) internal stresses in glass are nonlinear functions of the external loads, (2) initial glass strength is a random function of position and direction, and (3) glass strength undergoes degradation under the influence of wind load in accordance with the principles of fracture mechanics. The wind load must be treated as randomly fluctuating, rather than as an equivalent 1-minute static load, in such a performance study. Efforts to develop such analysis procedures are under way at a number of institutions.

Causes of Glass Breakage

The glass breakage and cladding damage during Hurricane Alicia could have been caused by one or more of the following mechanisms:

- 1. Wind pressures exceeding design values on building surfaces.
- 2. Missile impact from windborne debris and falling glass.
- 3. Faulty installation.
- 4. Stresses induced in glass by excessive structural displacement (racking).

These causes will be discussed individually in the following paragraphs.

Although building codes specify the design pressures for buildings and their parts and portions, current design practice for high-rise buildings is to conduct small-scale wind tunnel tests using scale models of the new building, adjacent buildings, and surrounding features in simulated atmospheric flow conditions (Kareem and Cermak, 1979). These studies help to identify the most critically loaded areas on a building while including the influence of adjoining structures, which is not possible using the code-specified values. Most major buildings in Houston's central business district have been tested in wind tunnels for pressure measurements as well as overall dynamic response. Pressure results from the tests are given in terms of nondimensional pressure coefficients. New buildings are designed by multiplying test-derived pressure coefficients by the reference pressure, l/2pU2, where U is the wind speed at 30 ft corresponding to the 100-year mean recurrence interval for Houston and p is the air density. Any error in the estimation of this wind speed can significantly influence the pressure magnitude, and hence the performance of windowpanes. In the building code of the City of Houston (1977), the design wind speed of 90 mph is given as the extreme fastest-mile speed 30 ft above the ground with a mean recurrence interval of 100 years (which corresponds to an annual probability of exceedence of 1 percent) for exposure category B as defined by the American National Standards Institute in 1982 (exposure similar to a suburban environment). Wind records from surrounding areas and the Houston Intercontinental Airport indicate that the wind speed over the CBD during Hurricane Alicia did not exceed the design speed, implying that wind pressures did not exceed design values (R. Marshall, personal communication).

Channelization of local wind by "street canyons" or nearby structures can increase the level of pressure excursions over those that would occur in the absence of surrounding structures. Wind tunnel studies show that pressures are increased mainly along the corners and leading edges of the principal buildings. For some locations of an obstructing building, the local peak pressure on the principal building can be doubled. The interference effects are more pronounced for wind azimuths 250-450 from the normal to the face of the building and are very sensitive to changes in wind direction. Incidentally, for the Allied Bank and InterFirst buildings, these directions correspond to the northeast winds that were quite prevalent during Alicia. The height of the obstructing building also greatly affects positions where local pressures are increased on the principal building.

In a proprietary twin tower study by A. Kareem, the influence of one tower on another was investigated. The results indicated that pressures on the first tower (principal) were significantly increased when the second tower (obstructing) was introduced. This study included the effects of surrounding buildings and other features of the terrain and represents a situation similar to that of the buildings in Houston. The Allied Bank and InterFirst towers were both tested extensively in boundary layer wind tunnels. However, during the wind tunnel study of the InterFirst Plaza, the Allied Bank Building was not present, since the former study was completed well before the construction of the Allied Bank Building. Therefore, pressure increases induced on the InterFirst Building by the Allied Bank Building were not included in design pressure levels. On the other hand, the Allied Bank Building was tested in the presence of the InterFirst Tower, which ensures that interference effects were considered in developing design pressures. In view of these facts, it is quite probable that channelization and interference effects may have contributed to the problem of most of the buildings except the Allied Tower.

Missile impact is an important source of damage to glass cladding and windowpanes during extreme windstorms when substantial windborne debris are present (Minor et al., 1978). Windborne gravel striking glass can cause scratches, cracks, fissures, or fracture of the window panel. Scratches and fissures weaken glass, making it easier to break. Sharp corners of loose sheet metal (from penthouse sidings and appurtenances on roofs) ricocheting from one surface to another can be a significant source of damage to glass in a cluster of buildings.

There are three regions of missile damage in tall buildings: lower, middle, and top. Damage from missile impact is usually concentrated at the lower plaza level, which extends upward to a height of about one street width. Street canyon effects often cause this region of a building to be exposed to very high wind velocities for certain wind directions. Under such conditions, windborne debris can be a continual source of missile impact and glass breakage.

The middle region on the facade, which extends to a little above the height of adjacent buildings, is exposed to missile impact from windborne roof gravel, pieces of tar, and sheet metal from ancillary structures on the roofs of buildings, such as penthouses. In this zone the influence of channelization and interference due to adjacent buildings is more pronounced.

The third zone, the top zone, extends upward from the middle zone to the top of the building. It is generally free of any influence from adjoining buildings.

In view of the above-mentioned regions and their vulnerability to missile damage, there is substantial evidence that missile impact had a significant role in the glass breakage in the central business district. Both the InterFirst and Allied towers had no glass damage above the height of the Tenneco Building, except a few panels. This reaffirms that the windowpanes in the top zone, designed on the basis of extreme design winds and wind tunnel pressure measurements, performed satisfactorily. Most of the glass breakage on the Allied and InterFirst towers was in the lower and middle zones. The Tenneco and Entex buildings have built-up roofs with mechanical penthouses that might have been major sources of missiles, including roof gravel, ripped sections of sheet metal, chunks of tar, and other materials. On these roofs, gravel is mixed with asphalt for several reasons; it is also a cheap and efficient ballast for roofing insulation. The potential hazard of significant quantities of loose gravel on roofs during strong winds should not be overlooked (Minor et al., 1978), regardless of recent advances in roof design methods. Figures 4.11 and 4.12 show a general view of the roofs of the Tenneco and Entex buildings. The scour pattern on the Tenneco roof indicates southerly winds, which were prevalent during the latter part of the morning as the eye of the storm passed to the west of the central business district.

Information on wind speed and direction available from the Houston Intercontinental Airport (north of the CBD), Hobby Airport (southeast of the CBD), Ellington Air Force Base (east-southeast of the CBD), USGS Cutter Clamp (east-southeast of the CBD), and the Houston Health Department Building in the Texas Medical Center (southeast of the CBD) reveals that the winds were approaching the central business district from the northeast during the early morning hours. As the eye of the storm passed just to the west of the central business district, the wind direction changed concomitantly in a clockwise direction to the southsoutheast (R. Marshall, personal communication). The location of the Allied and InterFirst towers, the orientation of their damaged faces, the northeast winds changing to the south-southeast during the passage of the storm, the availability of roof gravel on the Tenneco and Entex buildings, and the favorable conditions for loose gravel being dislodged, lifted off the roof, and accelerated by strong winds all point toward missile impact being a major contributor to the glass breakage. A survey conducted for the Code Review Committee of the City of Houston by a group of glass distributors revealed that more than 80 percent of the glass breakage was caused by windborne debris. This survey supports and reaffirms the above argument for glass breakage. Regarding the glass breakage of the Milam and Entex buildings, the Hyatt Regency, and the Sheraton-Houston Hotel, there is sufficient evidence, based on the prevailing wind directions during the storm, to indicate that missile impact was one of the major contributors. Nevertheless, for the Milam, Entex, and Sheraton buildings, the aerodynamic effects--excessive negative pressure near the corners of the buildings coupled with interference from adjacent buildings--cannot be ruled out as sources of glass breakage.

Pieces of falling glass from a tall building can become missiles as they are whipped around by the wind. If they strike and break other windows, more missiles are created. It is therefore hypothesized that once some breakage occurred, a kind of cascade effect took over in a localized area of the central business district where the glass skin of a number of buildings was exposed. It is also believed that the falling glass may have caused scratches, surface flaws, and pitting or abrasion of windows that did not break, significantly reducing glass strength.

The possibility of faulty installation practices should not be completely ruled out as a possible initiator or contributor to damage. A sound analysis and design of a structure do not preclude improper installation in the absence of strict construction inspection. Potentially dangerous situations relating to poor maintenance and improper installation of both glass and cladding stone or concrete were observed in the central business district (Engineering News-Record, 1983). Insufficient anchoring of facade panels of stone or concrete left some of these hanging precariously after the storm. Missing jamb blocks, which leave glass panels free to walk to the side, insufficient bite in the glazing system, which can overstress glass due to improper support conditions, and improperly installed gaskets were other noticeable features in the central business district. This suggests the need to improve the quality of construction practices and inspection.

Excessive structural displacement due to wind effects can cause in-plane stressing of glass panels, which can promote glass failure. The recent high-rise buildings with innovative structural systems--such as the Allied and InterFirst towers--underwent comprehensive analytical and experimental dynamical analysis to account for displacement-induced stresses. It is very likely that some of the buildings in the central business district did not go through such an exhaustive analysis, thereby increasing their likelihood of overstressing of glass panels due to excessive structural displacement.

GREATER HOUSTON AREA

Besides Houston's central business district, a few other centers of business had clusters of high-rise buildings, including the Galleria area, the Medical Center, and Greenway Plaza. No significant damage to the structures or cladding was reported in these areas. Twin towers with glass cladding in Greenway Plaza lost glass only near the mid-height of the buildings. This could have resulted from the adverse effects of the adjacent building or from improper installation. A number of other buildings in suburban shopping centers lost glass, side paneling, and penthouses. Signboards were also damaged. A majority of apartment complexes throughout the city experienced at least some cosmetic damage to the roof. Every housing subdivision experienced damage, either to roofs, wooden fences, trees, or occasionally windowpanes, the last being generally due to impact of windborne debris. Wood-shingled houses lost shingles in regions of separating flow such as eaves and ridges. Some brick chimneys were blown over.

The city was in shambles, with trees strewn across streets. Street lights, traffic signals, glass, and debris littered virtually every section. Electric power lines dangled throughout the city. Windborne debris, parts of billboards, sheet metal from buildings, and material from construction sites were deposited all around the city during the storm. In view of the amount of windborne debris, the Houston area could have fared much worse than the moderate damages it did sustain.

Hobby Airport, in the southeastern part of the city, accumulated debris from construction that was under way. The winds sent more than a dozen small aircraft tumbling before wrapping them up in knots at some hangars. Some of the small planes were scattered like tinker toys, overturned and thrown into fences and other planes. Some planes snapped their moorings in the strong winds. Windowpanes were shattered, spewing glass over the inside of the lobby and baggage claim area of the terminal building. The loss of glass could be attributed to one or more of the following: poor design, improper installation, or missile impact.

At private facilities near Hobby Airport, winds peeled the wall off Sky Travel's hangar just off the airport's runway and blew steel sliding doors off their guides and inside the building. Figure 4.13 shows the loss of a non-load-bearing brick wall of an airport hangar. The overall damage in the Hobby Airport area was quite heavy.

The Houston Intercontinental Airport, in the northern part of the city, experienced only minor damage. A number of cars parked at the airport lost windows to flying gravel, and cars were flooded with penetrating rains. During the high winds, windows in the control tower started creaking, but no damage was reported. Minor roof damage was reported to terminals A and B, and a skylight broke at terminal C. A cargo building reported roof damage. No planes were damaged at the airport, but the ramp service crew for Eastern Airlines had to rescue one plane that blew free from its chocks. Continental Airlines kept mechanics in the cockpits of each of their planes for the duration of the storm to keep the planes turned into the wind and to operate the brakes and flaps.

The Houston Sports Association, which operates the Astrodome and Astrohall facilities, reported some damage to the roof of the Astrohall. Toll plazas for the parking lot and many signs were damaged. No damage was reported at the Astrodome.

Along Interstate 45 approaching Houston from Galveston, one could see many billboards either tilted or stripped by high winds (Figure 4.14). Some billboards were uprooted from their foundations and demolished. Many billboards withstood the wind, but their messages did not. In some cases, the result was a patchwork of old and new advertising on the same board. The golden arches of McDonalds were peeled off at a number of locations. Gusty winds twisted metal sheeting, crumpled skin-stressed roofs, and toppled numerous gas stations (Figures 4.15 and Figure 4.16). The ripped sheet metal added considerably to the windborne debris, increasing the threat to human life and to structures.

Highway and freeway signs were damaged. Similarly, traffic signs proved vulnerable to high winds. They either sustained structural damage or failed due to loss of their supporting structures. Throughout the city, traffic signals stopped functioning due to either power failure or structural damage.

Almost every tree in the greater Houston area suffered at least some limb damage, and in many cases the whole tree was uprooted. Some of the trees were given a permanent tilt by the strong winds. The fallen trees triggered considerable damage to overhead transmission lines, resulting in power outages and failure of a portion of many houses. Some of the trees may have experienced root damage that is yet not apparent but may eventually lead to their loss. Limbs, branches, and leaves from trees contributed substantially to the overall debris in the city, which was reported to be in the range of 2 to 3 million cubic yards.

Destruction of boats in the Houston Yacht Club marina was almost total as Hurricane Alicia ripped through the area and piled boats on top of each other. Boats moored in individual docking bays were picked up and hurled about by winds and surge. Some large barges in the Houston ship channel got loose as well during the storm, resulting in damage to dock facilities (Figure 4.17). Some of the oil storage tanks near the Houston ship channel were floated from their original locations by high water (Figure 4.18).

GALVESTON

The beachfront houses along the West Beach area in Galveston were heavily damaged. Many of these dwellings were flattened into mounds of lumber. The subdivisions most damaged include Terramar, Bay Harbor, Sea Isle, Jamaica Beach, Pirates Beach, and Palm Beach (the last two are just east of Galveston Island State Park).

The Galveston seawall area, with its cluster of apartments and condominiums, suffered damage ranging from superficial cladding damage of roofs and walls (minor loss of shingles and roof tiles and glass breakage) to total destruction. Cladding damage due to inadequate fastenings accounted for the highest percentage of the total damage. In a majority of the houses, the roof structure was toe-nailed into the top plates and the top plates were nailed into wall frame studs. The studs were toe-nailed to the bottom plate, and the bottom plate was either nailed or bolted into the deck. This anchorage system does not provide good resistance to hurricane wind forces.

The mobile home parks on East Beach and Jamaica Beach were heavily damaged, with many mobile homes practically leveled. Winds and storm surge uprooted and demolished poorly anchored mobile homes.

Engineered Buildings

Few buildings in the Galveston area were engineered. Some of the ones that were are Islanders Inn (East Beach), the Galvestonian (under construction on East Beach), the American National Insurance Building, the Hotel Galvez, the Flagship Hotel, and By-the-Sea Condominium.

Islanders Inn
Islanders Inn is a ten-story high-rise condominium building on East Beach. It is located on the Gulf side of the seawall (Figure 4.19). It is a reinforced concrete building with a sliding door opening toward the Gulf in each unit.

This building suffered damage from wind and storm surge. Large glass panels were broken, letting in the storm surge and wind and leading to extensive water damage. The foundation experienced considerable erosion. One of the units on the ninth floor lost its ocean-side sliding door panel, which probably was pushed in by wind pressure. This resulted in a very high internal pressure and led to the loss of the doors downwind. This unit was totally soaked in water and experienced significant property damage. In general, most of the units experienced damage from water penetrating openings in the facade and sliding glass doors, which were not designed to inhibit water penetration.

The Galvestonian
The Galvestonian is a very large high-rise condominium, crescent-shaped in plan, under construction next to the Islanders Inn on East Beach (Figure 4.19). It bore the brunt of winds, waves, and flooding directly from the Gulf. The facade of the building experienced minor damage, and extensive erosion occurred around its foundation. However, the structural integrity of the foundation was not affected (Figure 4.20). The reinforced concrete structural system performed satisfactorily.

American National Insurance Building
The American National Insurance Building, which is located behind the seawall on Market Street, is the tallest building in Galveston. Completed in 1971, it has a large expanse of glass in the lobby that is recessed approximately 40 ft from the exterior walls of the building. Around the elevator shaft, large panels of glass were broken. The damage was not restricted to the glass; large granite facade panels were also dislodged from their seats, and the ceiling tiles of the open lobby were damaged (Figure 4.21). The survey indicated that damage was initiated by high wind pressure excursions due to flow separation and/or by wind channelization, perhaps coupled with some improper installation.

Hotel Galvez
The eight-story 72-year-old Hotel Galvez was hard hit (Figure 4.22). Many of the oceanfront windows blew in due to extreme wind pressure or the impact of windborne debris. One of the interior walls on

the fourth floor collapsed when its sheetrock became soggy with water blown in through smashed windows. There was cosmetic damage to the tiled roof and exterior wall at various locations (Figure 4.22).

Flagship Hotel

The 10-story Flagship Hotel, which is supported on pilings extending from the seabed, suffered major wind damage. Major portions on the tops of both the gulfward and landward walls were ripped away by windgenerated negative pressures. The roof was also damaged, as were several windows in guest rooms. Figure 4.23 shows some of the damage to the Flagship Hotel (note the debris collected in the parking lot by the repair crew). There was no apparent major structural damage.

By-the-Sea Condominium

By-the-Sea Condominium is similar to the Islanders Inn but has a steel frame structure. The building stands on the landward side of the seawall and experienced cladding damage. The damage was on the lower corners of the front (windward) face and side faces, the latter of which was probably triggered by the negative wind pressure induced by separating flow along the side face. Figures 4.24 and 4.25 show a general view and closeup of the damage.

Summary

The structural systems of the fully engineered buildings performed well. There was no evidence of structural damage to these structures except to secondary systems, including roofing, cladding, facades, and glass sliding doors. Several broken glass windows and sliding doors resulted from the force of the wind and the impact of windborne debris. Considering that these buildings experienced wind speeds close to the values recommended in various codes and standards, they performed satisfactorily with the exception of the nonstructural components, which perhaps did not receive individual engineering attention.

Pre-engineered Buildings

Most of the large commercial metal buildings performed well except for some superficial cladding damage. A preliminary survey of metal buildings indicates that the buildings with large openings and overhead doors showed signs of local damage around openings and doors. This can be attributed to the fact that in the past doors have generally not been designed to withstand the same wind forces as the building. Damage was generally confined to a small area, and no material was blown off the building.

A mobile home park on East Beach was totally destroyed by the wind and storm surge. The level of destruction is well described in Figure 4.26. The study team's survey indicated that very few mobile homes were properly anchored. The anchoring straps were corroded and therefore did not provide the expected resistance to dislodging wind and water forces. Some of the mobile homes supported on pilings on Galveston's West Beach were seriously damaged by the wind (Figure 4.27). A small mobile home park on West Beach was heavily damaged as well (Figure 4.28). The structural system for mobile homes is not designed to resist the storm surge and wind loads such as those experienced during the passage of Alicia. All mobile homes in this report have been classified as preengineered structures. Older mobile homes, however, may be better classified as marginally engineered or nonengineered structures. Some of the prefabricated modular construction performed well except for cosmetic damage.

Marginally Engineered Buildings

Low-rise apartments and condominium complexes were heavily damaged by Hurricane Alicia. Built-up flat roofs and overhangs suffered various levels of damage. The Victoria Hotel is a large three-floor resort hotel with parking on the ground floor underneath the main structure.

The building was extensively damaged on its eastern side (Figure 4.29). The open land between the Victoria Hotel and an adjoining complex provides conditions suitable for the wind to accelerate.

Forces produced by the upward wind pressure at the geometric discontinuity of the roof appear to have started the damage at the overhang of the top floor (Figure 4.30). Figure 4.31 shows a part of the overhang that was lifted onto the roof. The separated flow caused large fluctuating lifting forces capable of jarring the connections, which were already under sustained loads. The cumulative effects of the load probably triggered the failure of the overhang.

The overhang did have hurricane straps, but they were not properly tied to the main frame. This brings up an important point. The improper use of hurricane straps does not protect against wind damage during a hurricane. In fact, adequate protection depends on the number of hurricane straps, their spacing, and proper connections to the basic structural system, so that forces are redistributed to avoid concentrating stress on individual structural components at the points of attachment.

The Victoria Hotel also experienced glass damage, when loose gravel from the roof of the east wing damaged glass on the adjoining wing.

Apartment complexes all along the seawall had some damage, from loss of shingles to complete collapse of roofs, walls, and substructures. Figures 4.24 and Figure 4.32 show apartment complexes with roof damage. Another apartment complex that experienced extensive roof damage was the Enchanted Wind Apartments. A number of units in this complex had roof damage, and many were declared unsafe for occupancy. Figure 4.33 shows a failed roof truss system in those apartments. The brick veneer walls in some apartment complexes did not have proper ties, which resulted in many partial failures (Figure 4.34). Alicia's winds also inflicted heavy damage to the roof of the Antigua apartment complex. The modular-construction Delmar Apartments, which are adjacent to the Victoria Hotel, weathered the storm fairly well, with only minor damage. Residents reported many tornadoes in the area of the seawall during the hurricane, but reported tornadoes could not be corroborated by the documented damage.

Moderate to severe damage to small motels and seafood restaurants occurred along the seawall. The Sea Horse Motel, which has a circular restaurant, lost all its windowpanes. A U.S. Coast Guard building of mortar block construction right on the seawall experienced no apparent damage. The roof of

Guidos, a seafood restaurant across the street from the seawall, was damaged, leading to extensive interior rain damage. The old section of Galveston, with its old brick homes, weathered the storm very well, experiencing only cosmetic damage.

The old Post Office Building performed well structurally, as did the nearby City Hall Building. Water seepage and penetration during the rain and strong winds caused water damage in some areas of these buildings, including the radar room of the Galveston NWS station. It was amazing to note that beach sand had penetrated through crevices of windows on the fifth floor of the Post Office Building.

Around Galveston some marginally engineered structures, including a motel, lost roofs (Figure 4.35). Figure 4.36 shows the total collapse of a Galveston convenience store. In this case, loss of the roof system led to the failure of a load-bearing wall. The store walls had neither steel reinforcement nor a tie beam. At Galveston Airport a few hangars suffered extensive roof damage (Figure 4.37). Other small hangars and light planes were also damaged (Figure 4.38). A majority of the apartments, marinas, docks, and houses along Galveston Bay were damaged.

Non-engineered Buildings

Single- and multiple-family dwellings and small commercial units such as convenience stores, which generally receive no engineering attention, usually experience the heaviest overall damage during wind storms. Alicia was no exception. The hurricane ripped off the roofs and top floors of some buildings while merely taking a few shingles from others. Heavy rains contributed to water damage as homes left with gaping holes and collapsed walls were drenched by the downpour. Single-family dwellings near the water were extensively damaged along the 25-mile stretch of Galveston's West Beach from the seawall to San Luis Pass. Many beachfront homes were reduced to shambles by wind, surge, and wave action. Some were washed off their foundations and transported inland by the storm surge and waves.

Damage in these housing subdivisions was classified by the study team as major, moderate, and minor. Major damage is total destruction, meaning the structure must be totally rebuilt. Moderate damage means that the structure can be rehabilitated only by major repairs. Minor damage ranges from loss of shingles and siding to sparse local damage, such as broken glass and small missile impact. This damage assessment was subjective and done quickly, using both ground and aerial inspections.

The study team noted that many homes sustained only cosmetic damage while adjacent structures were demolished. Such a damage pattern often leads to the conclusion that a tornado touched down in the area, inflicting damage unevenly to the subdivision. It is important to look into other causes of such a damage pattern as well. The geometry and orientation of a structure with respect to the wind direction and surrounding houses are important determinants of wind resistance. The variation in the quality of construction and, in particular, the attention paid to the details and joints play a key role in determining whether a house will survive. In most of the damage seen, these conditions were more prevalent than tornadic action spawned by the hurricane.

The following sections briefly summarize damage in various communities along the West Beach area.

Bay Harbor

Bay Harbor is a small subdivision between the San Luis Pass road and West Bay. The study team estimated that major damage occurred to 50 percent of the houses, moderate damage to 40 percent, and minor damage to 10 percent.

Terramar Beach

This subdivision is adjacent to Bay Harbor and suffered very heavy damage. Sixty percent of the houses experienced major damage, and 40 percent experienced moderate damage. Figures 4.39 to 4.44 illustrate the damage in Terramar Beach. Figure 4.39 shows a house that lost a good portion of its roof. The damage was initiated at the ridge and triggered the roof's failure. The wall system was well constructed and survived as a result of diaphragm action. A geodesic dome in the background had only cosmetic damage. Another dome-shaped house shown in Figure 4.40 fared very well in comparison with the surrounding coventional houses. Besides structural and aerodynamic advantages, such structures perhaps receive more rigorous building inspections, which adds to their survivability during extreme wind storms. In Figure 4.41 the house on the right was totally demolished as a result of failed connections between the foundation piles and floor joists. The house in the middle lost the front portion of its roof, with the opening creating positive pressures inside the building that pushed the back wall out of its plane.

The seafront side of the house in Figure 4.42 was totally destroyed due to wind. The partial survival of the landward portion was perhaps a result of the large size of the house and its number of interior walls. These could have stiffened the structure and kept the leeward portion from blowing away. The house next door was a complete disaster. The foundation slab was partially washed away, and the rest of the foundation was exposed due to erosion and wave action. This did not have any bearing on the overall catastrophic failure of the house (Figure 4.43). The connections of the studs to the base and top plates and the roof to the top plate were poor, with no hurricane anchors. Figure 4.44 shows the details of some of the connections and corroded nails in studs.

Sea Isle

Sea Isle is the next community east of Terramar Beach. Damage there extended from the Gulf to the bay. The damage to houses on the Gulf was classified as 50 percent major, 40 percent moderate, and 10 percent minor. On the bay side, only 20 percent of the houses were severely damaged. Thirty percent had moderate damage, and the remainder had minor damage. In the northeast corner of the subdivision, the percentages of major and moderate damage increased to 30 and 40 percent, respectively.

Figures 4.45 to 4.48 exemplify some of the damage in Sea Isle. Figure 4.45 shows an oceanfront house that lost a good portion of its superstructure to wind forces. The extent of damage decreased for houses inside the subdivision (Figure 4.46), which experienced lesser wind speeds because of being sheltered. Figure 4.47 shows part of a roof lying on the ground. There were hurricane clips, but they did not extend to the wall studs and the end plate was dislodged from the wall system. On the bay side of the subdivision, a house had lost its second story completely (Figure 4.48) due to poor linkage between subsystems.

Jamaica Beach

Jamaica Beach, a small community on Galveston's West Beach, experienced moderate overall wind damage. Damage was estimated to be 30 percent major, 30 percent moderate, and 40 percent minor. Figure 4.49 illustrates damage to a timber-framed single-family dwelling in Jamaica Beach. The house lost its roof, but the back walls acted as a strong diaphragm system and prevented total collapse. A mobile home park was a site of total destruction (see Figure 4.28). Jamaica Beach is a completely independent city and is not bound by the Galveston City Code.

Palm Beach and Pirates Beach

Palm Beach and Pirates Beach are the next two major settlements eastward along Highway 3005. Some dwellings were totally demolished, while others had only minimal damage. The damage in Palm Beach was 30 percent major, 50 percent moderate, and 20 percent minor. In Pirates Beach the damage was 10 percent major, 30 percent moderate, and 25 percent minor.

Damage to superstructures in the Pirates and Palm Beach areas was primarily caused by wind. Storm surge and waves also washed away the sand around foundations, leaving foundation slabs unsupported between pilings. Figure 4.50 shows a large commercial building in which the gable-trussed roof collapsed on the inside due to the loss of its supports. The exterior brick wall, which appeared to be a load-bearing wall, collapsed, leading to the failure of the middle portion of the roof system.

Figure 4.27 shows a mobile home of fairly large size that was elevated on a piling foundation to alleviate storm surge damage to the structure--an innovative structural concept for mobile homes. The house experienced very heavy damage, especially in its middle portion. Relatively small end spans helped to stiffen the ends of the structure, but the large midspan resulted in a weak middle portion that subsequently failed.

Other Beach Subdivisions

A small seafront subdivision to the west of Jamaica Beach experienced about 90 percent major and 10 percent moderate damage. In this subdivision a large Japanese pagoda-type house faired very well (Figure 4.51). According to the owner, it was specifically designed for extreme winds. It suffered severe erosion around its foundation, which left a gap of about 3 ft between the sand and the grade slab. The house had a series of dunes in front of it that were all eroded. The only damage to the house was loss of a skylight, which perhaps had poor connections to the roof. This allowed considerable rain into the house. Four columns of pipe cross section, which were embedded in the ground and extended to the top of the house, were loosened by erosion, but this did not cause structural distress.

Damage between Spanish Grant and Sunny Beach was 20 percent major, 30 percent moderate, and 35 percent minor. Further east of Sunny Beach, near the intersection of Seven Mile Road and Highway 3005, a small subdivision was totally leveled. Low-rise condominium projects on the west side of San Luis Pass experienced damage from wind and storm surge. Figure 4.52 shows a complex with damage to the roofs of units on the left side. A nearby modular condominium project under construction suffered minor to moderate damage to some of the prefabricated units (Figure 4.53).

An aerial survey of the damage was conducted using a NOAA helicopter to help establish damage patterns. Figure 4.54 shows some of the damage along the West Beach area.

Summary of Damage to Nonengineered Buildings

The study team found that none of the residences with structural damage investigated west of the seawall complied with the code being enforced by the City of Galveston. The city annexed the areas west of the seawall in 1975. Houses built before 1975 were therefore not subject to the code. City of Galveston records show that approximately 3,000 buildings west of the seawall are currently on the city's tax rolls. During 1975, no building permits were issued. Approximately 50 percent of the permits for the 3,000 buildings have been issued since January 1, 1980. Prior to Hurricane Alicia, the City of Galveston employed one building inspector to inspect the structural aspects of all buildings under construction. The distance between the east and west city limits of Galveston is approximately 30 miles. Considering the distance and the number of buildings under construction, it was not possible to ensure that all construction complied with the building code. The city recognized this deficiency after Hurricane Alicia and hired three additional building inspectors.

In summary, the damage to non-engineered structures was typical of that from wind storms. The structural damage from the hurricane's storm surge and accompanying waves was relatively minor when compared with that from the wind and wind-driven rain. Foundations were eroded; some houses failed from inadequate embedment of piles; some were left permanently tilted after the storm.

None of the houses along the beachfront had adequate pile bracing. For elevated houses built above the design surge-plus-wave-height elevation, it is essential to incorporate pile bracings to provide additional lateral resistance to hydrodynamic and wind loads, which are increased because of an increase in exposure due to the higher elevation.

The predominant form of damage was to roofs, including loss of roofing or loss of part or all of the roof structure. When roofs were lifted off by the wind, the external walls usually collapsed. Total collapse of timber-framed houses was a common scene. Inadequate connections, such as the toe-nailing between the floor and roof and the wall frame, failed to provide the structural strength required to resist lateral loads induced by extreme winds. In general, sheathing material of low strength with inadequate connections to the framing did not provide additional strength through diaphragm action and was easily torn from the wall frame. Hip roofs fared relatively better than others, such as gable roofs, throughout the damaged areas. This can be attributed to the three-dimensional nature of the load-resisting system for hip roofs and to the relatively lesser severity of the aerodynamic loads on such roofs.

In conclusion, the damage patterns indicate that structural damage and failure was caused more by a lack of hurricane-resistant construction than by the severity of the storm.

Coastal Structures

All major and many minor coastal structures in the area seriously affected by the storm were observed and photographed. Major structures covered were the Galveston seawall and its fronting groins, the shoreward portion of the Galveston entrance jetties, the jetties and groins in the vicinity of the Bolivar ferry terminal, and the dikes of the Texas City hurricane protection project. Minor structures covered included some of the bulkheads and revetments around Galveston Bay and behind the West Galveston barrier island.

Visual inspection of all of the major coastal structures in the area showed only minor damage to any structure, except in the case of one or two groins in front of the seawall (Figure 4.55). These groins were built using chunks of concrete pavement apparently salvaged from the breakup of unwanted paved areas. Groin damage occurred in the immediate vicinity of the beach and did not affect the functional capacity of the structures. The seawall and other groins (Figure 4.56) sustained no damage visible from the seawall. No damage was observed at the Texas City hurricane protection project, and no damage was reported at either the Texas City or the Freeport hurricane protection projects. The study team observed minor damage to a concrete slab revetment at Seabrook during its ground survey. There were also reports of damage to other small private structures around Galveston Bay and along the front of Galveston Island west of the seawall.

INLAND AREAS

The following sections briefly describe the damage from Hurricane Alicia in small cities around Galveston Bay and Galveston Island.

Baytown

Baytown was damaged by wind and flooding. Flooding damage was especially bad because of a preexisting subsidence problem in the area. Floodwaters rose to the level of upstairs windows in the Brownwood subdivision, and the hydrostatic and hydrodynamic forces completely ruined many houses. Loss of building sidings and glass panels was common. The roof of a nightclub collapsed. A convenience store lost its sidewalls. Chemical industry plants in the area suffered minor damage. Some oil storage tanks were displaced from their original positions by the storm surge and wind.

Clear Lake

Some trees fell and there was some flooding in Clear Lake. But overall the residents of this multicommunity bay area had few major problems. Rising tides and torrential rains flooded roads, and debris was found everywhere--along the marinas and in the streets. According to a National Aeronautics and Space Administration official (Houston Chronicle, August 20, 1983), the roofs of more than 50 major structures at the Johnson Space Center were damaged during the storm. More than 200 trees toppled, 10 windows shattered, and three huge steel roll-up doors buckled. There was also damage to communications and tracking equipment.

Deer Park

Most of the damage in Deer Park was to the North Campus of Deer Park High School, which was being used as an evacuation center. The school lost a good part of the roof of the girls' gymnasium and the woodshop. A few windows were blown out.

Hitchcock

The hurricane uprooted many trees and damaged the roofs of houses in Hitchcock. A two-story funeral home on Highway 6 was severely damaged. It lost its brick siding, and its roof support trusses were deformed.

Kemah

The storm surge and wind caused damage in the Kemah area. Water flooded the Tide Inn Motel, reaching depths of up to 10 ft inside the building. The Kemah pier was lost under rubble. Many seafood restaurants suffered damage from wind and storm surge.

Pasadena

In Pasadena the damage was generally minor. Some engineered structures experienced glass damage due to windborne debris. The city building also lost some skylights, which provided easy access for the rain and raging winds to enter the top floor of the building and damage the interior.

Seabrook

The city of Seabrook, which is located on Galveston Bay north of Clear Lake City, is the site of numerous marinas, bayfront houses, and seafood restaurants. This area experienced damage due to both the storm surge and wind forces. The study team's damage survey indicated that the majority of the damage was initiated by the storm surge and then furthered by the wind force.

One dramatic structural failure involved a motel on an elevated foundation. Floodwaters lifed the structure off its foundation, which consisted of light-gage peripheral steel beams and pipe columns. Subsequently, the motel's superstructure floated inland. The impact of landing and complex forces induced by buoyancy and wave action led to catastrophic failure. Figure 4.57 shows the bent foundation frame and demolished wing of the motel. The elevated foundation system was not adequately designed for this region, where storm surge and wave action can induce significant hydrodynamic loads. The damage pattern suggested that the storm surge initiated the damage, after which the structure progressively failed as a result of wave and wind action.

A number of houses in Seabrook lost part or all of their walls or roofs. The damage pattern again suggested that failure was initiated by the storm surge. In Figure 4.58 a house fronting the bay lost its wall system due to wave action, which led to the collapse of the roof system. The three-story structure in Figure 4.59, perhaps marginally engineered, lost a brick veneer wall that was not properly anchored, and a combination of storm surge and wind action caused heavy damage. Figure 4.60 shows a closeup of a slab with anchor bolts. Obviously the house was uplifted due to poor connections. A view of the ground-level enclosure of a bayfront house shows damage due to storm surge (Figure 4.61). Once the enclosure lost one side, winds tore apart the interior of the house. The house on top did receive minor damage from high winds. A mansion in Seabrook, on top of a hill, survived the fury of Alicia (Figure 4.62). The mansion did not experience any storm surge effects and there was no evidence of wind damage.

Surfside

The Surfside community, which is located southwest of Galveston on the west side of San Luis Pass, was in the southwest quadrant of the hurricane. This area experienced flooding and strong winds that leveled many poorly constructed houses along the beachfront. Houses were twisted and dismantled. In some cases, trees and utility poles were hurled into houses, cutting through the structure and leaving the contents open to strong winds and heavy rains. The old U.S. Coast Guard Station at the western edge of the town had only minor damage.

Texas City

There was no major damage in Texas City, but there was light damage to roofs, signboards, brick siding, and transmission lines. Light poles at Texas City's high school stadium were destroyed. An apartment complex lost a sidewall, and a car dealership lost a large expanse of glass. The most significant damage was experienced by the top floor of a contemporary-style apartment complex (Figure 4.63). High wind gusts twisted and bent the radio towers at the police station as well.

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LIFELINES

LIFELINES IN MAJOR AREAS

City of Galveston

Galveston lost power to its water supply and sanitary service during Hurricane Alicia. However, using natural gas engines, water pressure in the system was maintained at 25 to 30 psi, which was somewhat lower than normal to account for line breaks that could not be immediately repaired. Galveston has its own well fields and also receives some water from Houston. Approximately 32 million gallons were kept in storage for emergency use during the period after the hurricane.

Beachfront homes were hardest hit by the storm. About 1,000 ft of small water lines were lost in beachfront areas. Temporary cutting and capping were necessary until the lines could be replaced. It took three days to restore power to the Thirtieth Street pump station, and eleven days to do so for the Fifty-Ninth Street station. However, auxiliary water supplies were able to take care of emergency situations. The Thirtieth Street station, which was activated by telephone, was without telephone service for about a month. During this time the station had to be operated manually.

using a number of small fossil fuel-powered pumps, 90 percent of the capacity of the sanitary lift stations was maintained. None of the 25 lift stations was equipped with standby power. It took one and a half weeks before electricity was restored to all the lift stations. Sand had clogged many of the beachfront sewer lines. These were still being cleaned out more than a month after the storm.

City of Galveston officials estimated that the total cost to repair the water supply and sewage systems in Galveston was $170,000.

Several smaller nearby communities such as Bolivar and Hitchcock lost water pressure. Rechlorination was required before full pressure could be applied again. Disruptions in telephone service made it difficult to communicate with employees needed for repair and cleanup. Radio and TV were interrupted by the general power outage.

The storm did not cut any highways, but some roadbeds were undercut on the main highway on Follets Island (see Figures 5.1, Figure 5-2, Figure-5-3). This undercutting occurred when the high water that ponded behind the island flowed into the Gulf. In one case, the undercutting extended through the highway pavement but not through the road shoulder. This allowed traffic to bypass the cut on the shoulder. Trees and debris also blocked some highways temporarily. Bridges were not damaged and could be used if the roads to them were not blocked. Some owners of beach houses now face the problem of their homes being at the edge of the water at high tide because the wind and wave action eroded the beach 3 to 4 ft vertically.

City of Seabrook

Power went out on the night of August 17, shutting down water supply and sanitary operations in Seabrook. A reserve water supply kept in an elevated storage tank was used before power was restored. Auxiliary power was used for about three days after the storm to operate the pumping stations. Seabrook's well system does have auxiliary power. The sewer system does not. Sewage systems ran over; however, there was no backup into homes. The sewage system was out for almost a week, because auxiliary power was not available and because generators and other equipment had to be cleaned and checked before sewers could be brought back into operation.

Loss of power was the main reason for problems with the water supply and sewer systems. There were some drainage problems in low-lying areas. Fallen trees, debris, and wind were the major reasons for power failure (see Figures 5.4-& 5-5 and Figures 5-6 & 5.7). Wind was a larger factor than was water from rains in causing the loss of power lines and poles. No temporary measures were used; only permanent repairs were made. Crews worked around the clock making repairs and putting services back in order. City of Seabrook officials estimated that the cost of damage to the water supply and sanitary systems in Seabrook was $50,000.

City of Houston

Public Transportation

All public transportation--taxi cabs, Metropolitan Transit Authority buses, and major intercity buses--as well as most private vehicles were off the roads from about 2:00 a.m. August 18 until the morning of August 19. Fallen trees, signs, and other debris caused the biggest road blocks. Trees were more susceptible to being blown over because of heavy rains preceding Alicia that had softened the ground. City of Houston officials estimated that the cleanup would take until the first week in October and cost several million dollars. Some prison help was to be used in the cleanup.

Water Supply

The Houston system managed to maintain water pressure, although there was some question about its adequacy to furnish water to all floors in high-rise structures and to facilities requiring normal water pressure. Pressure was felt to be adequate for fighting fires. Generally, the reduction in pressure was due to a loss of power and not to broken lines. Auxiliary power was not sufficient to maintain normal pressure. Debris blown into the West Canal blocked screens and required a continuous watch and cleaning operation. One treatment module lost a check valve, which resulted in a flooded pipe gallery during the hurricane. This was back in operation on August 20.

Assessment of damages was begun on August 18 and all systems were back to normal operation by noon on August 21, though some repairs were temporary.

The Houston Water Department has an Emergency Manual, and procedures contained in this were for the most part successfully followed using one control point for the staff. Damage to facilities of the Water Department was confined primarily to roofs of buildings, electric motors, switch gear, etc. Some fences and ground storage tanks were damaged by falling trees.

People were cooperative in the cleanup effort, with some volunteering to help. City of Houston Water Department officials estimated that damage to the water supply system was between $500,000 and $750,000.

Sanitary System

Houston operates separate waste and storm systems. When the power went out all treatment plants and pumping stations also went out, because none had auxiliary power. However, there were no complaints of backup in the system. Houston actually received more rain on September 19 than it did during the hurricane. The system was back in operation by Sunday, August 21. Repairs were necessary to tools, fences, and some motors, and water damage occurred at one plant. City of Houston Sanitary Department officials estimated that the cost of repairs was about $200,000.

Hospitals

Most hospitals had auxiliary equipment that enabled them to retain power. However, water pressure remained low until normal power was restored. In one case, a pumper from the fire department was placed on standby to ensure adequate pressure.

AREAWIDE LIFELINE SYSTEMS

Telephone Service

Approximately 20 percent of the telephone service in the Houston-Texas City-Galveston area was lost during and after the hurricane. Suburban areas experienced more problems than did the downtown area. Some 250,000 subscribers were affected to some degree (i.e., they could not call long distance or reach certain local areas) or had no phone service at all. Of these 250,000 people, an estimated 103,000 were without service for at least one day. An estimated 11,000 were still without service on September 15. All were expected to have service restored by October 1.

A telephone company strike reduced the speed at which repairs were made and increased the time subscribers were without service. In the opinion of some telephone personnel, reports of problems were slow in coming because customers were aware of the strike and felt that trying to report problems immediately with the expectation of expedient repairs was futile. Texas City and Galveston experienced heavy rainfall associated with the hurricane, which hindered repair service. Telephone service was not expected to reach prehurricane levels until November 1.

Rail Transportation

The Santa Fe Railroad evacuated their employees from Galveston Island about 4:00 p.m. on August 17. Rail cars were also moved from the island. The hurricane knocked out about 800 ft of track between Texas City and Galveston. The damage was caused by the loss of ballast by washout. Three trestle bridges were knocked out of line, but they were realigned in about a day and a half. Since the power was out in the Galveston area, it was necessary to bring in a generator to operate railroad signals two days after the storm. Debris had to be cleared from the tracks, along with 10 boats found on the tracks after the storm. Santa Fe Railroad officials estimated that the total cost of damage to the railroad was roughly $300,000.

Highway Transportation

No bridges were themselves impassable. Only when debris blocked a bridge or access to a bridge was the bridge not available for traffic. Interstate 45 (south), Highway 146, and NASA Road 1 were all blocked or partially blocked with debris on August 18. Interstate 45 and Highway 146 were both cleared in about three days, but NASA Road 1 took almost a week to clear. Most traffic signals were not operating, and some were damaged by wind or debris. Some were still not replaced or repaired more than a month later. There was also roof and glass damage to Highway Department buildings. The Texas Highway Department uses "breakaway" signs. Some of these were found to have broken at the breakpoint; others failed elsewhere. In District 12 (which includes both Houston and Galveston), damage to the highway system, including 3,000 highway and road signs, was estimated at about $3 million. The Texas Highway Department estimated that six hundred people, plus others from outside areas, were needed to direct traffic and help with cleanup operations.

Air Transportation

Houston International Airport did not report any damage to planes. However, damage to projects under construction was considerable. Alicia damaged the roof of the Cargo Building and caused leaks at expansion joints in the roof of the Terminal Building. This roof was also designed as a parking deck. Two to three hundred flights were diverted the day of the hurricane. Damage at the airport was estimated at $500,000 to $750,000. Hobby Field was closed from about 2:00 a.m. to 6:00 p.m. on August 18. Damage caused by wind and water to the Terminal Building, Freight Building, and FAA Building was estimated at about $500,000. Roofs, glass, sprung doors, and water were the chief causes of damage to these buildings. There were 20 to 25 parked aircraft that suffered some damage. No flights were allowed in during the shutdown period. It is the pilot's prerogative to take off, but none left during this time.

Power and Light

Alicia caused some 750,000 customers to be without power in the area, which is about 59 percent of the total customers. Eight thousand miles of power lines were out of working order, and 600 of these 8,000 miles were actually on the ground. There were 40,000 drops of lines, and 2,400 poles were broken. Of the some 1,100 distribution stations, 569 were out, along with 72 of 160 transmission lines. The hurricane made landfall about 1:00 a.m. on August 18. It took 12 days (11 workdays) to return the system to some semblance of normality. Roughly 3,000 people were in the field during this time. Texas Light and Power Company officials estimated that the total damage to power and light facilities as of September 23 was about $14 million. The total projected cost of repairs was between $18 and $20 million.

Radio and TV

For the most part, radio and TV were able to keep transmitting through the use of auxiliary power so long as towers and lines remained intact.

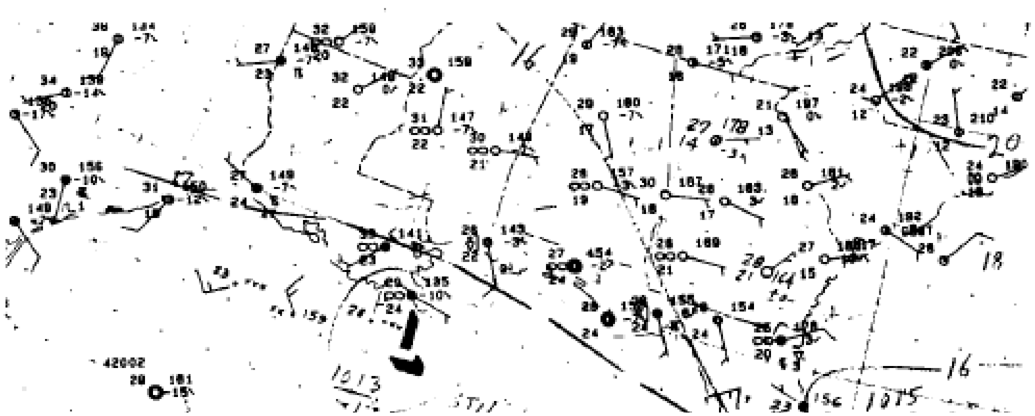
METEOROLOGY

STORM DEVELOPMENT AND HISTORY

The weather disturbance that later became Hurricane Alicia began to form in the north-central Gulf of Mexico during the night of August 14 and morning of August 15, 1983. Figures 2.lA-2.lD show a sequence of four regional surface weather maps that depict the development and intensification of Alicia into tropical storm and hurricane status. These analyses cover the four-day period from August 14 to 18. The first map (Figure 2.1A) shows the early stages of Alicia. It developed as a mesoscale (mid-sized) low-pressure area on the extreme western end of a frontal trough that extended from off the New England coast southwestward into the middle Gulf of Mexico on August 14-15. Figures 2.1B and 2.1C show the low-pressure area moving westward off the Mississippi and Alabama coasts into the north-central Gulf of Mexico, along with the remnants of the frontal system extending westward across Florida and into the western Atlantic. Though this developmental pattern may seem unusual, other similar cases of typhoon/hurricane development have been documented in the western Pacific and Atlantic. There, tropical cyclones have been known to develop on the southwestern end of old cold fronts that have moved off the east Asian and U.S. coasts, lose their thermal contrasts, and become quasi-stationary in the tropics or subtropics (Riehl, 1959; Simpson and Riehl, 1981).

In the case of Alicia, as with typhoon developments in the western Pacific, the old frontal zone became an identifiable source of cyclonic vorticity, which was the embryo of the storm. This type of tropical storm development more often occurs much earlier or later in the storm season. This is well illustrated by the analysis in Figure 2.1A, which shows the earliest detectable tropical depression stage of Alicia on the evening of August 14, when the system was centered over the northern Gulf of Mexico south of New Orleans.

Alicia was upgraded to tropical storm status on August 15 (Figure 2.1B), even though the surface pressures over the entire region remained rather high. Note that the minimum pressure of the tropical storm at this time was only about 1014 mb (29.95 in.). However, ships in the central Gulf of Mexico clearly indicated a closed circulation at that time. With these relatively high environmental pressures (approximately 1015 mb) around Alicia's circulation, the storm remained quite small and therefore generated winds stronger than those usually observed in tropical storms with similar minimum central pressures. Other cases of small tropical storms with relatively high central pressures have been observed in the southwest Atlantic (Simpson and Riehl, 1981). This condition persisted through August 16 (Figure 2.1C), when the system became a minimal hurricane.



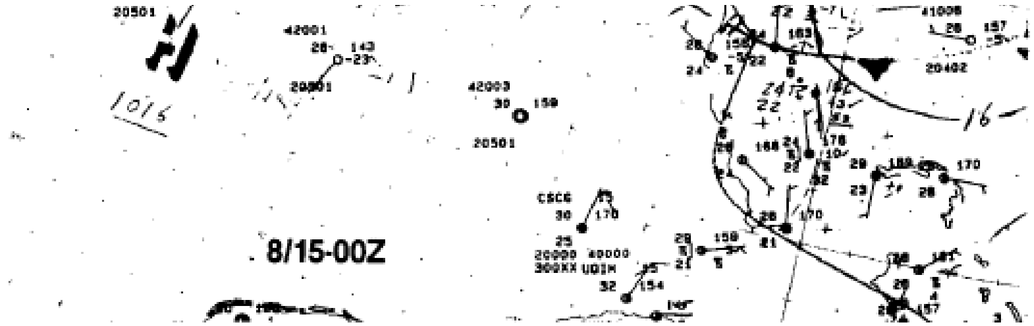


FIGURE 2.1A Regional surface weather chart for 0000Z (7:00 p.m. CDT, August 14, 1983). Solid lines are isobars analyzed at 4-mb intervals. Source: National Weather Service.

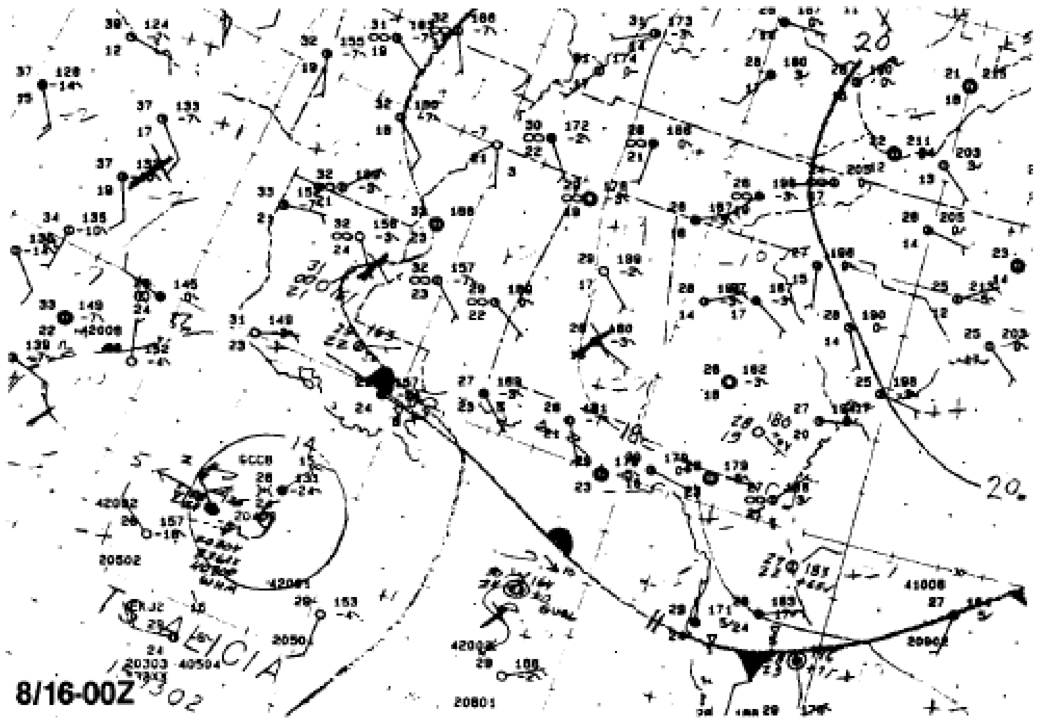


FIGURE 2.1B Regional surface weather chart for 0000Z (7:00 p.m. CDT, August 15, 1983). Solid lines are isobars analyzed at 4-mb intervals. Source: National Weather Service.

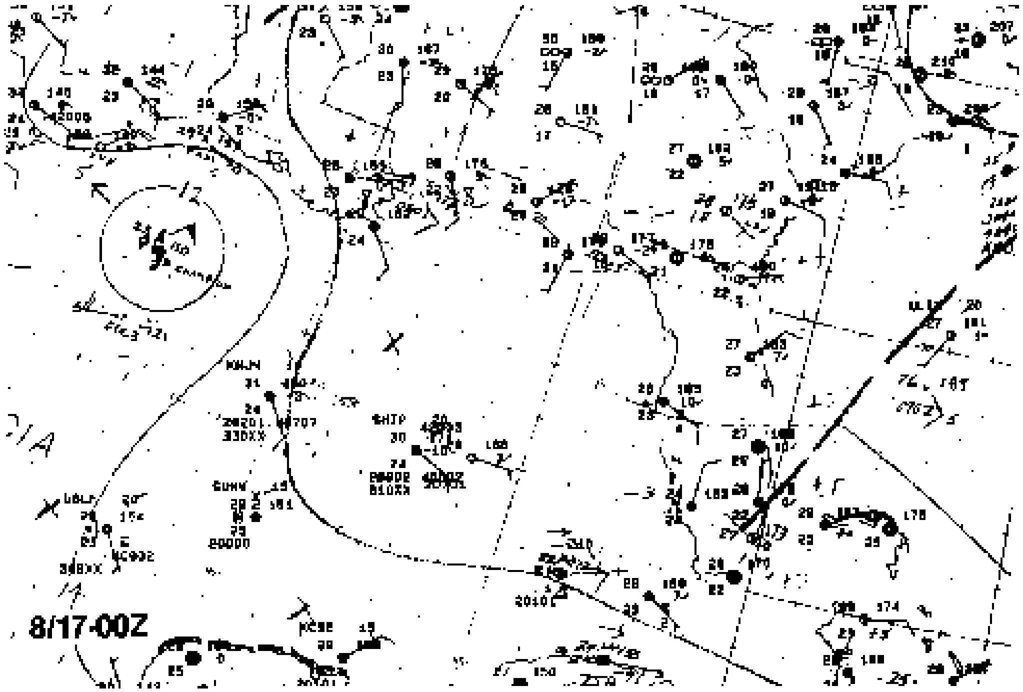
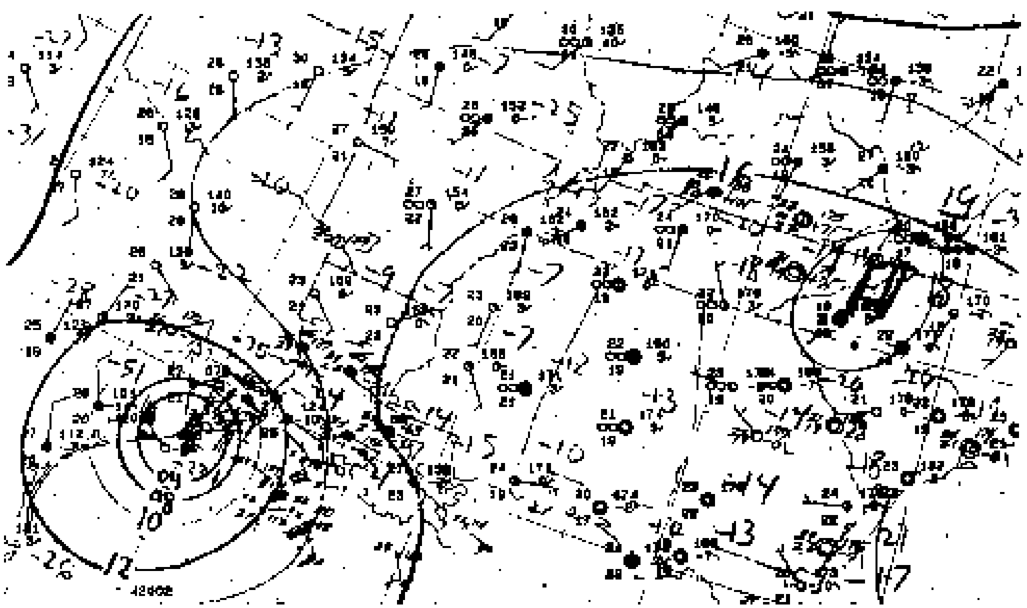


FIGURE 2.1C Regional surface weather chart for 0000Z (7:00 p.m. CDT, August 16, 1983). Solid lines are isobars analyzed at 4-mb intervals. Source: National Weather Service.



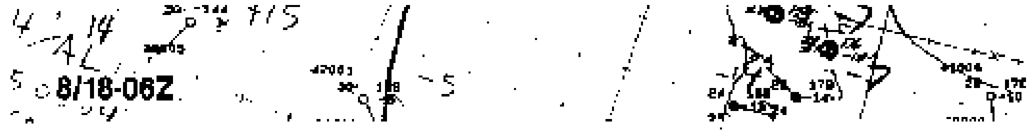
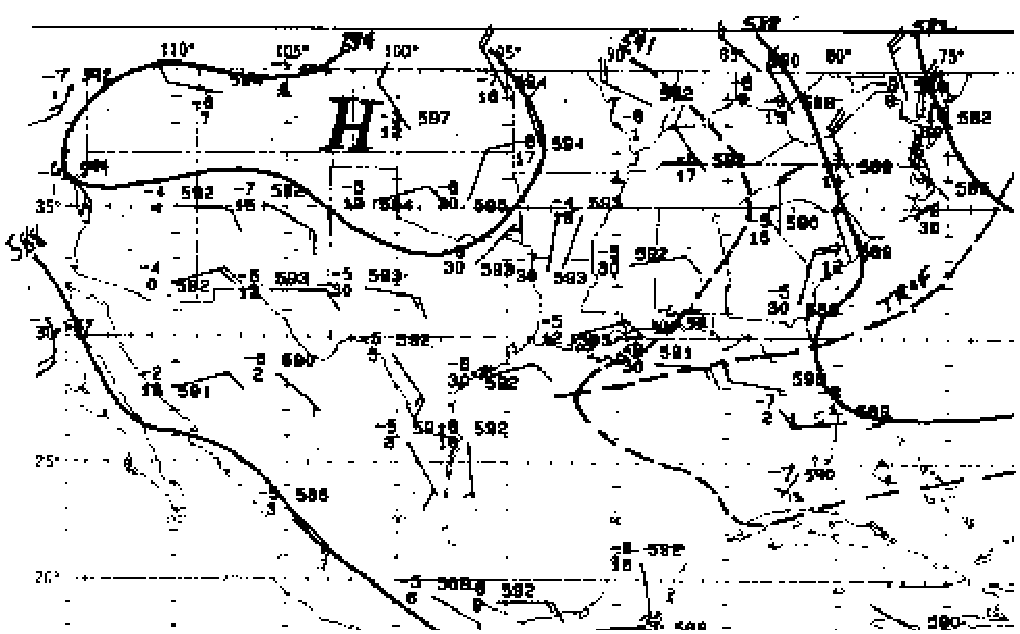


FIGURE 2.1D Regional surface weather chart for 0600Z (1:00 a.m. CDT, August 18, 1983). Solid lines are isobars analyzed at 4-mb intervals. Source: National Weather Service.

Hurricane forecasters often use "steering currents" around hurricanes to estimate or extrapolate their likely future direction and speed of motion. Steering currents over the storm were quite weak throughout most of Alicia's lifetime over the Gulf of Mexico. As shown in Figures 2.lA-2.lC, a high-pressure ridge was well established to the north of the storm. In fact, slight pressure rises were observed to the north of the storm center, with pressure falls along the Midwestern and Gulf states from August 15 to 17. The result of these pressure changes was that Alicia drifted toward the west through midday of August 16, when the storm turned toward the west-northwest.

The steering currents around the storm during this period are best illustrated by Figures 2.2A-2.2D, the first three of which correspond in times to Figures 2.1A-2.1C, showing the 500-mb analyses over the largescale regions surrounding Alicia (these 500-mb geopotential height analyses depict the large-scale flow around the storm at approximately 18,000 ft--i.e., the midtroposphere). The initial development of Alicia's circulation aloft was one that is very often observed and has been described for the Caribbean by Riehl (1954). In this case (data not shown), an upper trough broke into two parts near the eastern coast of the United States, the northern portion continuing east and the other part retrograding westward from the southeastern United States. A cyclonic envelope remains at the surface from an old front in these cases (Figures 2.1A and 2.1B), but the temperature contrast must disappear across the frontal zone, of course, or there will be no tropical cyclone, which is the most frequent case.



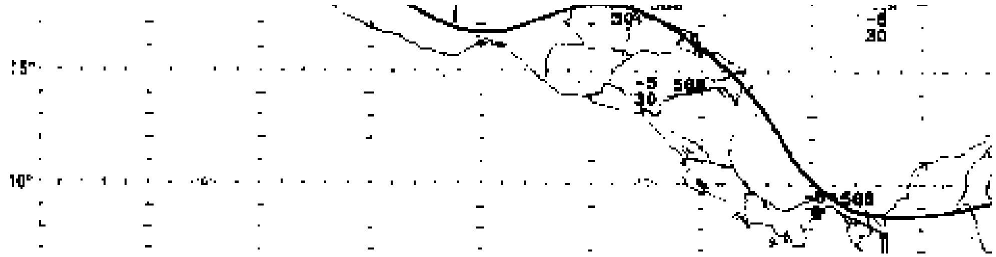


FIGURE 2.2A Regional upper-air analysis at 500 mb for 0000Z (7:00 p.m. CDT, August 14, 1983). Source: National Weather Service.

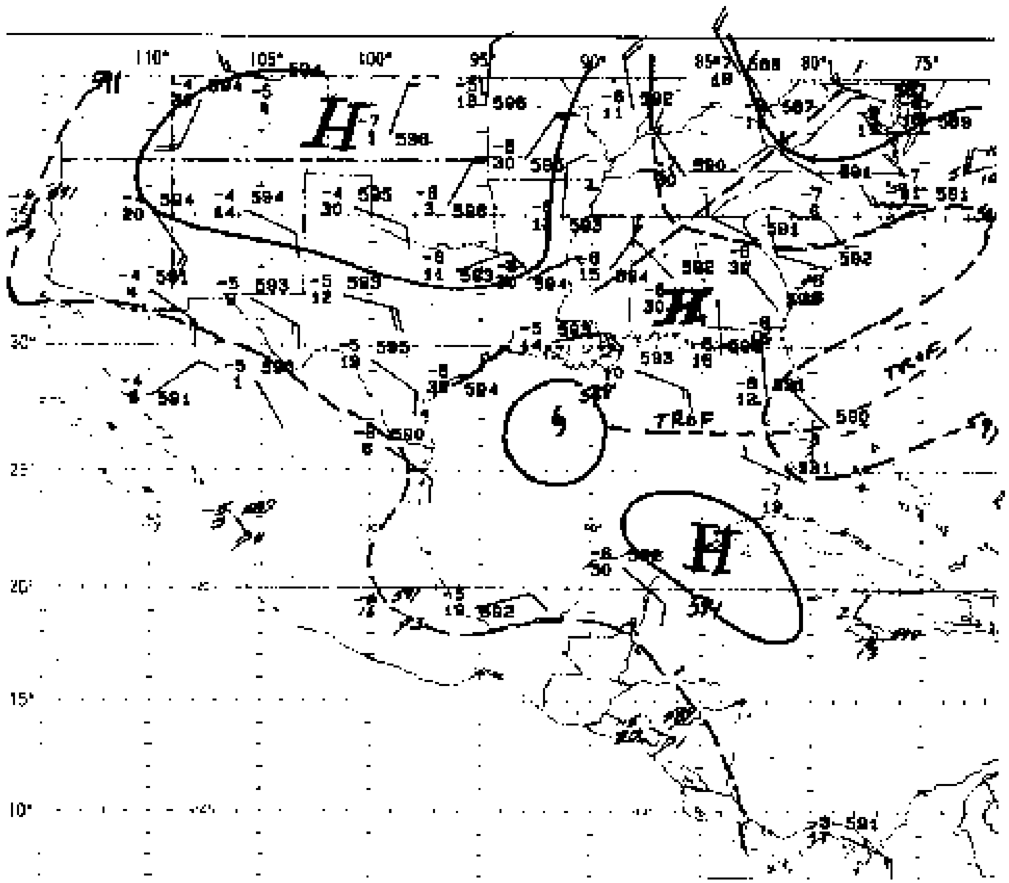


FIGURE 2.2B Regional upper-air analysis at 500 mb for 0000Z (7:00 p.m. CDT, August 15, 1983). Source: National Weather Service.

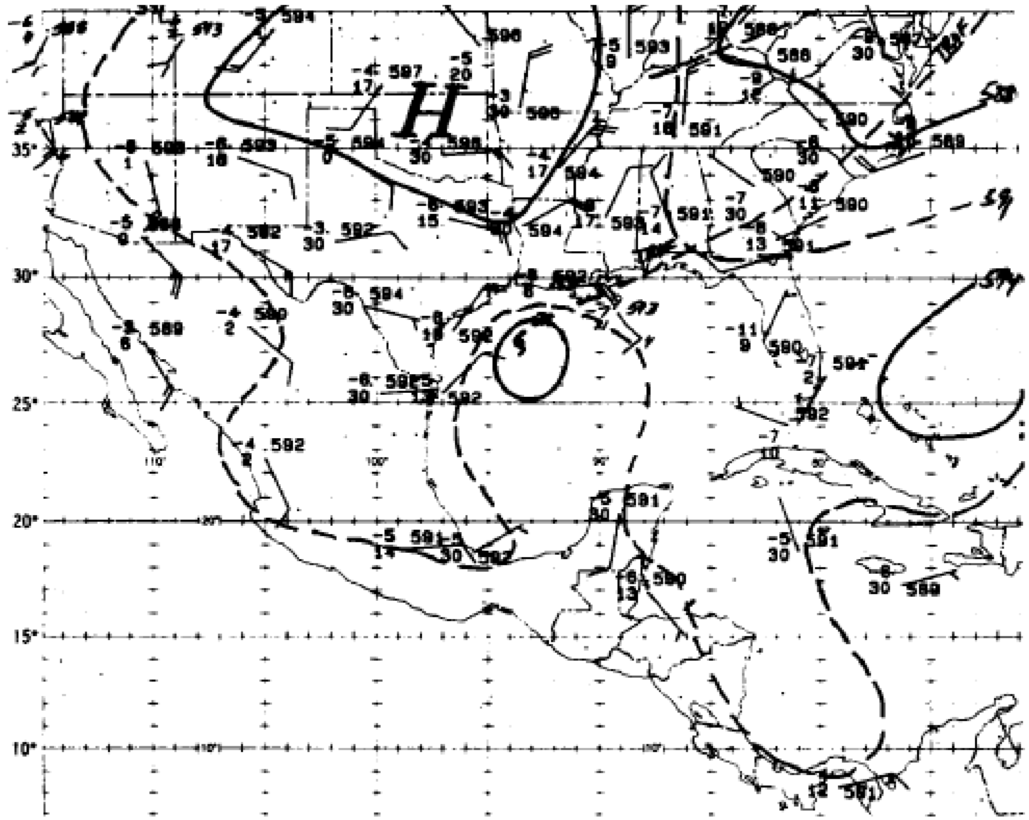
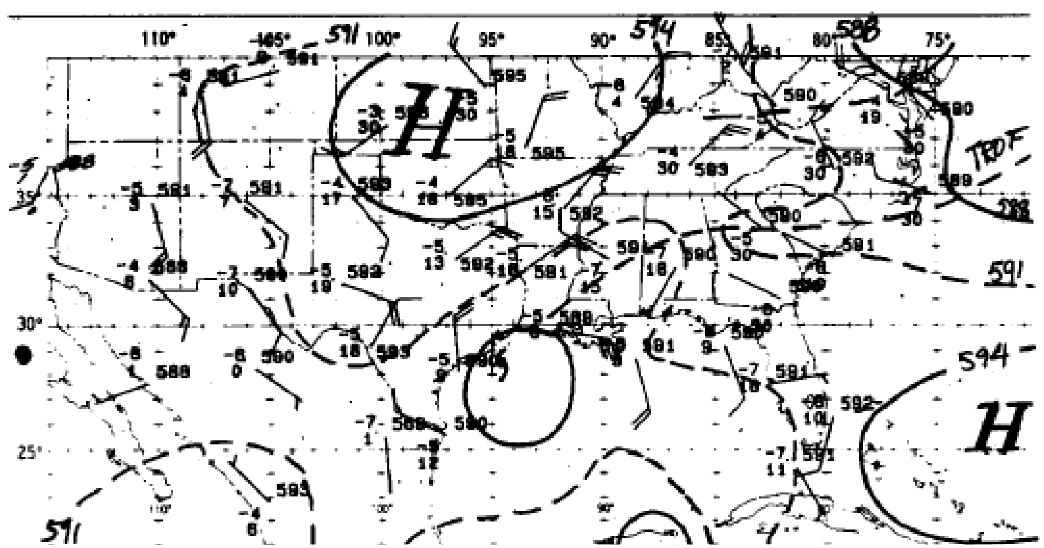


FIGURE 2.2C Regional upper-air analysis at 500 mb for 0000Z (7:00 p.m. CDT, August 16, 1983). Source: National Weather Service.



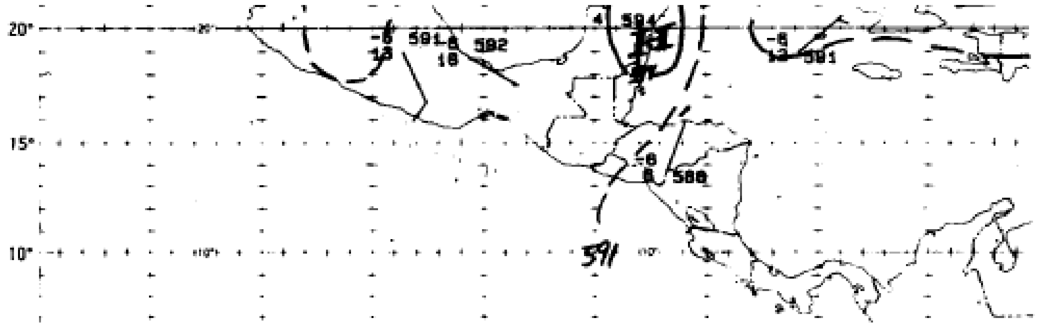


FIGURE 2.2D Regional upper-air analysis at 500 mb for 0000Z (7:00 p.m. CDT, August 17, 1983). Source: National Weather Service.

The final best-fit track of Alicia from tropical depression stage to after its landfall as a hurricane on the Texas coast is shown in Figure 2.3A. This track was derived from reconnaissance aircraft fixes (up to landfall), land-based radar fixes (Galveston, Lake Charles, Texas A&M-College Station, and Corpus Christi before and after landfall), and positions estimated from satellite data. Figure 2.3B shows the radar centers from the Galveston and Texas A&M radars. There are more than one apparent circulation centers in many hurricanes after landfall, and the radar center is not necessarily the center of circulation.

Hurricane Alicia's slow track toward the west-northwest continued at speeds less than 10 mph through the late afternoon hours of August 17. An important and unusual aspect of the storm's motion developed during the late night and early morning hours of August 17, when the eye of the hurricane began slow, erratic looping motions best characterized as cycloidal (see Figure 2.3B). These cycloidal motions in the eye's track occurred between about 7:00 a.m. and 9:00 p.m. CDT on August 17 and again during the two hours after landfall. Cycloidal motions in hurricane tracks are difficult to forecast and have only rarely been observed in the past. Shortly after 7:00 p.m. on August 17, Alicia turned rather sharply toward the north-northwest and began to gain forward speed toward its final landfall on western Galveston Island. There is no obvious explanation for this change in the storm's track from the available environmental data shown in Figures 2.2A-2.2D.

A sequence of NOAA geostationary satellite photographs (Figures 2.4A-2.4D), which correspond to the series of surface analyses presented earlier, illustrate the evolution of Alicia from weak depression to tropical storm and finally to a hurricane of moderate size and intensity at landfall (see Figure 2.4D, an enhanced-infrared satellite photograph). It should be noted that Alicia took a more northerly track as the high-pressure ridge to the north apparently weakened and broke apart into two cells (see Figures 2.IA-2.ID). At the same time, an upperlevel anticyclone became well established over the storm. A portion of the upper trough did not cross eastward but remained north of the Gulf Coast oriented east-west, with west winds at high levels above the coastal stations. Thus an upper clockwise circulation was already over the low-level storm on August 15. This factor, well known by hurricane forecasters to be conducive to storm strengthening, combined with the slow movement and long period over the warm (more than 290C) Gulf waters, resulted in Alicia's deepening at an apparently steady rate of 1 mb/h over the approximately two days prior to landfall (due to available potential energy for release). According to Riehl (personal communication), this long quasi-steady deepening from weak tropical disturbance to full hurricane strength is very unusual. Finally, it should be emphasized that the cycloidal motions noted above in Alicia's track on August 18 have been documented in a few other hurricanes before, most notably Hurricane Carla in 1961, which also devastated the Texas coast (for causal mechanism, see Yeh, 1950, and Novlan and Gray, 1974).

STORM CHARACTERISTICS AT LANDFALL

By most standards for Atlantic and Gulf hurricanes, Alicia was a mediumsized hurricane of only slightly greater than average intensity. It reached minimal category 3 status on the Saffir/Simpson scale at landfall (Simpson and Riehl, 1981, App. A). The Saffir/Simpson scale is a relative scale ranging in value from 1 to 5: 1 is a minimal hurricane and 5 is the strongest hurricane that could be expected (the best example of a 5 in this century was Hurricane Camille in 1969, which moved ashore in the Biloxi, Mississippi, area). Structural damage typically begins when winds exceed 90 to 100 mph. Therefore, a major hurricane is arbitrarily defined as a 3, 4, or 5 or one in which the winds exceed 110 mph. For reference, the 1900 hurricane that claimed 6,000 lives on Galveston Island (Tannehill, 1938) was a strong 4. However, most of the fatalities in the 1900 Galveston hurricane were a result of the high storm surge, which led the survivors to construct the 15-ft-high seawall that served so well during Alicia.

The eye of Hurricane Alicia made landfall on the extreme western tip of Galveston Island (about 25 miles southwest of the NWS radar site at Galveston) at approximately 1:45 a.m. CDT on Thursday, August 18. It should be emphasized, however, that most of the damaging effects of Alicia occurred over a much larger area. The minimum central pressure as determined by a NOAA P-3 reconnaissance aircraft at about the same time as landfall was 962 mb.

The hurricane's rainfall structure during the 12 hours prior to landfall is strikingly illustrated by the radar reflectivity maps in Figures 2.5A-2.5H. This unusual composite, obtained only once before from an NWS coastal radar for Hurricane Frederic in 1979 (Parrish et al., 1982), shows a shaded digitized sequence of radar photographs developed by NOAA hurricane research scientists from the NWS Galveston 10-cm radar and from a 10-cm radar at Texas A&M University. (Digital radar data were also acquired by University of Miami researchers on a weakened Hurricane David in 1979.) The different shades refer to reflectivity values, which are strongest in the eyewall and intense rainbands of the hurricane (proportional to rain rates of 2.0 to 4.5 in./h or more). The highest wind speeds tend to occur under or inside the highest radar reflectivities in the eyewall and major rainbands (Parrish et al., 1982).

The hurricane exhibited a very unusual "double eye" structure from about 0300Z (10:00 p.m. CDT) to 0600Z (1:00 a.m. CDT), just prior to its landfall, and surprisingly again during the two hours after landfall. This double-concentric eyewall structure was also documented by NOAA research aircraft in several earlier Atlantic hurricanes, including Hurricane Allen in 1980 when it was rapidly deepening as it approached the Yucatan Peninsula in the northwest Caribbean Sea (Willoughby et al., 1981). Some other recent storms exhibiting this structure include Anita in 1977, David in 1979, and a number of western Pacific typhoons investigated by instrumented aircraft.

The double-concentric eyewall structure in Hurricane Alicia is most apparent in Figures 2.5C and 2.5D, where the highest reflectivities occur in the northeast and north quadrants of the storm. During the three to six hours prior to landfall (Figures 2.5C and 2.5D), the outer eyewall collapses in the southwest quadrant of the storm (i.e., reflectivities diminish rapidly there). Moreover, the outer eyewall appears to begin to dominate the convective structure of the hurricane after landfall (Figures 2.5E and 2.5F). Finally, it should be noted that the distribution of maximum reflectivity in the forward portion of the eyewall was very similar to the reflectivity patterns documented by NOAA research aircraft during the most intense phases of Hurricane Allen and other intensifying hurricanes.

The interested reader should carefully consider the distribution of rainfall in Hurricane Alicia and its temporal evolution as the hurricane approached and made landfall, as shown in Figures 2.5A-2.5H. The evolution of the hurricane's precipitation distribution should be compared with the storm track shown in Figure 2.3B to infer the general surface rainfall maxima relative to Alicia's track. In Figures 2.5C and 2.5D the inner eye is approximately 25 km in diameter while the outer eye is approximately 80 km in diameter. Note that the double eyewall surprisingly redeveloped shortly after landfall (Figure 2.5F).

The NOAA P-3 aircraft was flying through the storm nearly continuously during the last 6 to 10 hours prior to landfall. Composites of the NOAA P-3 flight-level winds along its track at 5,000 ft are shown in Figures 2.6A and 2.6B. The first composite covers the period from 2200Z (5:00 p.m. CDT) to 0300Z (10:00 p.m.) on August 17, ending approximately four hours prior to the hurricane's landfall. Superimposed on the analysis of winds (the stream lines are solid and the isotachs, in meters per second, are dashed) is the hurricane's track as it approached landfall. A noteworthy and unusual feature is the strong wind maximum in the northern semicircle of the eyewall, where sustained wind speeds measured by the aircraft reached slightly over 100 knots (Figure 2.6A). Downstream from this wind maximum--i.e., in the northwest quadrant of the storm--the flow diverges markedly and resembles the "downburst" phenomenon documented by Fujita (1978, 1980) beneath some severe thunderstorms over land (small, very intense downdrafts that impinge on the surface and spread out rapidly). Also noteworthy is the fact that the analysis clearly indicates a double wind maximum in the northern semicircle of the storm, corresponding to the double eyewall noted earlier in the composite radar sequence (Figure 2.5C).

Figure 2.6B is a later composite windfield from the NOAA P-3 flights at the 5,000-ft level between 0500Z (midnight August 17) and 1200Z (7:00 a.m., August 18), the times closest to and just following landfall. The wind patterns around the hurricane at this time have changed drastically (that is, they have become "normal" again after some hours of unsteady readjustment). These patterns indicate that the maximum wind speeds occurred to the northeast, or to the right of the storm center, as it made landfall. Again, there was a double wind maximum corresponding to the double-concentric eyewall structure noted in the sequence of radar maps, with an inner wind maximum of at least 85 knots a short distance southeast of the center and a higher maximum of at least 100 knots, from the south-southeast, in the outer eyewall of the hurricane. Also noteworthy in Figure 2.6B are the strong westerly wind components to the south of the recurving storm center.

Finally, Figure 2.6C gives a composite of surface winds, converted from time to space, relative to the hurricane after it made landfall. The composite extends from 0300Z (10:00 p.m. CDT, August 17) to 1500Z (10:00 a.m. CDT, August 18). Again, the highest wind speeds reported were to the east of the storm center over the eastern portion of Galveston Island, extending north-northwestward along the western portions of Galveston Bay and inland. In addition, while direct measurements were lacking, another region of damaging winds and surge levels occurred just to the right of Alicia's landfall over western Galveston Island. A secondary wind maximum of more than 60 knots is noted to the west and southwest of the storm center in the Freeport area.

Figures 2.7A and 2.7B shows radial profiles of horizontal winds through Alicia's eye outward to the northeast (2.7A) and southwest (2.7B). Note especially the distinct double maximum wind speed in these figures, at radii of about 18 and 35 nautical miles from the eye, with the outer wind maximum the strongest at landfall. Powell (1982) used 10-m-level wind data over water (VO) and at coastal stations (VL) to formulate approximate relationships of the low-level (500 to 1,500 m) aircraft wind (Va) to the mean coastal wind and peak gust (VLG) at the same place relative to the storm center. For Hurricane Frederic in 1979, Powell found VLG = 0.8Va and VL = 0.56 Va. These relationships may vary from storm to storm and with the altitude of the aircraft, but they are useful to forecasters in their assessments of low-level aircraft reconnaissance data for issuing warnings.

The hurricane as a whole produced only average amounts of hurricaneassociated rainfall after it made landfall. Figure

2.8 gives a preliminary analysis of the rainfall pattern over the two-day period following landfall. Maximum rainfall totals occurred over extreme eastern Harris County northeast of downtown Houston and ranged upward to 10 to 11 in. Somewhat lesser rainfall amounts, about 8 in., were reported in the Galveston area, and secondary maximum of 9 in. on the Sabine River north of Orange, Texas, and 8 in. in Leon County northeast of College Station are noteworthy.

Rainfall totals in the areas near landfall are suspect because of the well-known tendency for rain gages to underestimate hurricane rainfalls due to eddy currents around gages during high winds. Experimental evidence gathered by Larson and Peck (1974) shows that gages underestimate the true rainfall by approximately 20 percent at wind speeds of 9 m/s. Moreover, Dunn and Miller (1960) speculated that rain gages probably catch less than 50 percent of the actual rain when wind speeds are greater than 25 m/s. The hurricane's pressure distribution near and following landfall may be discerned by studying the four barograph traces shown in Figures 2.9A-2.9D. The eye of the storm passed over the NWS office at Alvin, Texas, which is well inland, with a minimum of 967 mb. The steepness of the pressure fall and subsequent rapid pressure rise after the eye's passage are clearly shown in the Alvin trace (Figure 2.9A) as contrasted with the microbarograph traces from Baytown, NWS Galveston, and Ellington Air Force Base (Figures 2.9B, 2.9C, and 2.9D), all of which were located to the east and northeast of the inner eye depicted in the radar composites of Figure 2.5. The Alvin pressure trace is the only one of the four shown that was clearly affected by the eye of the hurricane, and in fact Alvin was probably influenced by the western portion of the eye as it moved northnorthwest. Ellington may have been briefly affected by the eye during the slow looping period in the track during the few hours after landfall.

Another interesting feature of the Alvin pressure trace is the indication of a weak high-pressure ring surrounding the core of the hurricane, which is evident in the minor pressure rises in the morning of August 17 and again after the eye's passage in the night hours of August 18. The hurricane near landfall appears to have been in what has been called in the literature the "immature stage" (Dunn and Miller, 1960). The Alvin barograph trace is very impressive in that respect, showing a sudden drop to a central pressure of 967 mb but a period of only 10 hours with pressures below 1000 mb. Forecasters seldom have to contend with this kind of central pressure tendency in storms around landfall.

The wind field in Hurricane Alicia, as obtained by NOAA's P-3 aircraft at 5,000 ft in the hours up to landfall, has been described earlier. Figures 2.10A-2.10D present a sample of anemometer records depicting some typical and some unusual wind regimes in Hurricane Alicia (locations of the anemometers are indicated in Figure 1.1). Two traces from the Alvin NWS and Galveston NWS offices should be taken as representative samples of the winds at landfall in the inner eyewall (Figure 2.10A) and in the space between the inner and outer eyewalls (Figure 2.10B). Likewise, Figures 2.10C and 2.10D are the anemometer traces from Dow Chemical Plants A and B at Freeport, Texas, which were located in the southwestern semicircle of Alicia's inner eyewall at landfall. Note especially the strong evidence of high sustained winds and peak gusts, with westerly components at the Freeport site, which are rather unusual in that normally weaker side of hurricanes. Another recent example of anomalously high west winds in hurricanes making landfall was documented by Fujita (1980) for Hurricane Celia in 1971. Many intense damage swaths were produced at Celia's landfall over Corpus Christi, Texas, with west-to-southwesterly winds up to 120 knots.

A synthesis of all available wind data obtained thus far for Alicia near landfall is given in Table 2.1, which includes both sustained winds and peak gusts for various locations in the Houston-Galveston area (for locations of the sites listed in Table 2.1, see Figure 1.1). Some of these wind records were obtained at nonstandard mast heights, as noted in the table. Therefore a map plot of Alicia's wind speeds is not being attempted at this time (Richard Marshall of the National Bureau of Standards is doing more detailed analysis and research on the wind records obtained from many sites during Alicia in southern Texas). No wind records are available in the region of Galveston Island between Sea Isle and Jamaica Beach, which includes the boundary of the inner eyewall of Alicia at landfall (see Figure 2.5). It is therefore suspected that the sustained winds and peak gusts given for those locations nearest the coast at landfall are low estimates of Alicia's actual maximum winds. Moreover, sufficient data in the Baytown region indicate gusts ranging upward to 110 to 120 mph, marking this area as one of anomalously strong winds that seem to be associated with the outer eyewall on the radar composites at landfall (Figure 2.5). The radar film from Texas A&M University (Figures 2.5F and 2.5G) gives additional evidence that the outer eyewall became the dominant convective band after landfall (with the highest associated wind speeds).

TABLE 2.1 Alicia's Winds near Landfall (the Night of August 17-18)

Station	Average Wind Speed[a]	Wind Direction	Time (CDT)	Peak Gust	Time (CDT)	Minimum Station Pressure (in.)	Time (CDT)	Anemometer Height	Notes
USCG Cutter Buttonwood (northeast tip Galveston Island)	80 knots	120	0115	110 knots	0230	29.27	0445	45 ft	
	83 knots	210	0500	105 knots	0500				
NWS Galveston	62 knots	SE	0218	89 knots	0134	29.22	0400	105 ft	
				82 knots	0419				
Dow Plant A, Freeport	60 mph	285	0245	88 mph	0316			~10 m	Speed based on 10 min.
Dow Plant B, Freeport	57 mph	295	0235	94 mph	0232			42 ft	Speed based on 10 min.
Texas City AAMN (ambient air monitoring network)	38.9 mph	079	2445			29.47	0100	10 m	Speed based on 10 min.
	73.0 mph	057	2445					90 m	Power failure at 0000 CST.
NWS Alvin	36 knots		0245	63 knots	0242	28.55	0525	10 m	Speed based on 10 min. Was in west side of eye (0525 CDT).
	38 knots		0635	62 knots	0636				
Ellington Air Force Base	48 knots	040	0255	69 knots	0624	29.00	0655	13 ft	Thunderstorms (0138-0455 CDT).
	48 knots	150	0755						
Hobby Airport	68 knots	190	0946	93 knots	0800			~20 ft	Thunderstorms (1519-1853 CDT). Control tower reported speed = 70 knots. Peak gust = 86 knots at 0400 CDT.
Exxon-Baytown	71 mph	140	0945	118 mph		29.44	0700	120 ft	Speed based on 30 min. Height corrections unknown (several gusts 110+ mph)
WSCMO Houston (IAH)	44 knots	080	0853	68 knots	0846			20 ft	Thunderstorms (1518-1853 CDT).
USCG Cutter Clamp	55 knots	135	0900	104 knots	0700	29.11	0730	35 ft	
City of Houston Air Quality (1115 N. MacGregor)				69 mph (050°)		0530		75 ft	Several gusts to 60-67 mph between 0700 CDT and 1000-1120 CDT. Questionable exposure.
				68 mph (200°)		1023			
Amoco, Chocolate Bayou	40 mph	045	23-24			29.49		10 m	Speed = average over 1 h.
	50 mph	050	22-23					90 m	Power failure at 00 CDT.
Braes Meadow (southwest Houston)	67 mph		06-07			28.85	0730	<10 m	Winds estimated using linear regression analysis of Hobby data. Speed based on 1 h, open terrain, and 10 m.
Diamond Shamrock (San Jacinto)	116 mph							80 ft	
USI (southeast of San Jacinto)	59 mph	130	0600	82 mph	0612			30 ft	Speed based on 15 min.

[a]Unless otherwise noted, speeds correspond to 1 minute.

One of the major problems encountered during the team's survey was the large number of anemometers in the Houston-Galveston area, both private and state or federally owned, that had no recording capability or backup power for emergencies. In particular, the small network of anemometers that comprise the Federal Aviation Administration-sponsored LLWAS (low-level wind shear alert system) at Hobby Airport provided no recorded wind data from Alicia.

Twenty-three tornadoes were reported to the National Severe Storms Forecast Center in Kansas City in association with Hurricane Alicia. Fourteen of these were reported to have occurred between 8:00 a.m. CDT on August 17 and 8:00 a.m. on August 18. This first group of tornado reports were concentrated in the area just southeast of Alvin, near the Hitchcock-Arcadia areas, and in the small coastal community of Baycliff on the western side of Galveston Bay. Less than half of these reported tornadoes could be corroborated by the study team's subsequent aerial damage surveys. All of the supportable tornadoes were apparently associated with a pronounced outer convective rainband and wind speed maximum, and were north and east of the storm's center during landfall on August 17-18. The other nine tornadoes reported occurred during the following 24 hours and were scattered over an area north of Houston to Tyler, Texas. Figures 2.11A-2.11C give aerial damage photographs in the area between Hitchcock and Baycliff from a NOAA helicopter at 1,000 ft over some of the suspected tornado tracks and one microburst (Fujita, 1980). All of these were embedded in the more general, spotty hurricane damage.

OFFICIAL FORECAST PERFORMANCE FOR ALICIA

In general, the forecasts issued by the National Weather Service's Miami National Hurricane Center for Gulf coastal areas threatened by Alicia were state of the art.

There are currently seven operational hurricane prediction models available to hurricane forecasters at the NHC. Only two of these models are dynamical--i.e., are derived from fundamental physical principles and the equations of motion and thermodynamics. The other models depend heavily on statistical approaches (e.g., regression equations) to predict the future track of hurricanes in the Atlantic, the Gulf, and the Caribbean. Neumann and Pelissier (1981a) have thoroughly described each of the seven operational models used by the NHC to derive the 'official forecasts" of hurricane motion and changes in intensity. They have also provided an operational evaluation of the seven prediction models. They remark that "none of the models can be singled out as clearly superior or inferior, each having at least one temporal, spatial, economic or utilitarian advantage. In practice, it is difficult to combine these advantages into one all-purpose model." Neumann and Pelissier therefore conclude that for some time into the future official forecasts and operational guidance for hurricanes will likely have to be subjectively synthesized from a number of different models, both statistical and dynamical.

A series of sample, yet typical, runs of the seven operational hurricane prediction models used at the NHC during the 24 hours before Alicia's landfall are shown in Figures 2.12A-2.12C. The starting point on each of the model plots is the position of the hurricane's eye, as determined by the hurricane forecaster in a best-fit fashion from aircraft reconnaissance fixes, satellite images, ship reports, and coastal radar. In a companion paper that analyzed forecast errors in Atlantic tropical cyclones, Neumann and Pelissier (1981b) point out that the most important forecast for the issuance of hurricane warnings along a coastal segment is the 24-hour projection. Of the various models whose results are shown in Figure 2.12A, which were run using the initial position of Alicia and other data at 0600Z (1:00 a.m. CDT, August 17), most forecast landfall in the Corpus Christi area about 24 hours later. The best forecast was made by the NHC-67 statistical synoptic model, which put landfall on western Galveston island, although its forecast of Alicia's 24-hour displacement was too great, putting the storm just to the northwest of Houston.

Similarly, Figure 2.12B indicates that the forecast models run from data available a little more than 18 hours prior to landfall (1200Z or 7:00 a.m. CDT, August 17) also :tended to move the hurricane too far to the left of its actual track. This kind of model bias is typical for hurricanes over the northern Gulf of Mexico and is reflected in the divergence of hurricane tracks from past climatology (Neumann and Pryslak, 1981). Even the more sophisticated dynamical models, such as the medium-fine mesh numerical forecast model and the Navy's nested-grid model, had Alicia moving much too fast and well to the left of its actual path. Again, for this time period, the NHC-67 model had the closest projection to the actual track, although it too predicted a track faster and to the west of Alicia's actual path.

Finally, the NHC model runs made at midday, just a little more than 12 hours prior to landfall (1800Z or 1:00 p.m. CDT, August 17) had biases and errors similar to the earlier runs. Again, the statistical models NHC-67 and CLIPER gave the best results. These results are consistent with the findings of Neumann and Pelissier (1981b) that there is statistically significant bias for translation speed in the 12-hour projection, and that large errors are principally related to the recurvature situation (when a hurricane's track acquires a northerly component of motion and "recurves" into extratropical latitudes), which was the case for Alicia after 7:00 a.m., August 16. However, these model runs for Alicia are not in concert with the finding by Neumann and Pelissier (1981b) that, for short-range projections, forecast errors for storms initially located in the Gulf of Mexico tend to be lower than average for all periods. Neumann and Pelissier also found that the mean forecast errors for short-term predictions vary considerably over the northern Gulf of Mexico, and that the 24-hour forecast error in the area around Galveston during the period considered (1970-79) is greater than average (109 nautical miles).

Another major factor contributing to the forecast errors for Alicia (and other storms in the Gulf of Mexico) is the paucity of surface and upper-air data needed to more adequately define the environmental structure of the hurricane, and especially the midtropospheric "steering flow" around it. Most vexing for this particular hurricane were its rather sharp turn to the right late in the afternoon of August 17, less than 12 hours prior to landfall, and its simultaneous though temporary forward acceleration.

NOTICE:

The Committee on Natural Disasters project, under which this report was prepared, was approved by the Governing Board of the National Researcn Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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CONCLUSIONS

METEOROLOGY

1. Alicia was only a slightly larger and more intense than average hurricane. However, it was unusual for the following reasons:

- o It developed and remained within about 200 nautical miles of the coastline.
- o It steadily deepened during the nearly two days prior to landfall.
- o For no reason discernible from the available data, it turned rather sharply to the right (toward the north-northwest) during the 24 hours before landfall.
- o It made cycloidal track loops while offshore and during its first two hours after landfall.
- o It had double-concentric eyewalls prior to and shortly after landfall.

2. Alicia was one of the most comprehensively observed hurricanes to ever affect the United States. It was probed by instrumented National Oceanic and Atmospheric Administration (NOAA) P-3 research aircraft up to the region of landfall (reconnaissance aircraft normally avoid penetration flights into hurricanes after landfall for safety reasons) and by at least four ground-based weather radars as well as by the usual array of weather instrumentation. Nevertheless, the study team found serious gaps in the current surface network near the coast. There is a pressing need to fill gaps in this network.

Recommendations: The following steps are recommended to close serious gaps in the current meteorological surface network near the coast:

- A. Backup emergency power should be provided for some of the many anemometers and other weather instruments, especially radars, in hurricane-prone coastal areas.
- B. Rainfall measurement capabilities should be improved, either by improved rain gage design or by use of radars and satellites, to more accurately define the distribution of rainfall in hurricanes making landfall.

3. The problems in predicting the time and place of Alicia's landfall and the serious consequences that could develop from such a failure make it clear that the federal government needs to give higher priority to improving forecasts of storm track and storm intensity changes, especially for hurricanes within 24 to 36 hours of landfall. The performance of the objective numerical guidance products currently available to hurricane forecasters indicates that the statisticaldynamical models developed 10 to 15 years ago often still outperform the more sophisticated dynamical prediction models (for the 12- and 24-hour forecast periods).

Recommendation
High priority should be given to the following urgent needs:

- A. New second-generation dynamical prediction models.
- B. Improved data on hurricane "steering flows,' probably from aircraft-released dropwindsondes

and satellites (VAS).

- C. Improved techniques for forecasting the development of hurricanes and additional observing methods to better define the low-level wind field in hurricanes approaching landfall. A promising approach appears to be the installation of Doppler radars under the NEXRAD (next-generation radar) program, which is a joint project of the U.S. Departments of Commerce, Defense, and Transportation. The radars will be placed in several coastal cities (and elsewhere in a U.S. network) during the latter part of this decade, replacing the National Weather Service's aging WSR-57 conventional radars.

4. Twenty-three tornadoes were reported during Alicia. Less than half of these could be verified. However, hurricane-spawned tornadoes have caused serious damage and loss of life during previous storms. Since the conditions under which these tornadoes occur are different from those associated with other tornadoes, a special study of tornadoes accompanying hurricanes is justified. A significant problem in the study of tornadoes in hurricanes is identifying their damage in the general damage associated with the hurricane. The study team surveyed the effects of Alicia on the fifth through eighth days after the storm. By this time the team found it difficult to separate normal hurricane wind damage from possible tornado damage because the rapid human cleanup of debris configurations masked the small-scale tornado damage paths, which are difficult to distinguish under ideal conditions, from the broader hurricane wind damage.

Recommendation

A. More research is recommended on the conditions that lead to hurricane-spawned tornadoes and on ways to improve the detection and warning of these tornadoes.

B. After future hurricanes suspected of having embedded tornadoes following landfall, aerial photography and surveys by qualified meteorologists and structural engineers are recommended no later than 24 hours after landfall.

STORM SURGES AND SHORE PROCESSES

Coastal Surges

- 1. Storm water levels in the Gulf of Mexico reached a maximum of 9 to 10 ft in the area from the west jetty of the Galveston entrance westward to and just past Bay Harbor on western Galveston Island, a distance of about 25 miles. The maximum water levels decreased slowly with distance both eastward and westward of this central area.
- 2. Maximum water levels in East and West bays just behind the barrier islands were generally 6 to 7 ft. However, in the bays behind Folletts Island, maximum water levels increased, reaching maximum elevations of 8 to 10 ft.
- 3. Maximum water levels around the west side of Galveston and Trinity bays reached elevations ranging from around 8 ft near Texas City and Baycliff to between 10 and 11 ft in the Baytown area.
- 4. With the exception of the 9.5-mile section protected by the Galveston seawall, almost all of Galveston Island was overtopped by a foot or more of water from the Gulf of Mexico. East

Beach, in front of the Galveston seawall, was overtopped by 3 to 6 ft of water.

- 5. Follets Island was overtopped by the high water level in the bay behind the island from San Luis Pass to within 4 miles of the Freeport entrance channel. This overtopping from the bay to the Gulf cut more than 30 distinctive channels starting at the beach, through the frontal dunes, and toward, to, and in some cases into the highway running behind the beach.
- 6. The western 3 miles of Bolivar Peninsula were overtopped by water coming from the Gulf. East of that point the front of the peninsula was overtopped, with water ponding between the foredunes behind the beach and a relic dune ridge on the island. When the Gulf water levels lowered, the ponded water ran back into the Gulf, cutting four large channels through the frontal dunes and beach.

Shore Processes

- 1. The most striking aspect of the shore processes during the storm was that all of the high-water line recession occurred to the right of where the center of the storm crossed the coastline, with a sudden sharp change of high-water advance just to the left of the storm center.
- 2. Retreat of the high-water line on western Galveston Island, measured from before and after aerial photographs, ranged from about 15 ft near the seawall to almost 200 ft near San Luis Pass. Along most of the beach from Jamaica Beach westward, retreat was more than 100 ft. At Terramar Beach and westward, recession of the high-water line was 170 ft or more.
- 3. The vegetation line retreated more than 1,000 ft at Terramar Beach, with an average retreat of 200 ft or more on western Galveston Island.
- 4. On Follets Island, the mean high-water line advanced an average of about 30 ft. Retreat of the vegetation line was small, usually less than 25 ft.
- 5. There was serious retreat of the high-water line (100 ft or more) for the first 17 miles to the right of the storm and significant retreat (20 ft or more) for at least 55 miles.
- 6. Changes in the vegetation line generally followed the pattern of changes in the high-water line, but vegetation line changes were larger--probably because they were a result of both erosion and overwash coverage.
- 7. Observations by the study team consistently showed that vegetation is a powerful scour inhibitor. This was true not only for the marsh grasses on the low portions of the undeveloped barrier island but for the whole range of grasses to lawn grasses in yards. Where water flowed across western Galveston Island, scour occurred along streets, sometimes ripping up the pavement, before it occurred on grass lawns or adjacent natural grassy areas.
- 8. Street ends and footpaths through the frontal dunes behind the beach, which were always the first places to permit scouring flows to pass no matter which direction the water flow came from, were focal points for both overtopping and scour. Often these initial openings were widened and deepened, threatening nearby roads and structures.
- 9. There was a marked difference in the frequency and appearance of scour cuts made in areas where water flowed from the Gulf to the bays as opposed to areas where water flowed from the bays to the Gulf. Where water flowed from the Gulf to the bays, there were few scour cuts and the cuts that were found were short and shallow, ending in an outwash deposition fan. Where water flowed from the bays to the Gulf, cuts were frequent and deep and it appears that if flow had continued long enough, scour would have cut completely through the island.

Recommendation The two types of scour cuts should be studied to establish their roles in barrier island

and inlet processes.

BUILDINGS AND STRUCTURES

In general, Alicia's winds did not exceed design values included in building codes in the Galveston-Houston area. In addition, damage from flooding and storm surge was limited to one or two localized areas. Therefore little building and structural damage should have occurred from Alicia, yet this was not the case. Reasons for damage and suggestions for studies or changes that would improve the performance of buildings and structures during future hurricanes are given for two areas, the Houston central business district and the City of Galveston.

Houston Central Business District.

1. During the passage of Hurricane Alicia through the Houston central business district, wind speeds did not exceed the design wind speed recommended by the city wind loading code. Accordingly, glass panels designed in accordance to the design wind and appropriately selected pressure coefficients--taking into account the influence of surrounding structures--should have performed adequately during the storm. The study team's damage survey in the wake of the storm found little or no evidence of glass failure due to inadequate glass strength. However, this does not prove that inadequate glass strength was not the cause of some damage. Aerodynamically critical locations on some buildings could have been exposed to high pressure levels, due to channelization and interference effects, far exceeding those values that would exist in the absence of surrounding structures.

Recommendations

- A. A wind tunnel study should be required for all high-rise buildings in central and suburban business districts. The favorable or adverse influences of proposed buildings on adjoining buildings should then be conveyed to their owners for possible action prior to the construction of the new buildings. Any changes in laws or codes needed to implement this recommendation will require careful phrasing and interpretation to avoid unnecessary delays in the construction of new buildings.
- B. For small buildings a stringent design review by a professional experienced in wind engineering should be required in lieu of wind tunnel testing.

2. It is certain that windborne debris--e.g., loose sheet metal, roof gravel, construction debris, broken glass, and parts of appurtenances from roofs--ricocheting in the street canyons was a major source of glass damage in the central business district.

<u>Recommendations</u> Local government officials in hurricane-prone areas should consider the following actions:

- A. Prohibiting the use of roof gravel in future construction in central business districts and other urbanized areas.
- B. Requiring either vacuuming, bonding gravel, paving, or construction of adequate parapets for existing gravel roofs.

- C. Ensuring structural integrity of rooftop appurtenances--such as sheet metal components--through improved structural design requirements.
- D. Instituting measures to control debris at construction sites, especially during the hurricane season.
- E. Requiring periodic inspections to ensure that appurtenances on roofs--such as aerials, antennas, skylights, vents, and other attachments-- are securely fastened.

3. Faulty installation practices contributed to some glass damage--e.g., missing jamb blocks, insufficient glass bite, and improper installation of glass and stone facade.

Recommendation Local government officials in hurricane-prone areas should consider design reviews and testing of products, followed by on-site testing and inspection, to minimize faulty glass installation in commercial buildings.

4. Penthouses are often not given proper engineering attention and are sometimes introduced after completion of wind tunnel tests. A penthouse is generally located in a complex flow field in which, because of separated flow, wind speeds exceed the code-recommended value. Properly located pressure taps in a wind tunnel study will help to assess overall loads as well as identify locations of high pressure excursions. The components of penthouses such as doors and any sheet metal siding must be appropriately designed and fastened to prevent failure during extreme winds, after which they can become dangerous windborne debris.

Recommendation Penthouses proposed for construction on existing buildings should be given proper engineering attention, including wind tunnel testing.

5. Missile-resistant cladding systems--e.g., laminated glass and exterior protective screens--are needed for essential facilities such as hospitals, fire and police headquarters, and schools, which often serve as evacuation centers.

6. During large storms, glass that is not broken may be damaged by scratching, pitting, or abrasion. The degraded glass could be hazardous during thermal cycling or a subsequent, less severe storm.

Recommendation A glass survey should be required of all buildings with a large expanse of glass after passage of a hurricane to detect any damage to large glass windows. Damaged windows should be replaced.

7. The extensive cladding damage caused by Alicia, which was not a severe hurricane, raises questions about the performance of nonstructural components of high-rise buildings. A prototype program of storm wind measurements would help to improve the performance of nonstructural elements. To supplement historical wind data, Monte Carlo simulation techniques, with elaborate modeling of reductions in wind speeds after landfall, could be used to define annual probabilities of exceedence for extreme wind speeds.

Recommendations

A. The architectural, engineering, construction, and meteorological communities, cities in coastal regions, the National Science Foundation, and NOAA should consider a joint effort to make wind speed measurements in and around selected coastal cities to define wind speeds during extratropical and tropical storms.

B. Designers should investigate the consequences of a storm passing through the Houston area with wind speeds exceeding the recommendations of the Houston code, especially on the cladding features of high-rise buildings.

City of Galveston

1. Fully engineered structures withstood the conditions of the storm satisfactorily, with occasional failure of nonstructural components such as roofing, surface cladding, facades, and glass windows and doors.

2. Preengineered Structures

- o Most large commercial buildings performed well except for some superficial cladding damage.
- o Metal buildings with large openings and overhead doors showed signs of local damage around openings and doors.
- o Mobile homes performed poorly. A majority of the units on East and West beaches were a total loss. Mobile homes generally fail in extreme wind conditions. Failure usually starts in the structural system and the skin system. Inadequate ground anchor systems lead to overturning of some homes during storms, resulting in severe damage.

3. Marginally Engineered Buildings. Many apartments and condominiums were heavily damaged. Weak links in the overall structural system and limited redundancies caused most of the structural damage, leading in some cases to total failure.

4. Nonengineered structures performed poorly, especially on Galveston's West Beach. The damage was mostly from wind except in a few cases. In the Seabrook area the damage was primarily caused by storm surge but was accentuated by wind gusts. Most of the damage to timberframed houses could easily be traced to inadequate fastening of roof components such as shingles, to poor anchorage of the roof systems to the wall frames, to poor connections of the wall studs to the sill plates, or to poor connections of sill plates to the foundation slab or deck. Hurricane clips were practically nonexistent in all the demolished houses except a few, where the clips were improperly installed. The performance of elevated wood-framed construction along the coast can be significantly improved by providing properly embedded piles, pile bracing, and adequately fastened elevated-joist floor systems. A framed structure with proper anchorage and the least possible number of weak links can minimize wind-induced damage. Enclosures at grade level should be of breakaway construction to limit the transference of loads induced by storm surge to the superstructure. Builders must be encouraged to provide storm shutters for protecting windows and other glass openings from wind pressure or windborne debris. Officials should consider a clause in the city building code for proper installation of elevated air-conditioning condenser units.

Recommendations Beach community officials should consider the following:

- A. Providing code requirements for appropriate anchorage, bracing, and connection, especially in wood structures.
- B. Establishing code requirements for adequate fastening of elevated air-conditioning units.
- C. Including code requirements for effective storm shutters.
- D. Inspecting ongoing construction to ensure compliance with code requirements.
- E. Consulting with structural engineers to develop code requirements for lateral bracing of piling supports for beach area buildings.

5. Hurricane Alicia caused little or no damage to major coastal structures in the area. The Galveston seawall had no apparent damage and obviously prevented major damage to the City of Galveston. The Texas City and Freeport hurricane flood control projects functioned satisfactorily and were not damaged by the storm.

In summary, most of the damage from Alicia in the Houston-Galveston area was caused by a lack of hurricane-resistant construction rather than by the storm. This is so because most of the damage was caused by winds, and measured winds rarely exceeded building code design speeds. Provision of adequate fastenings and anchorage for houses in Galveston, and control of the availability of windborne missiles in the Houston area, would have substantially reduced the damage caused by Alicia.

LIFELINES

In almost all instances, lifeline services were interrupted and unable to function for varying periods during and after the storm. Electricity is itself a lifeline and affects more of the total lifeline system than any other lifeline. Other lifelines--communications, water supply, sewage disposal, and hospitals--depend on a power source. With the exception of areas outside the seawall in Galveston, electric power failure was caused by wind and windborne debris. It appears that there are three general approaches to the problem, each of which will afford a different level of lifelines reliability. These approaches are:

- 1. Eliminate damage caused by wind and windborne debris. This can only be accomplished by designing any aboveground distribution system to resist the forces of hurricane winds and windborne debris. Where practical, distribution systems and their components should be buried.
- 2. Eliminate potential debris. This may be accomplished by designing all structures and structural components, including signs, to resist hurricane-force winds and by establishing a minimum distance that trees and large shrubs must be planted from distribution systems.
- 3. Reduce the dependence of other lifelines on the electric power lifeline by providing standby power for the communications, water, sewage, and hospital system lifelines.

Recommendations To improve the reliability of lifelines in hurricaneprone areas, the following steps could be taken. Obviously no single solution by itself is practical. It therefore appears that the most cost-effective solution is a combination.

- A. All future lifeline installations should either be buried or designed for hurricane-force winds.
- B. Ordinances should be passed requiring that all signs be designed to resist hurricane-force winds.
- C. Utilities should adopt procedures for ensuring that trees and shrubs along the rights-of-way of utility distribution systems are kept trimmed.
- D. Standby power should be installed for all essential lifeline functions.

WARNINGS, RESPONSES, STORM EFFECTS, AND RECOVERY

1. Alicia strongly highlighted a known problem. In areas with long evacuation lead times, the current error in hurricane forecasting results either in frequent 'unnecessary" evacuations or in occasional delays in evacuations for so long that a major storm will strike a largely unevacuated population. The best solution to this dilemma is to improve the 24- to 36-hour forecast of hurricane position and intensity. Forecasting needs are discussed further in the meteorology section of this report.

2. Until forecasts are more reliable, communities must be prepared to deal with the situation that Galveston almost faced: a severe hurricane making landfall on an unevacuated population. Areas at high risk of such a situation should identify structures where residents would be safe from wind, surge, and wave effects. These facilities could be used as refuges of last resort. They would not be operated as shelters, nor would they be ideal for evacuees. They would simply be safer than the evacuees' own homes. This vertical refuge concept is fraught with problems (Baker, 1983b) and should not be relied upon as an alternative to conventional evacuation. Studies are currently under way in a number of locations to answer many of the questions that have so far hindered the implementation of this concept.

Recommendation Local officials should identify and make arrangements for the use of local structures to be used as refuges of last resort in case of evacuation failure.

3. The approaches taken to recommend evacuation in the warning area varied widely among communities and were not always related to variations in risk. The Jamaica Beach police went door to door in their area urging residents to leave, whereas the City of Galveston merely advised its West Beach residents over commerical radio to evacuate. The Jamaica Beach approach is clearly preferable and usually the most effective. The single most important variable affecting the public's response to warnings is local officials' advice, but it must be absolutely clear to people that the advice applies to them. In Hurricanes Frederic and David, residents of Mobile and Miami who understood that they were being advised to evacuate were more than three times as likely to leave as neighbors who did not understand that the advice applied to them (Leik et al., 1981).

4. The decision whether to evacuate is a benefit-cost decision-- i.e., it involves deciding whether the probable benefits exceed the probable costs. One of the costs is finding and providing oneself with adequate shelter, and in the Houston-Galveston area there is very little coordination among communities to provide shelter for one another's evacuees. In Hurricane Allen the average Galveston evacuee drove over 150 miles to find shelter, partly because there was no provision for shelter for the 35,000 or so Galveston evacuees in the immediate Houston area (Baker, 1982). This deters evacuation by increasing the cost of leaving. The Houston-Galveston area is not unique in this regard.

Communities in such a situation must recognize that the absence of intergovernmental agreements with neighboring communities that could act as hosts will make evacuations more difficult.

Recommendation Local officials should seek understandings and agreements with nearby inland communities for the use of suitable public buildings as evacuation centers and make the designated centers well known to their coastal populations.

5. The Federal Emergency Management Agency is using its Section 1362 authority to "relocate" residents of the Brownwood subsidence area of Baytown. It is questionable, however, whether this action would have occurred had there not already been a "buy out" plan developed for the area, albeit by another agency under a different program. This example accentuates the oft-cited point that communities need to have plans already "on the shelf" if substantial postdisaster hazard mitigation programs are to be adopted. Residents are anxious to rebuild after a disaster and will not wait months for officials to draw up a plan from scratch.

6. Perhaps the biggest surprise in recovery efforts after Alicia involved debris removal, particularly in the Houston area. Problems of scale surfaced that were previously unexperienced and unanticipated, as debris removal was more costly and took far longer than most anyone expected. Other large metropolitan areas, such as Tampa-St. Petersburg and Miami, should take particular note of this point and review their debris removal plans in light of the experience in Houston.

Recommendation Local officials should plan for debris cleanup and removal after hurricanes.

STORM SURGES AND SHORE PROCESSES

METHODS

Coastal Surges Two types of coastal surge estimates are given in this report--those from tide gage measurements and those from field evidence gathered during the team survey, including debris lines, water marks in closed buildings, and vegetation caught on fences.

NOAA maintains two tide gages in the immediate Galveston area and other gages at Freeport and Sabine Pass. A few additional gages, operated by companies, Civil Defense offices, and other public agencies, were operating in the area affected by the storm.

Water marks in closed buildings are good indicators of maximum water levels that do not include the effects of wave action. However, during the Hurricane Alicia investigation, water marks were difficult to distinguish, probably because the flood waters contained little or no suspended sediment. No water marks were observed on the outside of buildings, and water marks inside buildings were composed of bits of vegetation, including seeds. Debris lines, usually composed of loose vegetation, were common (Figure 3.1) and were usually a clear, though not precise, indicator of maximum water level, including the effects of wind waves and run-up. Where their height spanned the flood level range, fences were also good indicators of maximum water level because bits of floating vegetation were caught by the individual fence strands. Thus the line between bare and "clothesline" strands clearly indicated the maximum water level (Figure 3.2).

Unless otherwise noted, all water levels given in this report are referenced to the national geodetic vertical datum (NGVD). This datum is 0.33 ft below mean sea level (MSL) at the Pleasure Pier tide gage. Estimates of water levels from tide gages are based on information furnished by gage operators. Estimates of water levels from water marks, debris lines, and fences were made by visually estimating the level of the evidence above the ground or another nearby surface, such as the surface of a road or paved parking lot, and then obtaining the level of the pavement surface from surveys or the 7.5-minute series of topographic quadrangle sheets (quad sheets) published by the U.S. Geological Survey (USGS). These estimates are probably accurate to +1.5 ft.

Shore Processes

The study team made observations of beach and dune erosion, overwash, and scour by waves and overtopping storm water. In addition, estimates of horizontal beach changes were obtained from aerial photographs taken before and after the storm. Both sets of photographs were taken by NOAA's National Ocean Service (NOS). The Nbefore" set was taken on October 15, 1982, and November 5, 1982. The "after" set was taken on August 24, 1983, seven days after the storm's passage. The scale of the 1982 photographs was approximately 1 to 40,000; the scale of the 1983 photographs was approximately 1 to 30,000. Data were scaled from the photographs along selected lines using a scale divided into 600 parts per foot. Therefore individual measurements are accurate to about +30 ft. and changes measured between the two sets of photographs may be in error by as much as 50 ft. The lines selected were mostly streets perpendicular to the beach, and measurements were made from cross streets, usually the street that ran nearest the beach, to the beach feature of interest. Horizontal beach features measured were the high-water line, the vegetation line just behind the beach, and, where beach scarps existed, the scarp line.

The high-water line was easy to see in the 1982 photographs as the line between the wet lower beach and the dry upper beach (Stafford, 1971) and appeared to be a consistent measure of the high-water position. However, waves and the surge from Alicia caused flattening and attendant widening of the beach and in many areas left a visible erosion scarp. Also, sand transported offshore during the storm was already migrating onshore as a low bar near the water level. All of these factors, coupled with water seeping from the groundwater buildup during the storm, made the after-storm measurement of high-water level no more than an indication of beach advance or retreat.

Scarp and vegetation lines were easily visible and their position could be determined accurately. Therefore measured changes in these features were good indicators of horizontal changes caused by the storm. In areas where there was overtopping of the beach and dunes that produced overwash (a surface sand deposit extending landward from the beach (U.S. Army Corps of Engineers, 1977)), the change in the vegetation line was a measure of the magnitude of the overwash. Where there was beach and dune erosion that ended in a scarp (an almost vertical slope along the beach at the landward limit of erosion), the change in the vegetation line was a measure of the beach and dune recession caused by the storm. In some areas, overwash deposits were found to extend inland from scarps. In these cases, the magnitudes of both the beach and dune erosion and the overwash deposits were well defined.

STORM CONDITIONS AND EFFECTS

Coastal and Inland Surges

Galveston Island

Maximum water levels along the front of Galveston Island varied from 6 to possibly 12 ft during the passage of the storm. The NOS tide gage on Pleasure Pier operated through the maximum water level of the storm and recorded a maximum water level of almost 9 ft at 1:24 a.m. on August 18 (see Figure 3.3). Since the tide level at that time would have been 1.7 ft, the storm surge magnitude was about 7.3 ft. Observations along the front of Galveston Island during the survey showed that there was no overtopping of the seawall. However, there was considerable overtopping of East Beach and the western portion of Galveston Island all the way to San Luis Pass.

Maximum water levels along the back of western Galveston Island varied from 6 to possibly as much as 9 ft. The NOS tide gage on the back of Galveston Island (Pier 21) recorded a maximum water level of 5.8 ft at 2:12 a.m. on August 18 (see Figure 3.3). Observations along the back of Galveston Island indicated that the water level was generally not more than 1 to 2 ft above the land level, which was estimated at about 5 to 7 ft from USGS quadrangle sheets. From the available evidence, the maximum water levels along the back of the island increased from about 6 ft at the eastern end of the island to about 9 ft three miles east of San Luis Pass. Evidence to the west, behind Follets Island, shows that the bay water level increased to more than 10 ft in Christmas and Drum bays.

Along the front of East Beach the beach and lower dunes were overtopped by 2 to 4 ft of water, which then flowed landward toward the seawall. When the seawall stopped the northward movement of the overtopping water, it turned eastward and ran over the shoreward section of the north jetty into Galveston Inlet. Scour near the junction of the north jetty and the seawall was intense (Figure 3.4). The land and jetty level in this area is about 3 ft above NGVD, and thus the depth of the flowing water was between 4 and 6 ft.

Some of the higher dunes on the front of East Beach were not overtopped. However, they were partially eroded while acting as headlands and causing accelerated flow in lower areas between high dunes and between high dunes and adjacent structures. Figure 3.5 shows the seaward side of an eroded high dune and the seaward portion of the associated erosion channel. Figure 3.6 shows the body and landward end of the same erosion channel looking toward the Gulf. This channel was between the dune shown and a condominium immediately to the east.

Observations on Galveston Island west of the seawall showed that the front of the island had been overtopped by a foot or more of water along most of its length. Two areas not overtopped, a 1/2-mile section about 1/2 mile east of Galveston Island State Park and a 2-1/2-mile section eastward from Sea Isle, were higher than 10 ft in elevation. In other areas, debris lines on fences and against embankments and dunes along the highway, when added to the elevation of the highway and dunes estimated from USGS quadrangle sheets, indicated Gulf water levels that varied from 8 to 11 ft, including the effects of wave action. Evidence that water had flowed across the body of the island from the bays toward the Gulf began about 3 miles east of San Luis Pass. otherwise, all evidence pointed to a flow of water from the Gulf toward the bays.

Follets Island

Follets Island is immediately west of Galveston Island across San Luis Pass. Only the eastern 8-1/2 miles of this island were covered by the study team's ground survey. In this area the evidence was remarkably consistent: water flowed only from the bays to the Gulf, and water elevations in the bays were about 10 ft. Evidence of water levels consisted of debris lines on the bay side of the dunes at distances of 1.5, 2.0, 4.5, 7.5, and 8.5 miles from the east end of the island, as well as a stranded houseboat between the highway and the dunes fronting the Gulf at the 4.5-mile point (see Figure 3.7). Highway elevations were estimated from USGS quadrangle sheets.

Evidence for the direction of flow consisted of the location of debris lines on the bay side of the dunes and the characteristics of several cuts through the dunes and body of the island between the highway and the Gulf. These cuts appeared to start at the beach when the water from the bays poured seaward through a low point in the dunes. Sand from the beach and dunes was flushed seaward and carried away by the currents and turbulence in the surf zone. As this process continued, the channel was cut further and further inland. Most of the cuts ended seaward of or at the highway. However, one cut extended completely through the highway, and other cuts ended in the highway pavement (see Figures 5.1-5.3). Figure 3.8 shows the landward end of one cut, and Figure 3.9 shows the extent of the breach made through the backbeach dunes.

Bolivar Peninsula

Bolivar Peninsula lies eastward across Galveston Inlet from Galveston Island. The first 11 miles of the peninsula were surveyed by the study team. The 5 miles of the island east of Galveston Inlet are low, with maximum elevations of 6 ft. East of the 5-mile point a relic dune ridge rises near the middle of the island (front to back) and extends eastward to the limits of the survey. Maximum elevations of the dune ridge vary from 9 to 11 ft.

Debris lines on fences, scour adjacent to the highway, and the way the grasses were bent showed that the first 5 miles of the peninsula had been overtopped by water flowing from the Gulf toward the bays. Evidence of over topping ended abruptly where the road rose from the lower elevation to cross and run behind the relic dune ridge, and there was no further evidence of overtopping on the part of the peninsula surveyed. Thus the evidence indicates that water levels in the Gulf along the western part of Bolivar Peninsula were higher than 6 ft but lower than 10 ft. Also, indications are that the maximum water level in Galveston Bay adjacent to the western end of the peninsula was less than 6 ft.

Mainland Areas Around Galveston Bay

Only two mainland areas adjacent to Galveston Bay were covered by the ground survey: Seabrook and the Texas City hurricane flood protection dike, which are both on the western side of the bay. The debris line on the Texas City dike was low on the front of the dike, indicating maximum water levels there of less than 5 ft. At Seabrook, along Todville Road, it was evident from scour in the yards of houses and damage to structures that water levels had been 3 or more ft above the ground level, but no evidence was found to better define the actual level. However, in the Baytown area, a tide gage in the Baytown area recorded a maximum water level of 10.4 ft above mean sea level at 8:30 a.m. CDT on August 18 (see Figure 3.3). In addition, instrument surveys of debris lines made by Busch, Hutchinson & Associates, Inc., for the Baytown Civil Defense Office showed maximum water levels in the Baytown area to be between 10 and 11 ft.

Shore Processes

Major shore processes produced by the storm were beach and nearshore profile adjustments to the unusual storm conditions, erosion of the dunes behind the beach, overwash, and channels cut through the beach and nearshore dunes by overtopping of storm waters. The effects of these processes that could be measured from aerial photographs were changes in the position of the Gulf high-water line, changes in the vegetation line behind the beach, and the position of scarp lines left by the erosion of beach and dunes.

Table 3.1 summarizes the results of measurements from aerial photographs taken about a year before the storm and a few days after the storm. Measurements in the table are arranged from east to west, starting at High Island on Bolivar Peninsula, extending along the front of Bolivar Peninsula across Galveston Inlet, and along Galveston and Follets islands westward to Freeport Inlet. Distances along the coast are relative to the point at which the eye of the hurricane crossed the coast, which was near San Luis Pass. A total of about 70 miles of coastline are covered; about 55 miles to the east (right) of the storm and about 15 miles to the west (left) of the storm.

The striking aspect of changes in the high-water line is that essentially all of the erosion is to the right of the storm. More erosion to the right of the storm would be expected, since the strongest onshore winds in the storm were to the right of the storm as it crossed the coast. However, the strong demarcation at the center of the storm is striking, because some erosion would be expected by waves in front of the storm before it reached the coast.

A second significant aspect of changes in the high-water line is that the largest erosion rates occurred just to the right of the storm's center and that erosion of 100 ft or more extended up to 17 miles to the right of the center. There was little or no beach in front of the Galveston seawall either before or after the storm. Therefore no measurements could be made there. While erosion rates of more than 100 ft were measured on Bolivar Peninsula, they were not common, and erosion was approaching zero at High Island 55 miles to the right of the center of the storm. Thus there was serious erosion for at least 17 miles to the right of the storm's center and significant erosion for 55 to 60 miles to the right of the center.

Changes in the vegetation line generally followed the pattern of changes in the high-water line. Changes in the vegetation line were larger because the vegetation line can be changed by both erosion (the vegetation is carried away) and overwash (the vegetation is buried).

The largest change in the vegetation line (over 1,000 ft) was measured at Terramar Beach. From both the ground survey and the aerial photographs, it was obvious that most of this change was caused by overwash, which buried the vegetation under up to 3 ft of sand. Where a scarp existed after the storm, it was possible to measure the amount of erosion of the vegetation line and the magnitude of the overwash deposits (see the last two columns of Table 3.1). Where there was no scarp, it was not possible to determine how much of the recession of the vegetation line was caused by erosion and how much by overwash.

An erosion scarp was common along western Galveston Island, uncommon along Bolivar Peninsula, and nonexistent in the measurements made to the left of the storm's center. On western Galveston Island the vegetation line receded over 100 ft at all points where measurements were made except for two adjacent points between Jamaica Beach and Sea Isle. The ground survey showed that this area was one of the limited areas not overtopped by storm waters on western Galveston Island. Retreat of the vegetation line was over 200 ft at three of the measurement points on Bolivar Peninsula and over 100 ft at three others. Retreat of the vegetation line tapered off in the vicinity of High Island 55 miles to the right of the storm's center.

An additional observation made during the study team's ground survey was that the native grasses on the barrier islands were surprisingly effective in preventing scour and erosion of the islands in all areas unaffected by significant wave action--that is, in all areas more than 200 ft behind the Gulf beaches. Though the storm surge overtopped most of western Galveston Island, the only erosion observed in areas behind the beach was in places where the grasses had been removed for some kind of construction.

SUMMARY

The recession of the beach and vegetation line was most severe immediately to the right of where the eye of the storm crossed the coast. Serious recession of the beach and vegetation line extended all along the 18 miles of western Galveston Island that are unprotected by the seawall. Significant recession of the high-water and vegetation lines extended at least 55 miles to the right of the storm center but were tapering off at that point. Beach and vegetation line changes were surprisingly small in the first 15 miles to the left of where the storm crossed the coast. Grasses inland from the beach provided exceptionally effective protection for areas subjected to the flow of overtopping wave and surge water as it flowed across the islands into the sounds.

WARNINGS, RESPONSES, STORM EFFECTS, AND RECOVERY

WARNINGS

Advisories Issued by the National Hurricane Center Table 6.1 summarizes the advisory information issued by the NHC. The initial bulletin came at 5 p.m. on Monday, August 15, almost 60 hours before the eye of the storm made landfall. At that time, Alicia was a 45-mph tropical storm 375 miles east of Corpus Christi. Its probability of affecting Galveston within the next 72 hours was 17 percent, the highest of any location, but no more than 3 percentage points greater than that at five other sites (Table 6.2). The advisory mentioned that hurricane warnings might be posted for Texas on the following day.

At 11 a.m. the next day (Tuesday, August 16) a hurricane watch was posted from Grand Isle, Louisiana, to Corpus Christi, Texas. Overnight the storm had increased in intensity only slightly, but between the 5 a.m. and 11 a.m. advisories its winds had increased from 50 mph to 65 mph. Its "total" probability of hitting Galveston was still only 21 percent, with the probability of its hitting within the next 24 hours 17 percent (Table 6.3). Port Arthur and Port O'Connor had 72-hour probabilities almost as high as Galveston's. The advisory said Alicia could become a hurricane later that day.

By 5 p.m. it had. With winds of 80 mph and the storm 175 miles southeast of Galveston, hurricane warnings were posted from Morgan City, Louisiana, to Corpus Christi. Until that time Corpus Christi had been the reference point. Galveston's probability of being hit had almost doubled to 36 percent over the past 6 hours, and its margin over other locations was growing (Table 6.4). Of its 36 percent probability, Galveston's chance of being hit within the next 24 hours was 35 percent. The advisory mentioned that deteriorating weather conditions could reach the coast Wednesday morning.

By the time most people had gone to bed Tuesday night (11 p.m.), little had changed except that Alicia had drifted 35 miles closer to Galveston. The city's total probability of being hit had grown to 46 percent, almost 20 percentage points higher than the next highest location's. For the first time in the advisories, a mention of landfall was made. The advisory noted that tides were expected to be 4 to 6 ft above normal Wednesday afternoon near where the hurricane made landfall and that some low-lying roads would be flooded by daybreak, but no specific landfall point was stated. At 5 a.m. Wednesday, August 17, the last advisory containing probabilities was issued.

At 51 percent, Galveston was 17 points higher than Port O'Connor and 26 points higher than Port Arthur (Table 6.5). Not until the 11 a.m. advisory, however, was it stated that probabilities were being discontinued because preparations for evacuation should already have begun. Since 5 p.m. Tuesday the winds in Alicia had been 80 mph--a minimal hurricane. Until 5 a.m. Wednesday, all advisories noted that Alicia was likely to strengthen. The next three, however, said only that further strengthening was possible.

At 1 p.m. Alicia was reported to have 100-mph winds, up from 85 mph just two hours earlier. For the first time the storm was described as "dangerous." By 5 p.m. the winds were 110 mph, and what had been a weak hurricane just before noon was bordering on being a Saffir-Simpson category 3. Tide heights of 10 ft were now being predicted, with deteriorating weather conditions already occurring. The 5 p.m. Wednesday advisory said that Alicia could become a major hurricane later that night.

All of the public advisories since 2 p.m. Tuesday had projected the storm to move west-northwest. At about 5 p.m. Wednesday, Alicia was 85 miles south-southeast of Galveston. Actually the west-northwesterly forecasts on Wednesday were consistently too westerly, as the storm was turning more northerly. Anyone projecting the path of the storm (or receiving the actual forecast positions) at 5 p.m. Wednesday would have expected Alicia to make landfall around Matagorda (80 miles southwest of downtown Galveston, 55 miles southwest of the western tip of Galveston Island). In fact, had the probabilities been continued, Galveston's would have climbed above the 51 percent last reported, but Port O'Connor's probably would have increased also, at least over the next six hours.

Thus, although Alicia was becoming stronger, at 5 p.m. Wednesday its forecast track was well to the southwest of Galveston. However, none of the NHC public advisories mentioned a forecast landfall location. Rather, they continued to refer to the warning area. Even statements about heavy rain, tornadoes, and tides referred only to southeast Texas, the upper Texas coast, or southwest Louisiana. The NHC's reluctance to mention a landfall point in its public advisories stems from concern that people will place too much emphasis on that point.

By 9 p.m. Wednesday, winds in Alicia were 115 mph and the storm had moved to within 60 miles of Galveston. Tide heights were now predicted to be 12 ft, and hurricane-force winds were predicted for the middle and upper Texas coast "within the next several hours." At 11 p.m. winds were still at 115 mph, but the forecast movement was now to the northwest (rather than west-northwest). By 3 a.m. the eye of Alicia was reported to be over the western tip of Galveston Island moving north-northwest at 6 mph. Wind gusts of 102 mph were reported in Galveston.

Local Statements by the National Weather Service

The Galveston office of the National Weather Service was in direct contact with the NHC and other NWS offices throughout the threat and conferred with and advised local officials. Based on those conferences, the Galveston office issued 'local statements' giving information pertinent to the local area: evacuation recommendations, road conditions, tide forecasts, and so forth. Table 6.6 summarizes the content of the local statements. During the period covered in the table, four tornado warnings were issued. After the 3:30 a.m. statement on Thursday, the Houston NWS office in Alvin began issuing bulletins concerning the storm as it moved farther north.

Evacuation recommendations for specific places were generally coordinated with local officials, who usually issued their own statements to the media as well. Many consultations with local officials were not reflected in the local statements. For example, the Galveston NWS office contacted officials on Bolivar Peninsula at 10 p.m. Wednesday night to advise them that people being sheltered on the peninsula be moved to High Island.

Perhaps the most notable statement took place at 10:15 p.m. Wednesday, when the Galveston NWS office noted the possibility of a more northerly turn with the potential for landfall at Galveston. This was somewhat at variance with the latest NHC advisory, but Galveston's statement had been coordinated with the NHC. The Galveston NWS office was concerned about "underwarning" Galveston, and the NHC was concerned about "underwarning" the area to the south.

Dissemination of Warnings by the Media

All of the media in the Houston area gave Alicia a great deal of attention starting with the first advisory. The Tuesday editions of all three major newspapers in the area (the Galveston Daily News, Houston Post, and Houston Chronicle) carried front-page stories about Alicia on Tuesday. The Post included a full-page tracking chart, a list of safety rules, and a discussion of the new probability warning system. The Chronicle had similar coverage without the tracking chart. The Galveston Daily News published the entire probability tables for two advisories just as they came off the teletype.

The National Weather Service had hoped (and urged in preseason workshops) that the media would simply report the "total" probability value for places rather than giving the probabilities for various time increments. In fact, the probabilities given for intermediate time frames of more than 24 hours but less than 72 hours cannot be used alone. They are cumulative increments that must be added to probabilities for preceding time periods. For example, in Table 6.2 the first column gives the probability that Alicia will hit Galveston within the next 24 hours or less: 9 percent. Add to that the probability in the next column (5 percent) and you get the probability that the storm will hit during the next 36 hours or less: 14 percent. The second column does not say, however, that there is a 5 percent chance of Alicia hitting more than 24 but less than 36 hours in the future. An article in the Daily News misused the probabilities in that manner on Tuesday.

On Wednesday the Post devoted extensive space to Alicia, including a map of evacuation routes, an article on how to decide whether to evacuate, and a probability table with the probabilities correctly summed across the columns. A front-page story quoted the National Weather Service as saying the storm would reach land between 5 p.m. and 9 p.m. Wednesday. The Chronicle said that landfall was expected between Palacios and Galveston (note the 1:30 p.m. Wednesday Galveston local statement in Table 6.6) and listed shelter locations. The Daily News, in an edition dated Thursday, August 18, but published early Wednesday evening, referred to the NWS's Palacios to Galveston landfall point but quoted a Texas Department of Water Resources meteorologist as saying that landfall was expected at Port O'Connor. The headline on the article, however, read "Weather Service Forecasts Landfall at Port O'Connorn (italics added).

Radio and television stations transmitted the advisories and local statements, as well as local officials' statements and their own (the media's) observations. All the television stations displayed the probability distributions along the coast and attempted varying degrees of explanation. Some of the stations had run special segments on the probability system when it was first announced at the beginning of the season. Cable News Network (CNN) displayed probabilities in a manner comparable to local stations, but the Weather Channel displayed risk zones (high, moderate, etc.) without using the actual probability values. Representatives of the three largest market stations in Houston (there are no television stations in Galveston) were uncertain whether their news and weathercasters used anything other than the "total" (72-hour-or-less) probabilities. Conversations with station representatives and observation of broadcasts about Hurricane Barry later in the season left the impression that probabilities for lesser time periods were occasionally used.

All three of the largest Houston stations stayed on the air throughout the storm. When the Galveston NWS office lost its radar, Channels 11 and 13 switched to the Lake Charles NWS radar; Channel 2 had its own. Station representatives said they had made no early forecasts of landfall locations, but Wednesday afternoon or evening Channel 2 made at least one reference to a Freeport landfall. The stations broadcast interviews with officials and residents from various locations in the area and reported weather and road conditions throughout the storm's approach and duration.

Although the television stations stayed on the air, many residents lost electricity Wednesday evening or Thursday morning and relied on transistor radios. KGBC, the designated Emergency Broadcast System station for Galveston, stayed on the air throughout the storm with power from an auxiliary generator. Its representatives complained on the air about the inaccessibility of Galveston officials for information. Many of the radio stations had "call-in" programs for residents to report conditions in their areas or ask questions. KIKK/KTRH had set up a system (PIES--Public Information Emergency System) that connects many of the emergency operating centers in the Houston area with most of the television and radio stations and newspapers in the area. A local Civil Defense official could alert media recipients that a message was forthcoming in 30 seconds, then the recipient could record the message for broadcast. The system was apparently used extensively by some officials.

RESPONSE TO THE WARNINGS

Most emergency response organizations and industries began gearing up to take action on Tuesday, August 16, although some waited until Wednesday. The state convened a group of 28 agency representatives in Austin (the governor's Emergency Management Council) to provide technical input for local decisions. The group included meteorologists from the Department of Water Resources. The state communicated the results of computer simulations of tide heights, wind speed, and how much "safe" time remained before evacuation decisions must be made. The program was an outgrowth of a regional hurricane evacuation study (Ruch, 1981) for Brazoria, Galveston, Harris, Fort Bend, and Chambers counties by the Texas Department of Public Safety (DPS). The state provided "hard copy" communications to locals over the Law Enforcement Communications Network. In addition to the "real time" calculations being performed by DPS for Alicia, local emergency preparedness officials had simulation results in tabular form prepared as part of DPS's regional evacuation study showing tide heights and "safe" evacuation times for a variety of storms, to which Alicia could be matched. In general the state provided purely technical support for evacuation decisions, although there were reports that on Wednesday the governor urged the mayor of Galveston to advise evacuation for all of the island rather than just parts. DPS sent a mobile communications unit to assist law enforcement officials, and 60 state police officers were sent to help with traffic control.

The petrochemical industry is very important to the Houston area, and it is extremely expensive for some of the refineries to stop operations. In the Texas City-La Marque area, Monsanto and Marathon closed down, as did Dow in Freeport. Amoco and Union Carbide continued operations. Workers phoning Amoco on Wednesday morning to find out whether they were to report to work heard a tape recording saying that the storm was dissipating and that hurricane conditions were not expected in Texas City. A 2 p.m. Wednesday tape said that Alicia would hit the Port O'Connor-Matagorda area and that hurricane conditions were still not expected in Texas City.

The ports of Houston and Galveston were closed early Wednesday. Seven oceangoing ships were secured, cranes were lashed down, and container stacks were lowered and spread out. In the Port of Galveston, trains were removed from the island. Public transportation ceased late Wednesday. Galveston's city buses stopped running at 4 p.m., and the Bolivar-Galveston ferry stopped at 5 p.m.

Most hospitals discharged those patients who were able to leave early; only emergency cases were accepted on Wednesday (one hospital performed a heart transplant at the height of the storm). Some of the Houston hospitals put aluminum droplogs in place to keep water out of their basements and stocked up on blood and sandbags. The Houston Blood Center arranged for boats as well as normal vehicles to deliver blood if necessary. Medical unit helicopters were grounded Wednesday afternoon.

Nursing homes and retirement centers generally had prior arrangements for a hurricane threat. Some residents of the Moody House Retirement Center and the Turner Geriatric Center in Galveston were taken by friends and relatives to homes in the Houston area, and staff moved into the centers to help care for those who stayed. One facility, the Holland House Retirement Home in Gulf Breeze, had arrangements to evacuate to a Conroe church but did not exercise the option. Forty people from Taft Nursing Home near Hitchcock stayed at a local school, where they were fed. Two children's homes in Galveston (Lasker and Yeager) evacuated their children to the mainland.

Oil rigs in the Gulf of Mexico were evacuated on Tuesday. Rigs operated by Shell, Borah, Penzoil, Texaco, Amoco, Sun Exxon, Conoco, Zapata, Gulf, and Tenneco evacuated over 2,000 workers altogether.

Table 6.7 summarizes the evacuation actions taken by many of the communities in the warning area. Information in the table is derived from a combination of personal interviews with public officials, records of official agencies, and newspaper reports. The quantitative response rates are no more than estimates, reflecting what seemed to be the consensus of a number of sources. Civil Defense authority resides at the level of local governments in Texas and is extremely fragmented. This allows for independence in decision making but results in practically no coordination among governments. Thus situations arose in which adjacent communities facing comparable degrees of risk took very different responses. Kemah officials, for example, made no evacuation recommendations one way or the other to its residents, while nextdoor Seabrook sent vehicles through neighborhoods with loudspeakers urging evacuation. On the western tip of Galveston Island, police in the town of Jamaica Beach went door to door advising evacuation, while neighboring Sea Isle, which is part of the city of Galveston, and Pirate's Beach, which is an unincorporated area of the county, heard over commercial radio that they should leave.

The most controversial evacuation decision occurred in the city of Galveston. Studies have calculated that evacuation of the island has to begin as much as 26 hours before landfall if everyone is to leave with traffic flowing smoothly (Ruch, 1981). Thus a go/no-go decision has to be made early. When Galveston officials reached the time for a decision, the storm was a weak hurricane, intensification to category 3 was not expected, and the most likely landfall location was forecast to be well to the southwest of Galveston. When the storm became dangerous Wednesday afternoon, it was too late to initiate a large-scale evacuation of the island, and the predicted path was still to the south anyway.

There is evidence that some of the meteorologists in an advisory position placed undue confidence in the forecast track. One purpose of the probability information is to quantify the error in the forecast track, but the probabilities were discontinued early Wednesday morning.

One reason Galveston and state officials were reluctant to play it safe and suggest an early evacuation was their belief that residents were unhappy about the early precautionary evacuation officials had urged during Hurricane Allen in 1980. Allen was an extremely severe hurricane at the time, and 65 percent of Galveston's residents responded, many taking leave from work on Friday and making a "three-day weekend" visit to the residence of a friend or relative inland. Allen came ashore south of Corpus Christi, making the evacuation of Galveston "unnecessary." A survey of 200 households in Galveston indicated that of the people who had evacuated, only 10 percent said they would do anything differently in a similar situation. Very few were critical of officials for "crying wolf" (Baker, 1982). However, of those who were unhappy, a number expressed their displeasure to city officials, and officials apparently over-generalized from those reactions.

Less recognized was the treatment of communities on the west end of Galveston Island, where the highest elevation is generally between 6 and 10 ft and there is no seawall. Part of the City of Galveston is on the west end of the island, physically separated by as much as 20 miles from the main part of the city. City officials acknowledged the severe danger to that area and recommended as early as Tuesday evening that residents evacuate. However, police or other personnel were never sent to the area with public address systems. In the Sea Isle development, for example, the property owners association (which performs a quasiadministrative role) never received direct communication from city officials or from the Galveston NWS office. The unincorporated county communities on the west end of the island had a similar experience.

The evacuation was nevertheless largely successful in these areas. Perhaps one reason for this success is that residents were aware of actions being taken in nearby Jamaica Beach, where police went door to door Tuesday evening imploring residents to evacuate. The Jamaica Beach police and mayor's office were never in direct contact with the Galveston NWS office or with the Texas Department of Public Safety in Austin during the hurricane threat.

One of the factors compounding the problems of evacuating Galveston Island is the lack of shelters available. No provisions have been made for sheltering Galveston evacuees off the island. For residents who have friends or relatives in safe areas of Houston where they can stay, this is probably of no consequence. But for residents who have no such nearby off-island refuge, the lack of shelter probably inhibits their evacuating to some extent.

Evacuation rates varied greatly from place to place, mainly as a function of the vulnerability of the location (beachfront areas routinely evacuate at a 90 percent rate) and actions taken by local officials. In a few cases--most notably south Harris County around Hitchcock and the Brownwood subsidence area of Baytown--life-threatening (and life-saving) rescues had to be performed in chest-deep water.

Alicia provided food for thought concerning the concepts of vertical refuge and vertical evacuation. Vertical refuge is a plan in which multistory structures in risk areas serve as refuges from storm surge for people who were unable to evacuate by conventional means because they did not leave early enough. Vertical evacuation is similar, except that the population is not urged so strongly to attempt to leave early.

The rationale for vertical refuge is the sort of scenario Alicia almost posed: a storm that has intensified to "killer" proportions or changed its track too quickly to evacuate everyone at risk by conventional means. Alicia illustrated just how plausible such a scenario is. On the other hand, the window breakage in downtown Houston, the damage to an interior wall of the Galvez Hotel, and the near panic that followed these failures illustrate drawbacks to the concept.

A survey of 200 Galveston-area residents conducted after Alicia suggested that the public's response to the probabilities was very good (Baker, 1983a). It is clear that the probability information did not deter people from evacuating, and almost everyone reported understanding the information and finding it useful.

Summary

Hurricane Alicia struck what is regarded by preparedness professionals as a potential disaster area in terms of the difficulties of evacuation. At the time city officials had to decide whether to advise residents to evacuate, the hurricane was of near-minimal intensity and was expected to make landfall well to the southwest of Galveston. But the storm intensified before landfall and turned more northerly than predicted. Had its intensity been even greater--say a bad category 3 or weak category 4--and had its track resulted in more flooding of Galveston Island from the bay side, the decision not to evacuate the island might have proved tragic. In this case, it proved correct. Nevertheless, Alicia emphasized the tremendous risk public officials are taking when they decide against advising evacuation while not being certain of a storm's future behavior.

Warnings and local officials' advice to residents throughout the Houston-Galveston area served their purpose reasonably well. As in most hurricane threats, evacuation from high-risk beachfront areas was almost total. Also typically, evacuation from moderate-risk areas (flood-prone areas inland from the open coast) was substantial but far lower than in the highest risk areas.

Alicia was the first hurricane for which landfall probabilities were issued, and the system appeared to function well. Evacuation from highrisk areas late Tuesday and early Wednesday was not deterred by the fact that Galveston's probability of hitting the area was only 50 percent or less. If anything, the system's "accuracy" in Alicia's case might contribute to overconfidence in the system's ability to "predict" where future storms will strike. The fact that the NHC ceased issuing probabilities very early Wednesday morning probably permitted some observers to place undue confidence in the forecast landfall location later on Wednesday. Alicia was a difficult hurricane to deal with from the standpoint of response. Overall, however, the response of both officials and the public to the threat was good.

STORM EFFECTS

Tallies of the death toll from Alicia vary between 10 and 20, depending on the extent to which deaths indirectly attributable to the storm are included. Bodies of two men were found in Clear Lake, presumably drowned while staying on boats docked there. Four men drowned in bayous in Houston suburbs, two of whom had gone swiming late Thursday afternoon, and a 10-year-old boy drowned in a storm drain in Dallas. Other deaths were connected with Alicia's winds, mostly as a result of falling trees. An elderly woman died when a tree fell onto her house; a man's car ran into a fallen tree; a tree fell onto the car of an evacuating family, killing an occupant; a 14-year-old girl was killed by a falling tree when she went outside her house to move a car; and a man was killed in Dallas when a road sign fell onto his truck. Examples of indirect fatalities were a repairman who was killed in a fall while working on a power line and two people who died in a fire caused by a candle being used in lieu of electricity. Had evacuation from the West Beach area not been so extensive, the death toll could easily have been higher. The "official" Red Cross estimates were 17 deaths and 3,243 injuries (Interagency Hazard Mitigation Team, 1983).

After passage of the storm, rescue efforts continued in some locations. At noon on Thursday, 30 people were rescued from flooding near the San Jacinto Monument east of Houston, and 100 elderly residents of an apartment building in Galveston were stranded on upper floors due to damage and debris on the first floor. The Texas Department of Public Safety estimated damages of $1.2 billion; the American Insurance Association estimated that total losses could equal $1 billion; GAB Business Systems also put the total loss figure at $1 billion; and the Texas Catastrophe Property Insurance Association said damage could be between $715 million and $1.65 billion. The Corps of Engineers published estimates that were considerably lower. As shown in Table 6.8, the Corps, based on its own surveys, estimated tentative losses of $256 million in Galveston, Harris, Brazoria, and Chambers counties. Table 6.9 gives the Red Cross's estimates of damage to residential property.

Besides the loss of life and property damage, life was affected in a number of ways. Electricity and telephone service were disrupted over a wide area, and it took weeks to get services restored in some locations. Other services, such as water and waste treatment, were lost when power was lost. At least two breweries shipped bottled water to some communities. Refrigerated food could not be kept, and ice was in extremely short supply. Fuel deliveries were interrupted and electrically powered gasoline pumps failed, resulting in refueling problems for emergency vehicles in some areas. Many items were in short supply, and at least 60 formal complaints of price gouging were being investigated by the Texas Attorney General's office.

August temperatures are uncomfortable on the Gulf Coast, and in Houston 31 "cooling centers" were set up for people whose air conditioning or fans were made useless by the electrical outage. Having lost food due to lack of refrigeration and not being able to prepare hot meals, many people depended on volunteer groups such as the Red Cross and Salvation Army for meals. By the Monday following the storm, roughly 100,000 meals had been served, and the Red Cross was estimating that their total could eventually run as high as 400,000 meals served. A local grocery store was giving away thawed food, and the U.S. Department of Agriculture donated surplus food commodities.

Many area schools postponed their fall opening by several days, and some merchants noted an interruption in normal back-to-school buying. Other businesses--glass and building materials, for example--experienced a surge in buying. Some businesses were covered by "business interruption" insurance. Health care operations returned to normal very quickly, but blood supplies in the area ran lower than expected. The shortage occurred because the normal donation/collection routine was interrupted.

Looting was reported on the first day after the storm (Thursday): 22 people were arrested in Galveston, 65 in Houston, and 11 in Texas City. Curfews were imposed in Galveston, Hitchcock, La Marque, and Humble. On Friday only two arrests for looting were made in Galveston and none in Houston. On Thursday morning police set up barricades to keep people out of the downtown area of Houston where glass had fallen, and roadblocks were set up in many communities to keep people who did not own property there out of damaged areas. Such a roadblock was set up to control access to Galveston Island on Thursday morning, but it was discontinued at 6:30 p.m. Most nonresidents heard that they-would not be allowed on the island, so they did not try to enter. Waist-high debris was not completely cleared off the causeway until Thursday afternoon. About 100 National Guard troops were brought to Galveston to help enforce the curfew and protect property, but there was considerable attention in the press to the fact that the mayor objected to the decision and noted that it was made in his absence. A week after the storm, the guardsmen were replaced by state police.

Aside from complaints about the time taken to restore electrical service, the recovery problem with the highest public visibility in Houston related to debris removal. The Corps of Engineers estimated that 2 million cubic yards of debris were in the Houston area, or about a million pickup truck loads. Most of the debris consisted of trees and limbs, which people piled alongside streets to be picked up. The time and expense involved in dealing with such a volume of debris were apparently beyond anyone's expectations. As the debris accumulated in and along streets, concerns grew about fire hazards and about localized flooding as normal drainage patterns were obstructed. One of the first debris-related problems was the shortage of chainsaws, and a "chainsaw brigade" of 35 workers was brought from Dallas to help. On August 25 the mayor of Houston announced that the National Guard would assist in the cleanup, but on the following day the state said there had been a misunderstanding and debris cleanup was not a function of the Guard. The state did provide 30 trucks, but their 5-yd3 capacity was considered smaller than ideal, and 12 were dispatched to Seabrook. The City of Houston let $2 million in removal contracts, then followed it by another $3 million. These costs were expected to double before the work was completed.

Many residents were homeless after the storm, particularly those from the hardest-hit beach and bayfront locations. It was estimated that over 3,000 people needed housing, and FEMA began attempts to rent 2,000 units. Some people remained in public shelters for more than a week.

The Red Cross opened a total of 111 shelters in 22 counties, housing over 25,000 evacuees. Over 1,000 volunteers and 150 staff workers were involved in these efforts. The Red Cross's expenses were estimated to be as high as $5 million, and representatives of the organization said that they needed to raise $1 million. The Gulf Coast United Way advanced the Red Cross $300,000 (promising another $500,000 if needed), and a number of businesses made substantial contributions. Red Cross officials were wary, however, of taking steps that would adversely affect the United Way's annual fund drive.

RECOVERY

President Reagan declared Harris, Galveston, Chambers, Matagorda, Brazoria, and Fort Bend counties disaster areas shortly after Alicia, and on August 29 added Liberty, Montgomery, and San Jacinto counties. FEMA opened three assistance centers in the Houston area on the Tuesday following the storm, where individuals could apply for the categories of aid summarized in Table 6.10.

Table 6.11 gives the number of applicants for each of the four major categories of assistance. Of the 8,600 applicants for individual family grants, 6,800 had been approved by the end of December 1983. Approved grants averaged $1,700 per family and totaled $11 million. FEMA also approved 135 projects under its public (community) assistance program. The projects cost a total of $43.26 million, 75 percent of which came from FEMA (Federal Emergency Management Agency, personal communication, 1983).

TABLE 6.11 Number of Applicants for Major Categories of Individual Federal Assistance (through October 19)

Type of Assistance	Number of Applicants
Family grants	8,634
Temporary housing	3,002
SBA loans	5,938
Unemployment assistance	679

SOURCE: Federal Emergency Management Agency, personal communication, 1983.

By the end of 1983 not all of the claims made under the National Flood Insurance Program (NFIP) had been settled. There had been 14,500 claims filed, 3,000 of which were closed without payment for various reasons. A total of nearly 7,000 claims had been approved at an average figure of $11,000 per claim. Total NFIP payments will probably exceed $100 million (Federal Emergency Management Agency, personal communication, 1983).

The Property Claims Services of the American Insurance Association estimated that there were $675.5 million worth of insured losses (excluding claims for flooding, crops, highways, utilities, and military property). These losses involved 275,000 claims. Included in these figures are $150 million in claims against the Texas "Catpool,m which is underwritten by 600 companies comprising the Texas Catastrophe Property Insurance Association. The pool was formed to provide wind and hail coverage in 14 coastal counties for high-risk properties whose owners would not otherwise be able to obtain coverage. Catpool's average claim was about twice as high as other claims; the pool does not include Harris County (Texas Insurance Information Institute, personal communication, 1984).

Alicia will leave her mark on the Texas coast for years to come, not just in terms of physical destruction but in other ways as well. The Texas State Board of Insurance noted, for example, that actuarial rates are figured on the basis of a 10-year loss average and that Alicia will therefore increase the rates of homeowners insurance. A 75- to 100-ft recession of the "continuous vegetation line" along the beach in some places moved the state property line inland to the point that some structures, which had withstood the storm, were not located on state property, and state officials were trying to reach an accommodation with owners.

Building and rebuilding were viewed critically, despite the eagerness of owners to rebuild or restore their properties as rapidly as possible. Galveston imposed a temporary moratorium on substantial repairs or replacement while it reviewed the adequacy of the enforcement system for its codes. One outgrowth of this review has been an increase in the emphasis placed on building inspection by the city. A number of signs were destroyed in Houston, and those that had not been in conformance with a 1980 law governing size, height, placement, and so forth were required to comply with the new standards if they were to be replaced.

Probably the most drastic postdisaster recovery issue involved the Brownwood housing development in Baytown. An upper-middle-class subdivision on a small peninsula jutting into Galveston Bay, the Brownwood area had been experiencing severe subsidence due to withdrawal of groundwater for several years. Since 1940, the area has subsided over 9 ft, leaving most of the 300 homes less than 2 ft above mean high tide. Some residents had received three or four flood insurance claims during the past 10 or 15 years. Twice in recent years, Baytown residents rejected $7 million bond issues to match $32 million to be provided by the Corps of Engineers to purchase Brownwood properties and relocate the residents. In Alicia, surge heights reached approximately 10 ft in the Brownwood area, destroying most of the homes there and causing at least 50 percent damage to all others.

FEMA has offered to use Section 1362 funds to purchase all insured properties (which include all but 14) in Brownwood, to assist residents in relocation, to provide funds for clearing of damaged homes, and to make available restricted Small Business Administration loans to some residents being involuntarily relocated. The average replacement value of homes in the Brownwood area is $80,000, but their average fair market value before Alicia was only $30,000. The 1362 funds used to purchase property only make up the difference between flood insurance claim receipts and fair market value. The average coverage in Brownwood, however, was $60,000, exceeding in most cases the fair market value. Thus little 1362 money will actually be necessary to supplement the roughly $20 million in flood insurance claims expected. All in all, the FEMA purchase arrangement will cost (including insurance claims) between $22 million and $25 million, considerably less than the federal share of costs in the plans rejected by voters earlier (Interagency Hazard Mitigation Team, 1983).

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Fig 4-1 Go Back

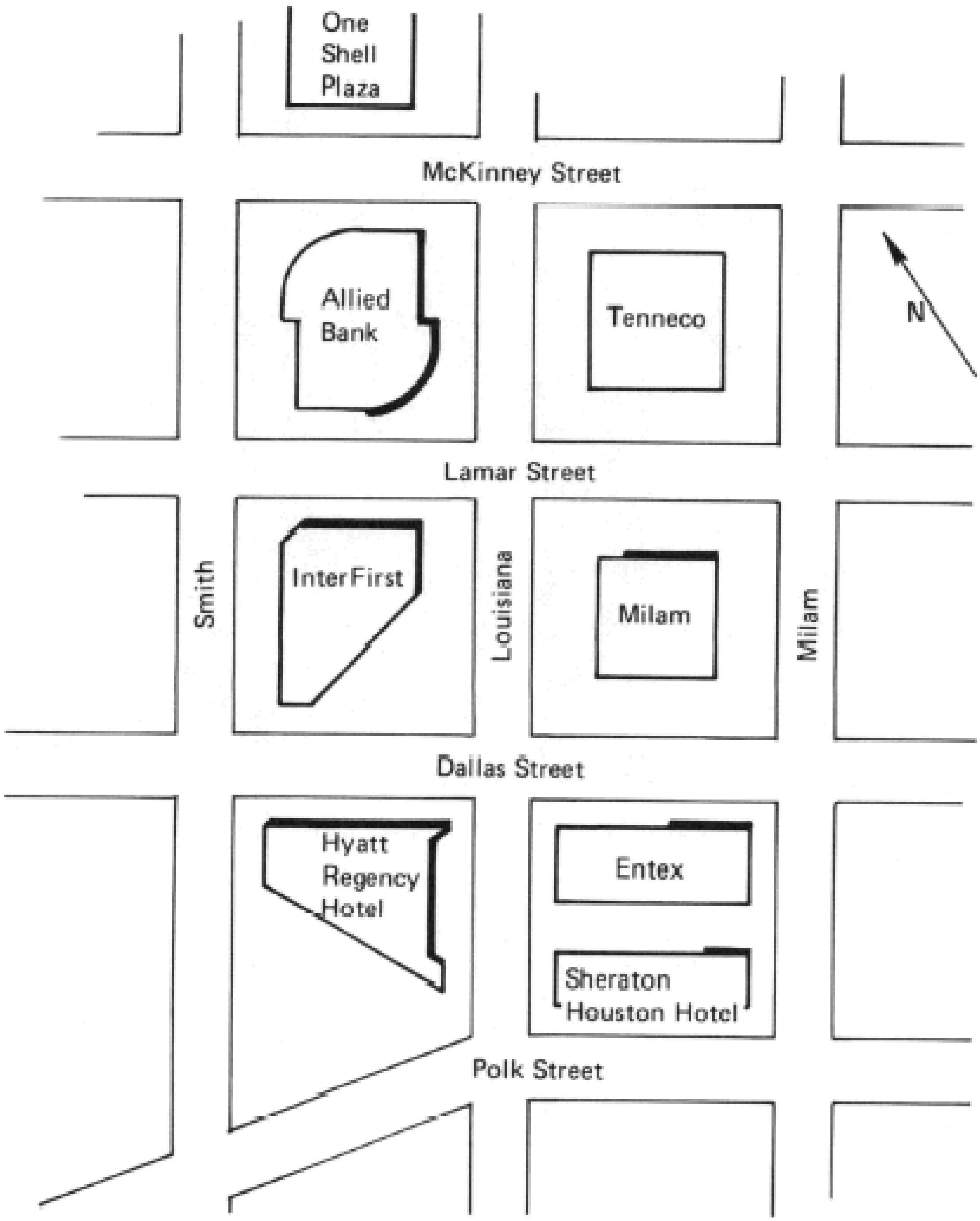


FIGURE 4.1 Areas of extensive glass breakage, indicated by bold lines, in the Houston central business district.

Go Back

FIGURE 4.10 Window damage to the Sheraton-Houston Hotel.

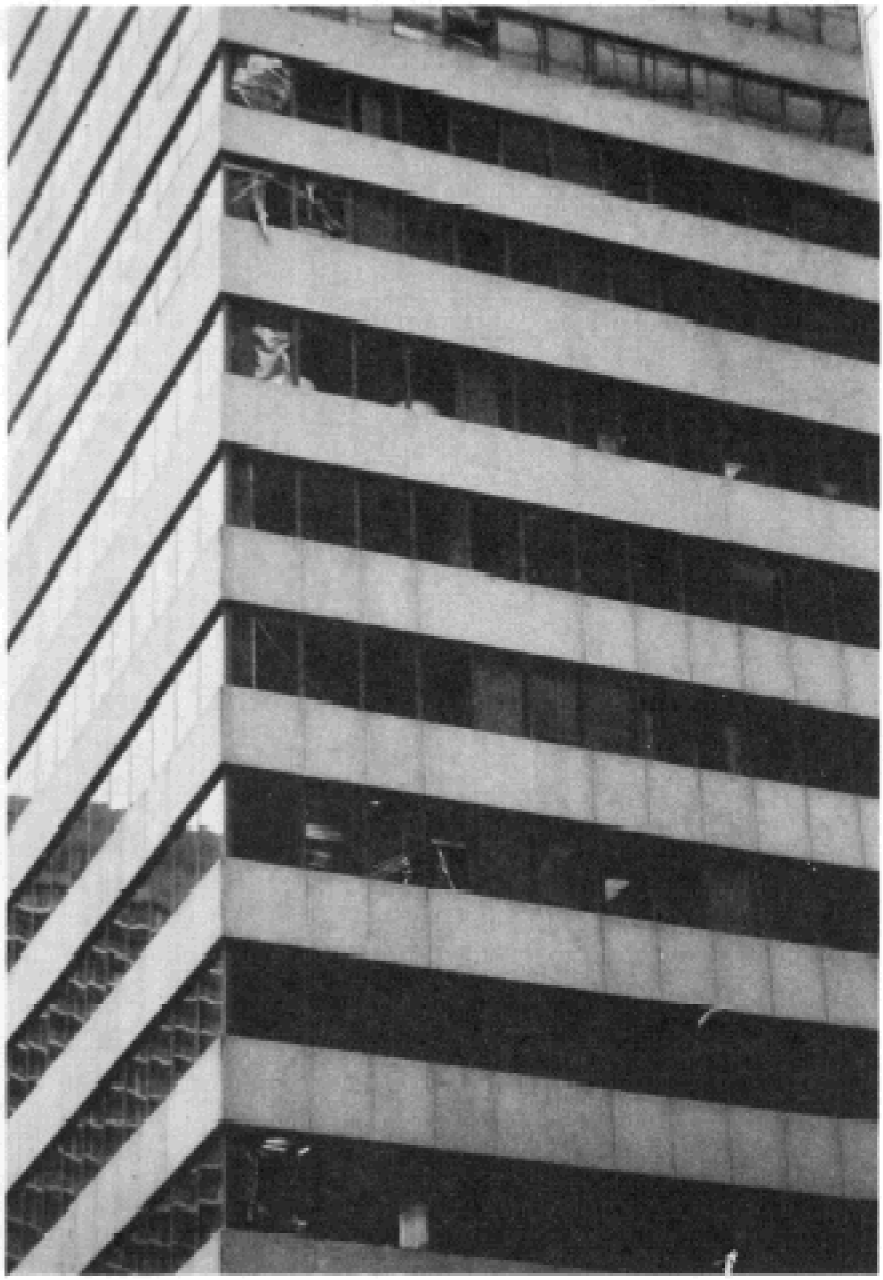


Fig 4-11 & 4-12 below Go Back

FIGURE 4.11 General view of the roof of the Tenneco Building.

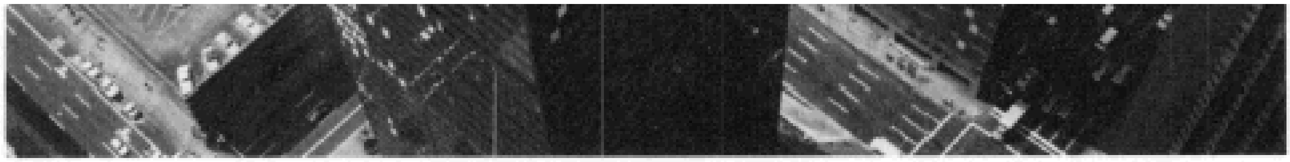


FIGURE 4.12 General view of the roofs of the Milam and Entex buildings.

Go Back

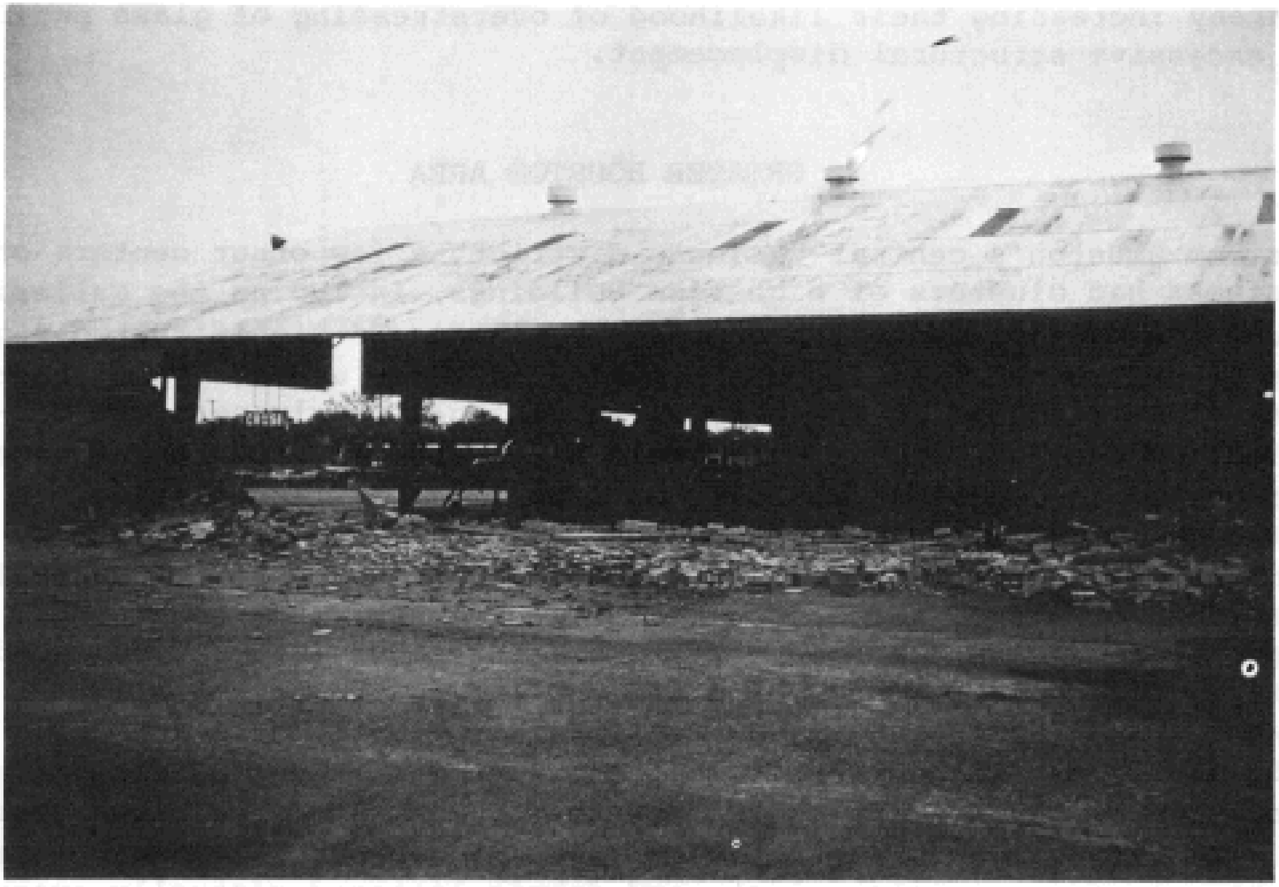


FIGURE 4.13 Collapsed brick wall of airport hangar at Hobby Airport.

Fig 4-14 and Fig 4-15 (below) Go Back

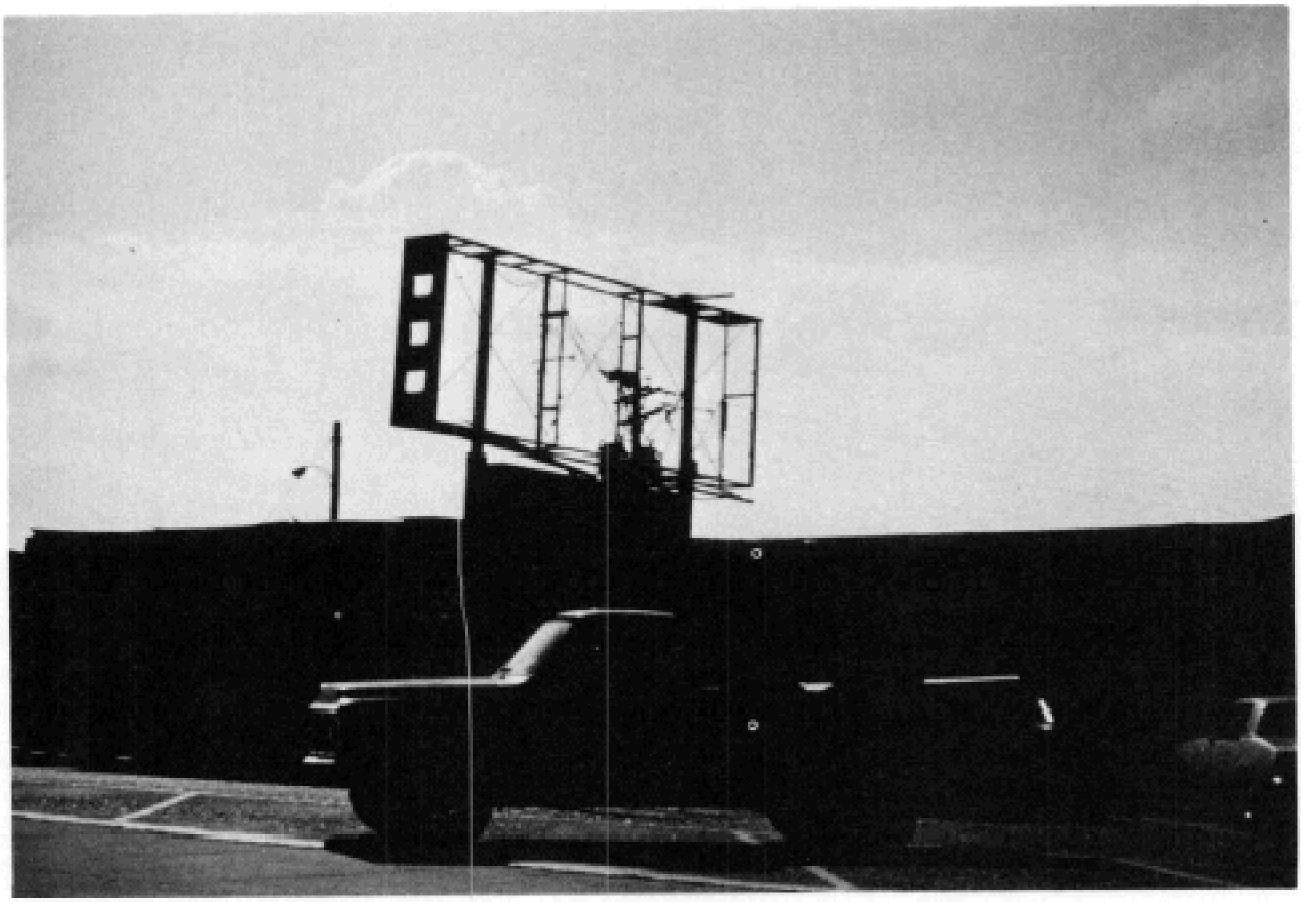
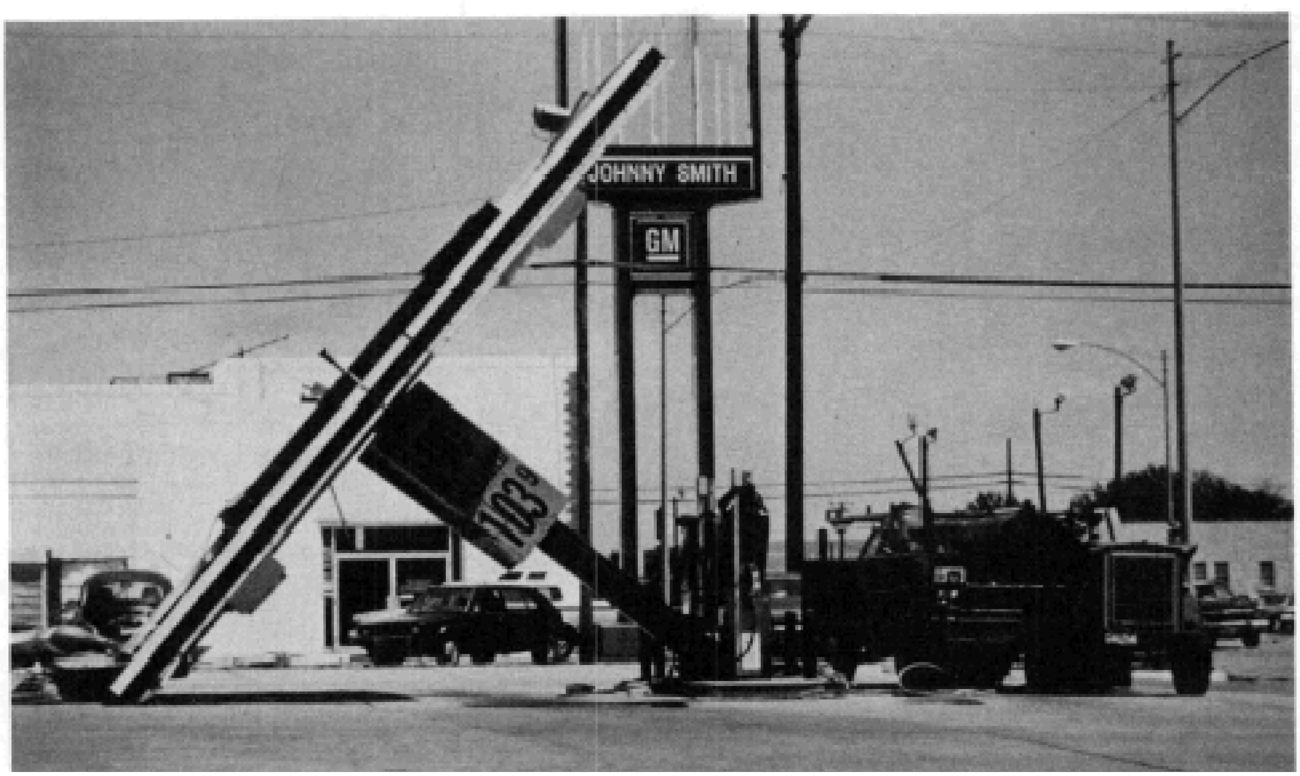


FIGURE 4.14 Damaged billboard.



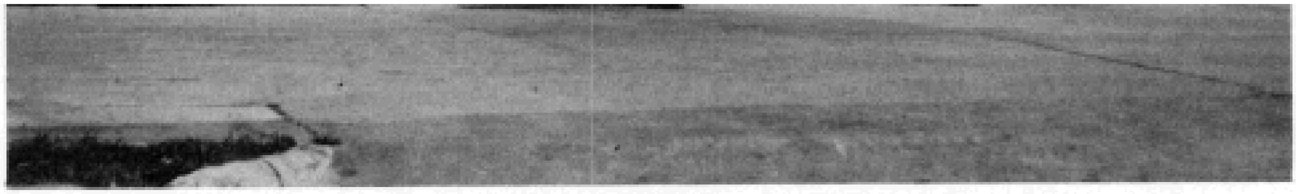


FIGURE 4.15 Example of failure of a roof support pedestal column.

Go Back

FIGURE 4.16 Failure of sheet metal roof at a gas station.

Figure 4-17 and Figure 4-18 (below) Go Back

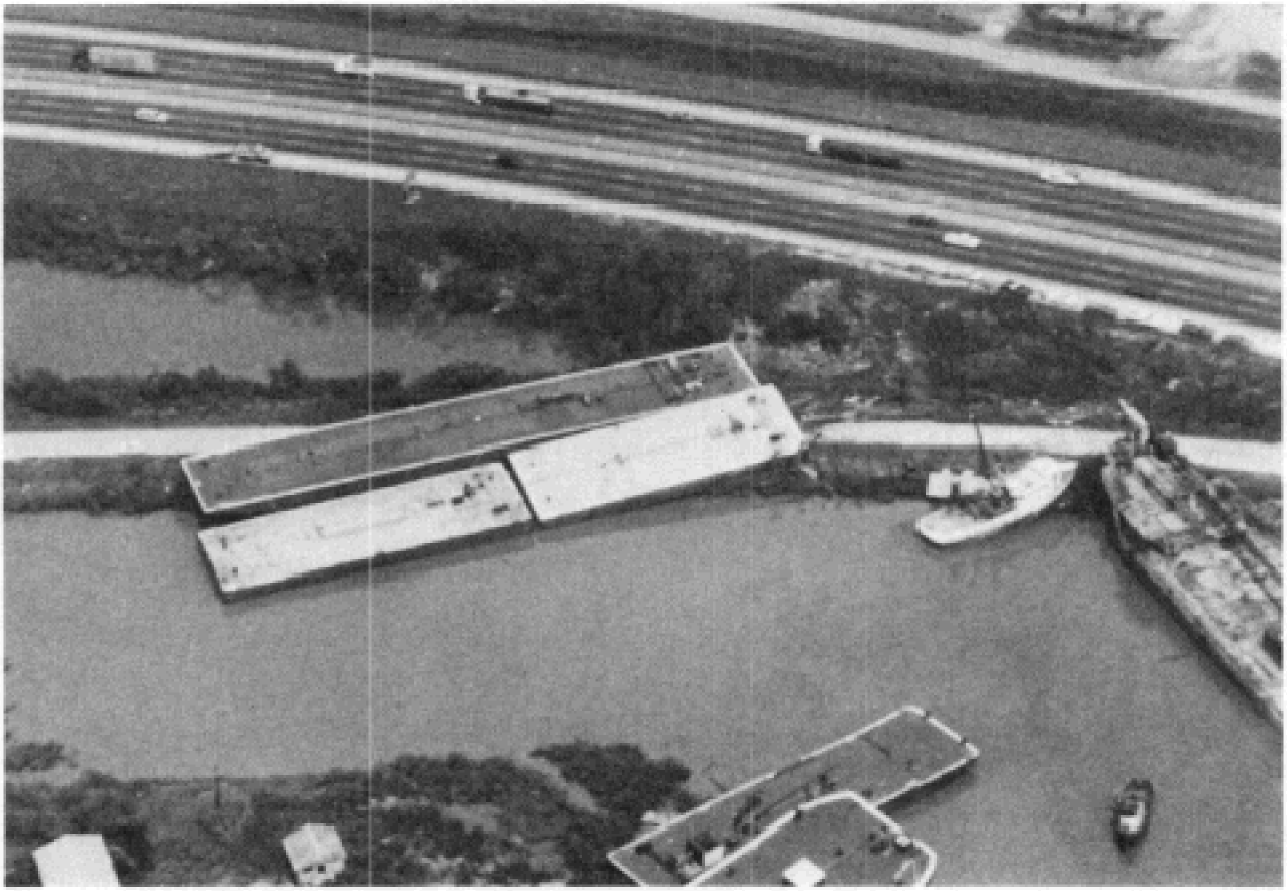
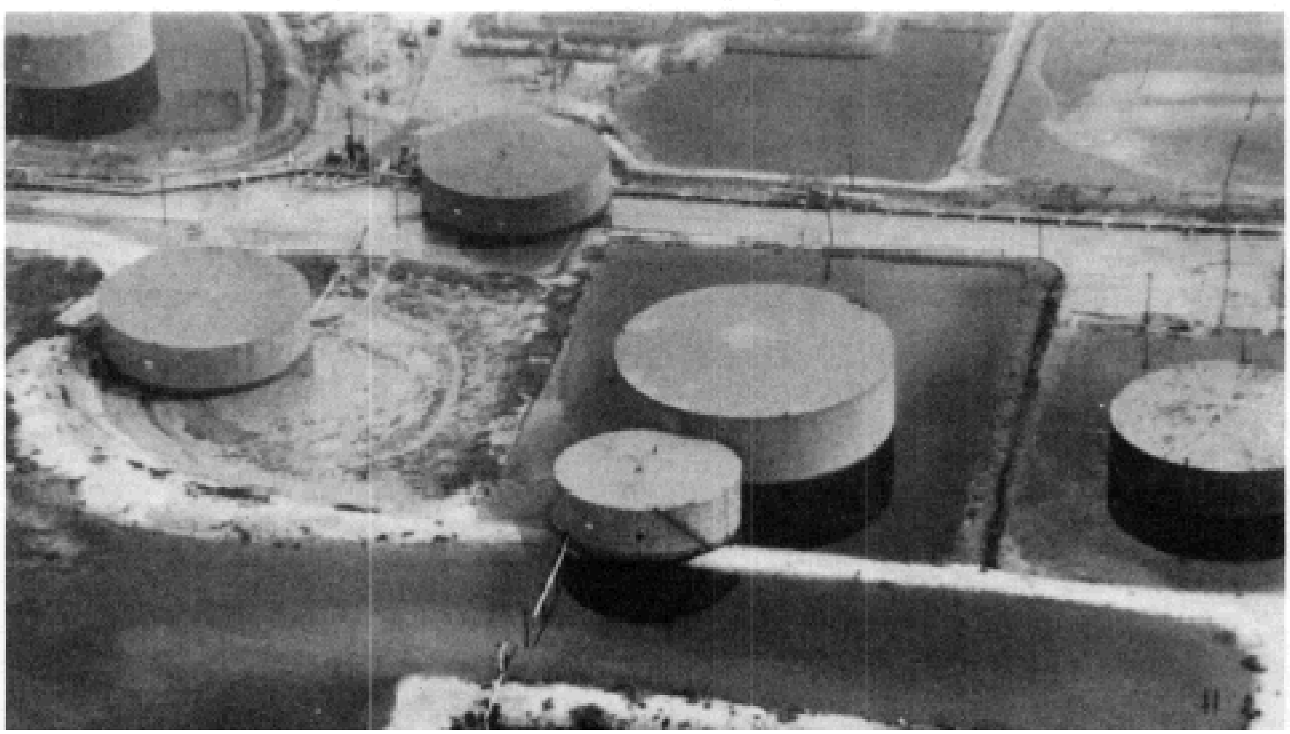


FIGURE 4.17 Barges and a tanker in the Houston ship channel area.



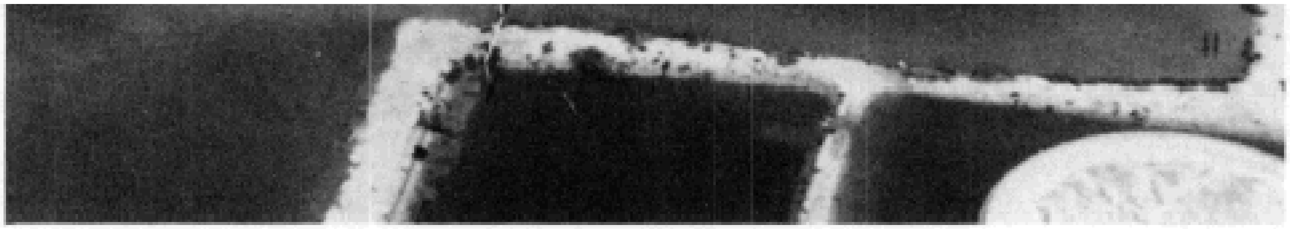


FIGURE 4.18 Displaced oil storage tanks.

Figure 4-19 and 4-20 (below) Go Back

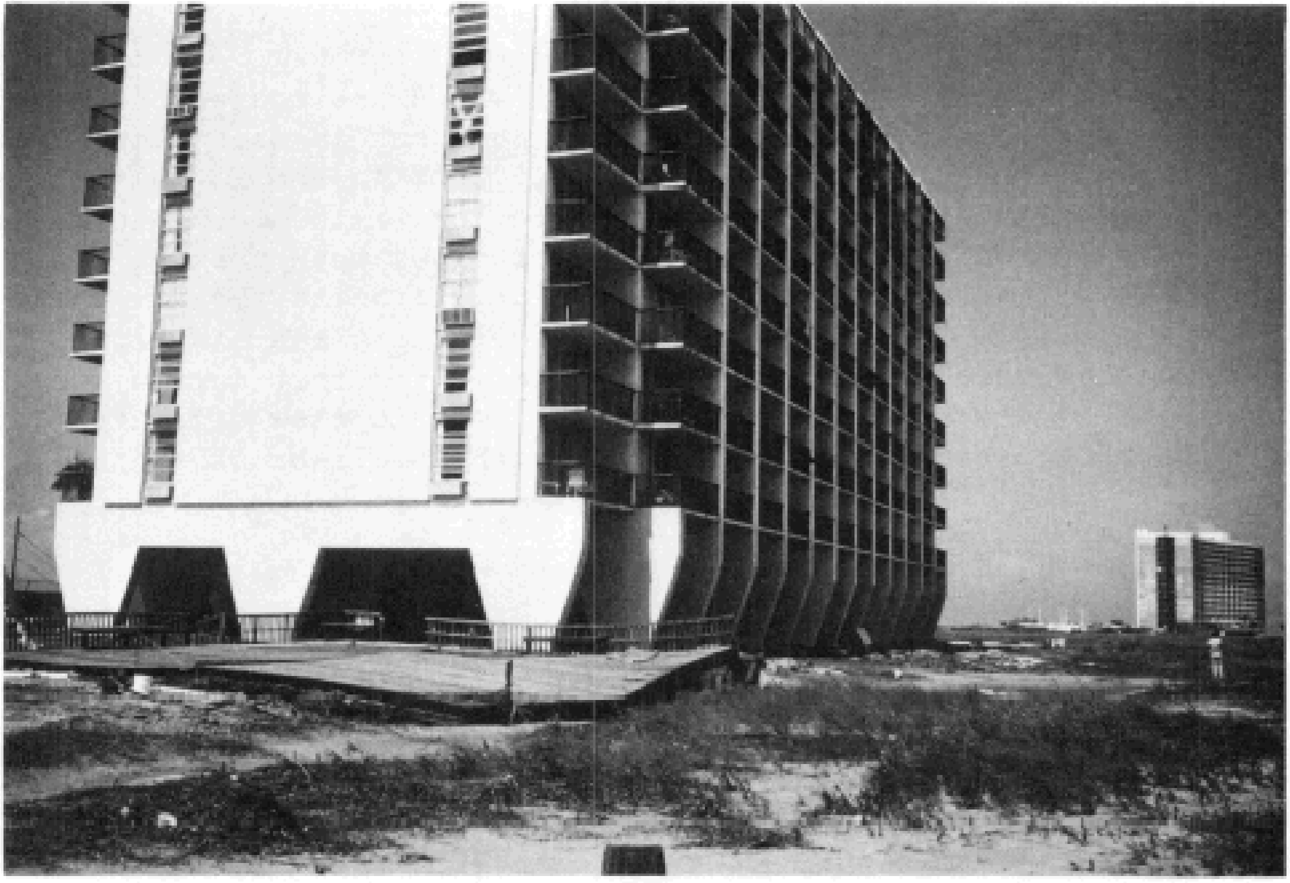


FIGURE 4.19 General erosion and damaged deck around Islanders Inn and the Galvestonian (in the background).

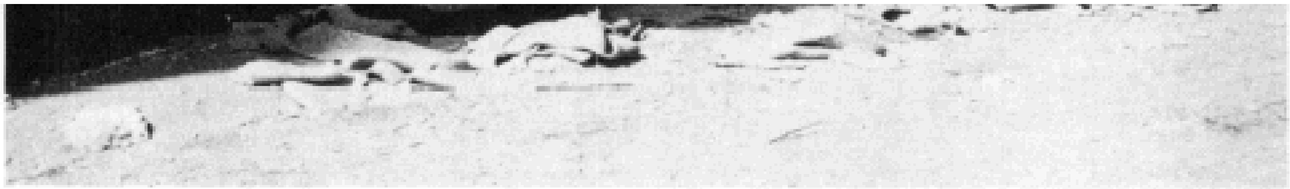


FIGURE 4.20 Erosion around the foundation of the Galvestonian.

Fig 4-2 [Go Back]

FIGURE 4.2 General view of the Houston central business district toward the west.

Go Back

FIGURE 4.21 Damage to facade and glass of the American National Insurance Building.

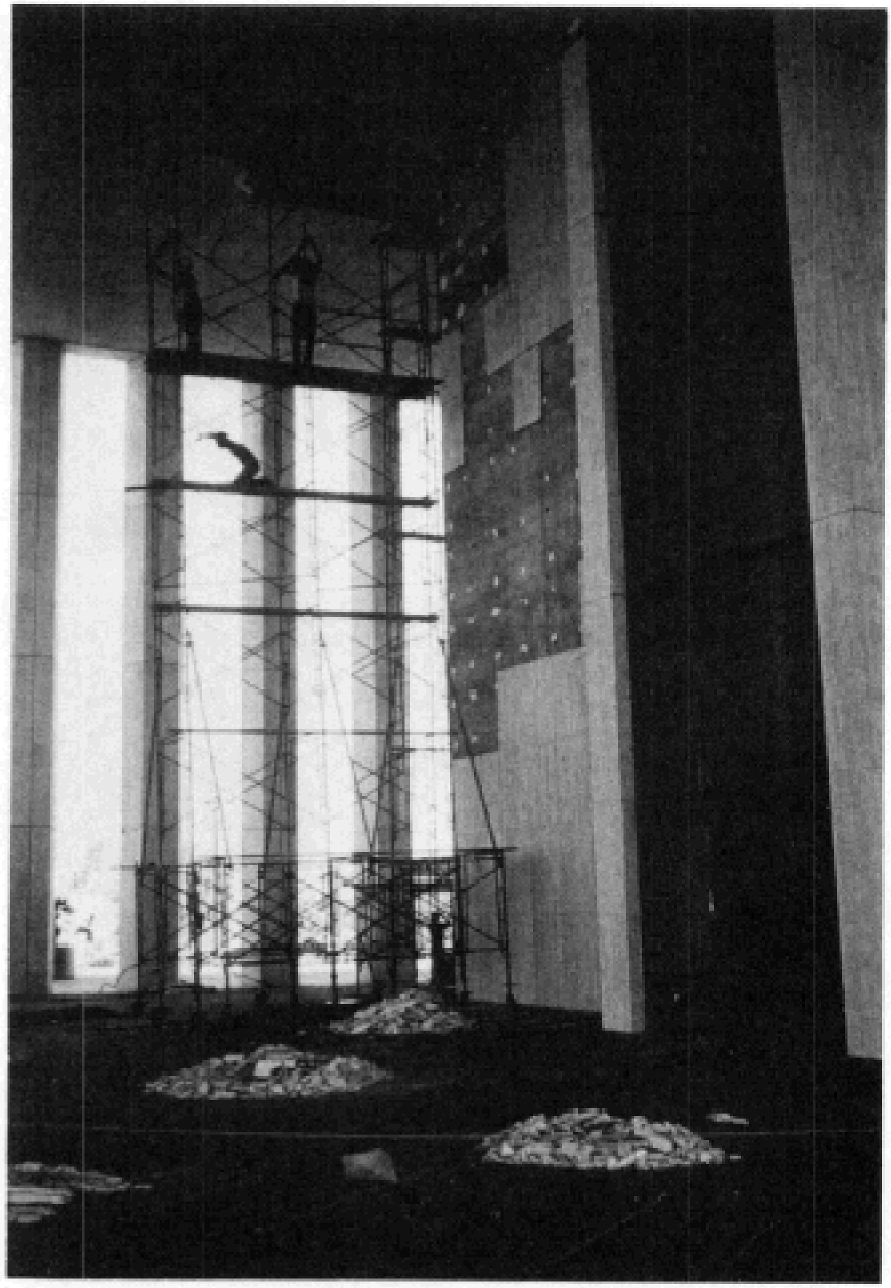


Figure 4-22 and 4-23 (below)   Go Back

FIGURE 4.22 Damage to tiled roof of the Hotel Galvez.

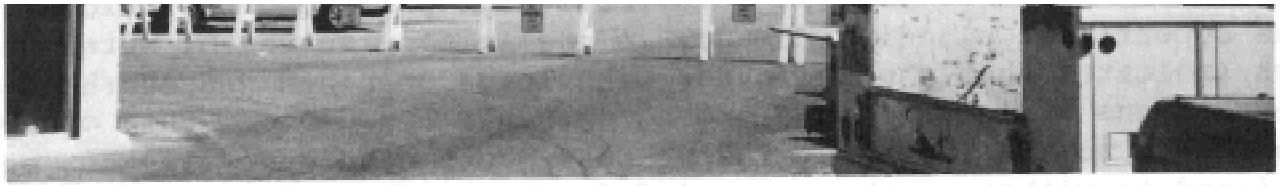


FIGURE 4.23 Damage to the facade of the Flagship Hotel.

Figure 4-24 and 4-25 (below) Go Back

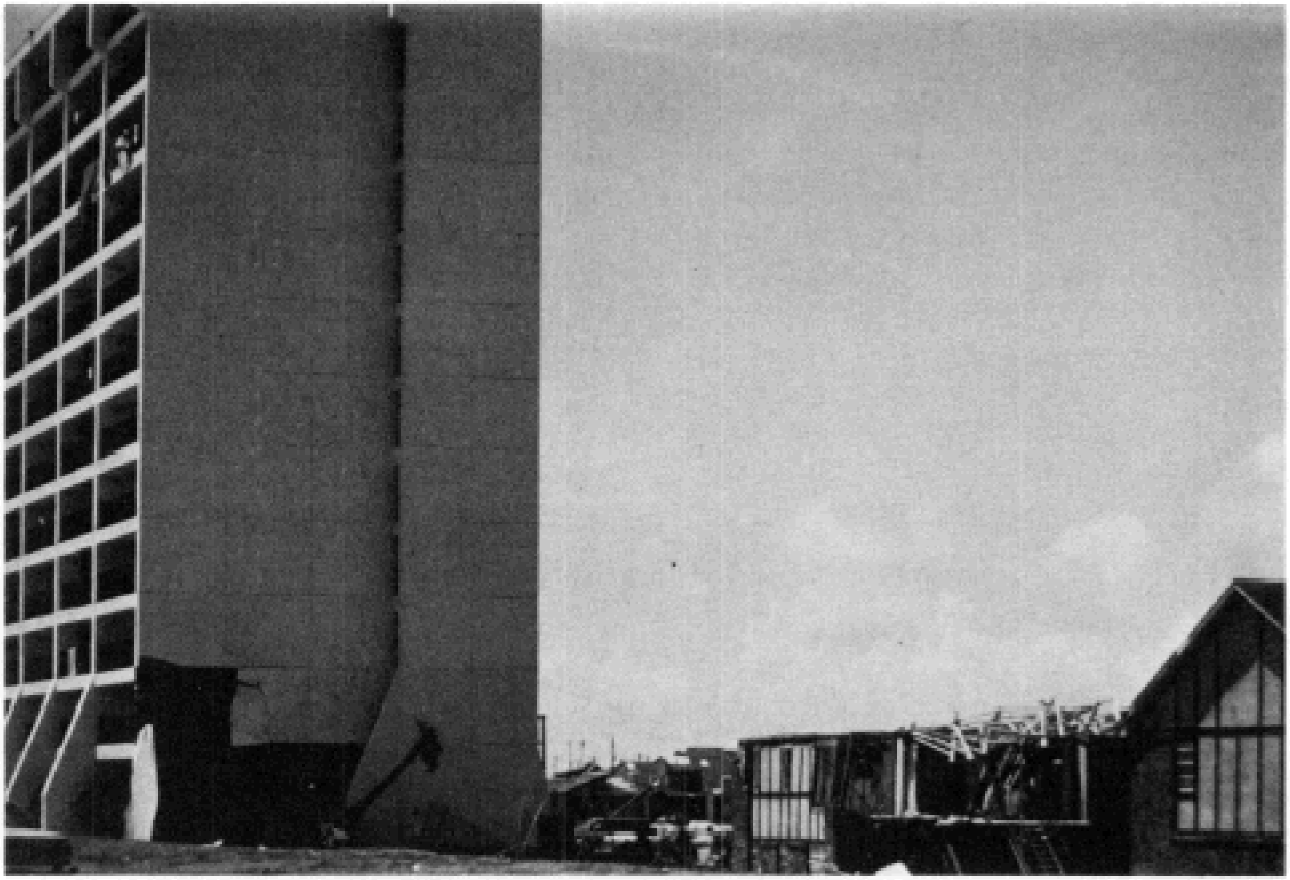


FIGURE 4.24 General view of damage to condominiums on the sea-wall.

FIGURE 4.25 Closeup of damage to the facade of By-the-Sea Condominium.

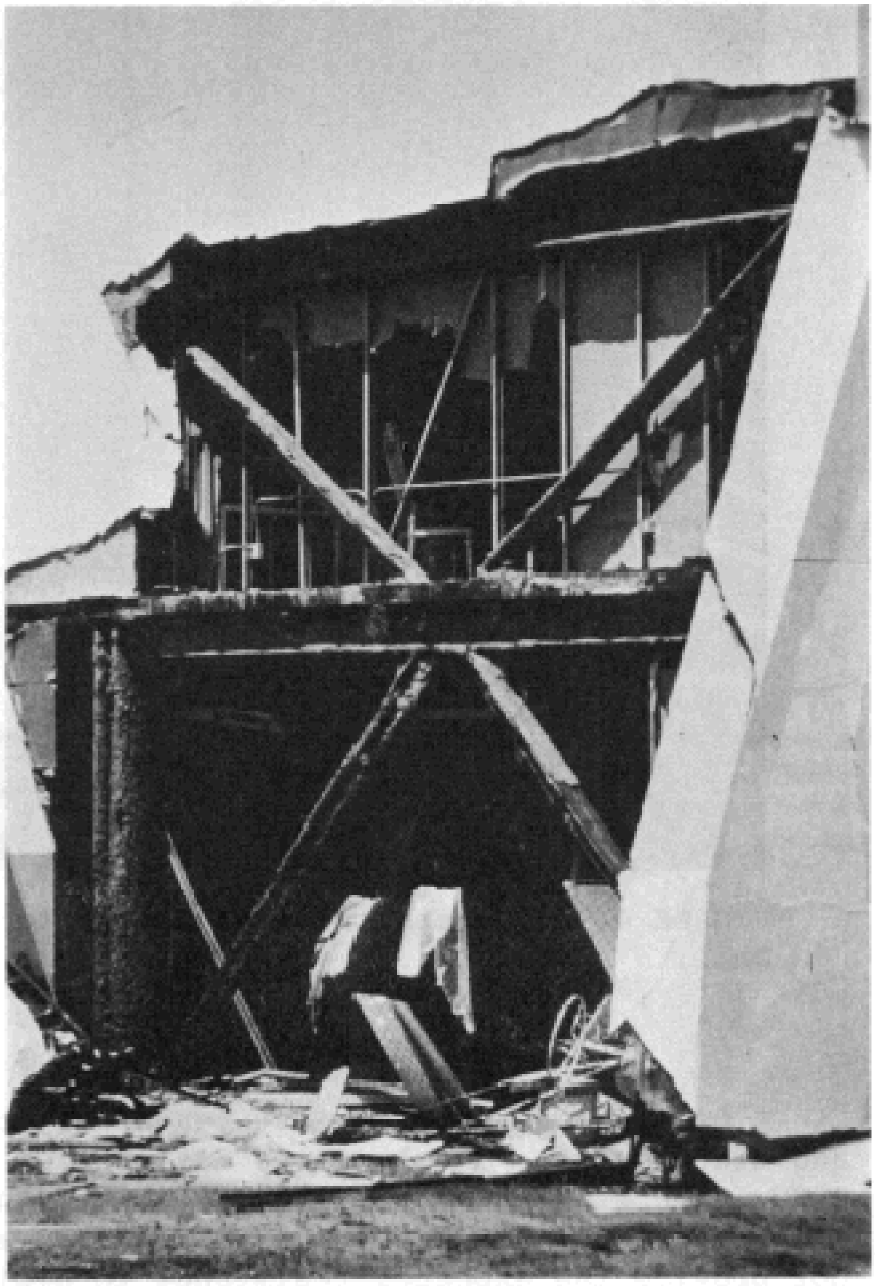


Fig. 4-26 and Fig 4-27 below Go Back

FIGURE 4.26 Damaged mobile home park on East Beach.

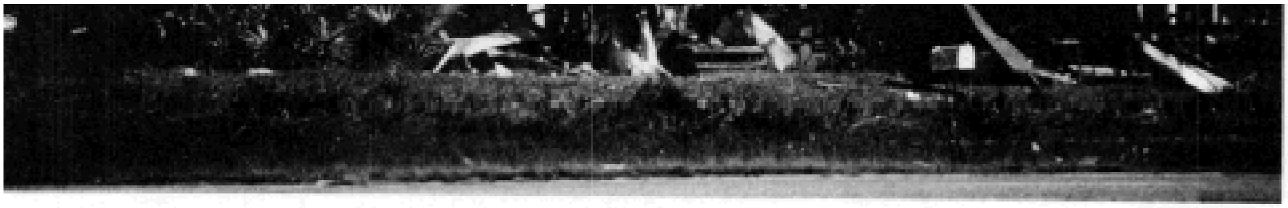
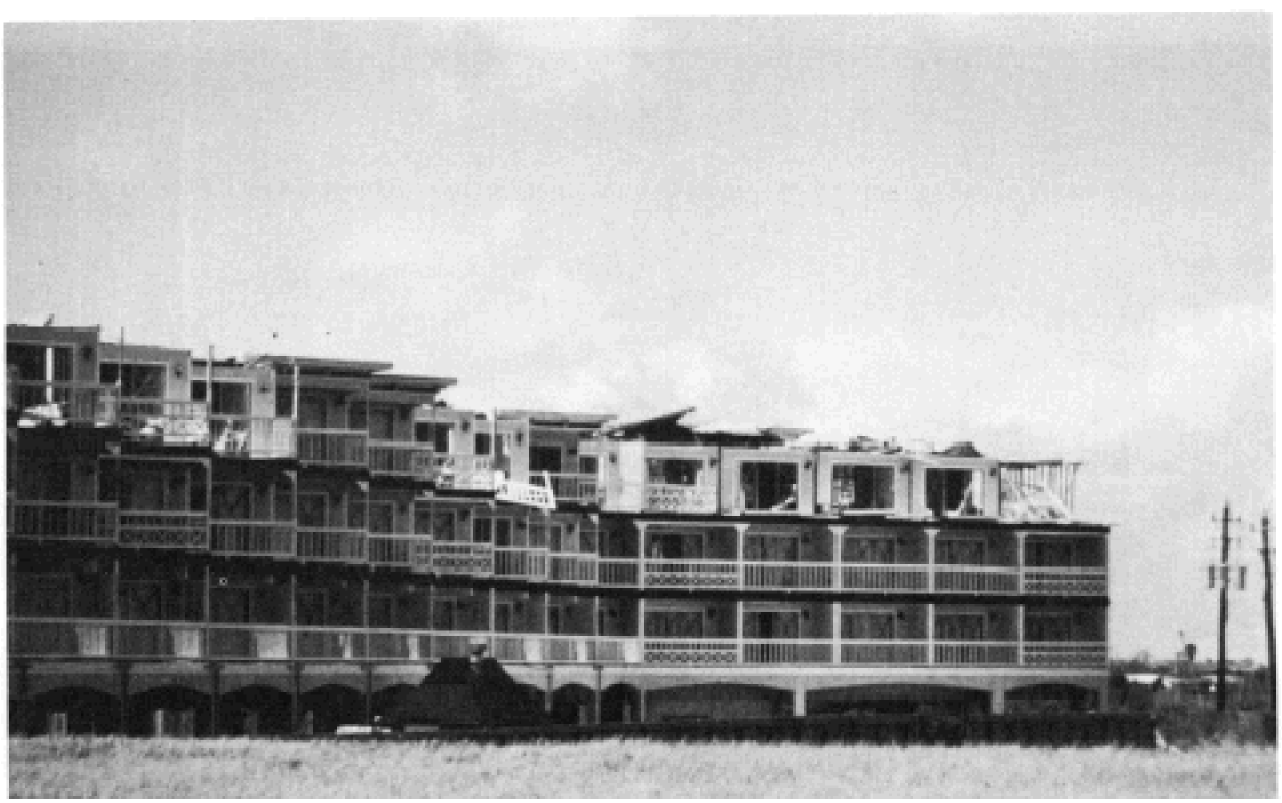


FIGURE 4.27 Damage to an elevated mobile home on West Beach.

Fig 4-28 and Fig 4-29 below Go Back

FIGURE 4.28 Damaged mobile home park on West Beach.



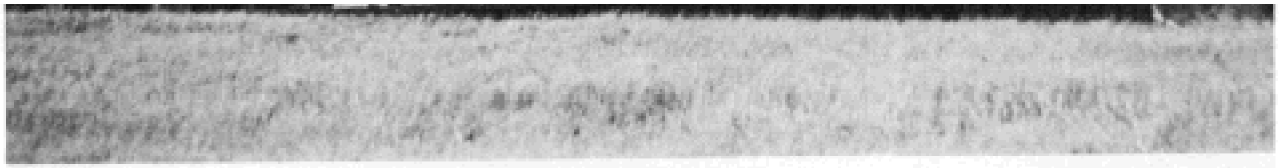


FIGURE 4.29 General view of the damaged wing of the Victoria Hotel.

Go Back

FIGURE 4.3 Glass damage on the southwest face of the Allied Bank Building. Dark shapes are reflections of adjacent buildings.

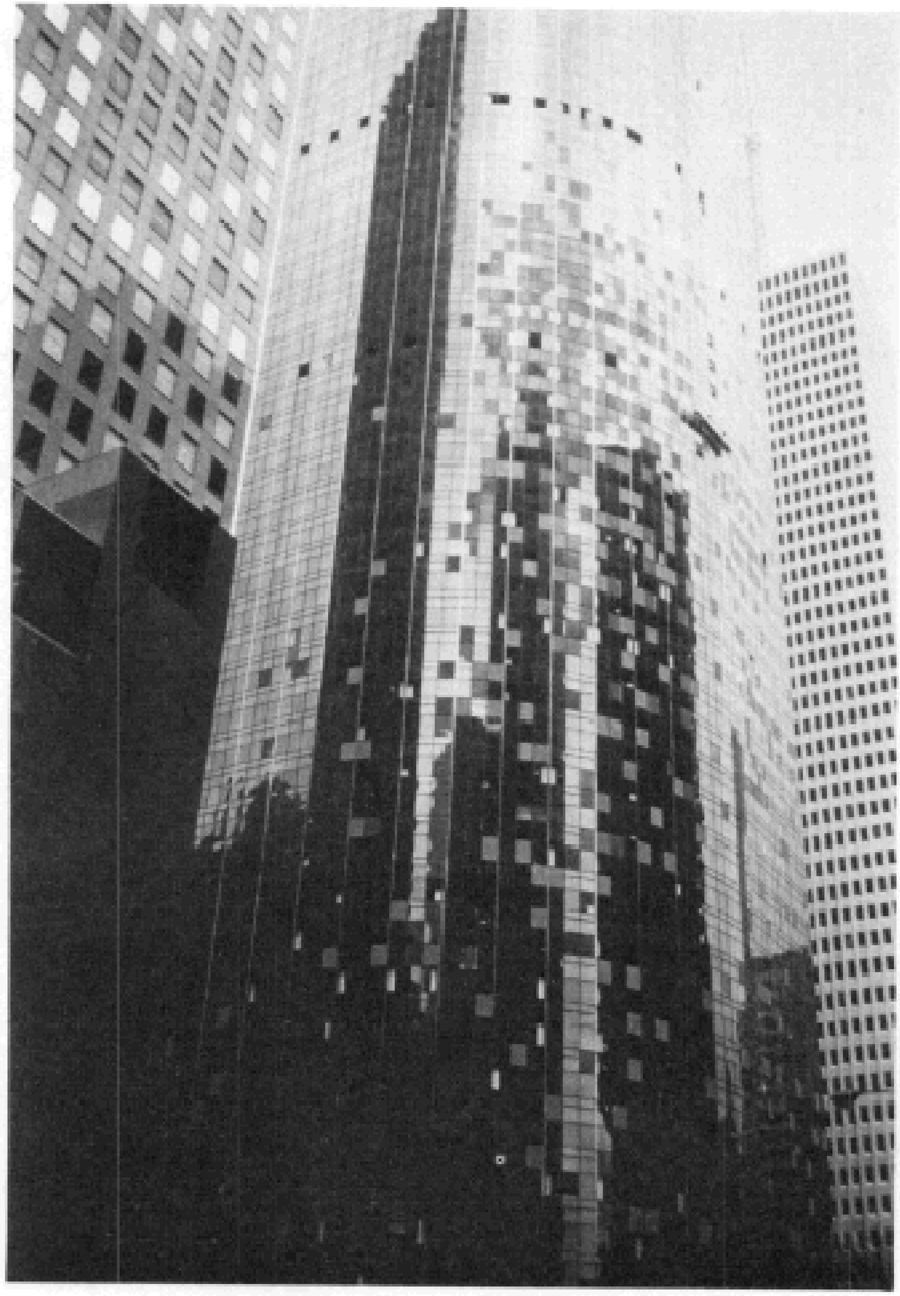


Fig 4-30 and Fig 4-31 (below) Go Back

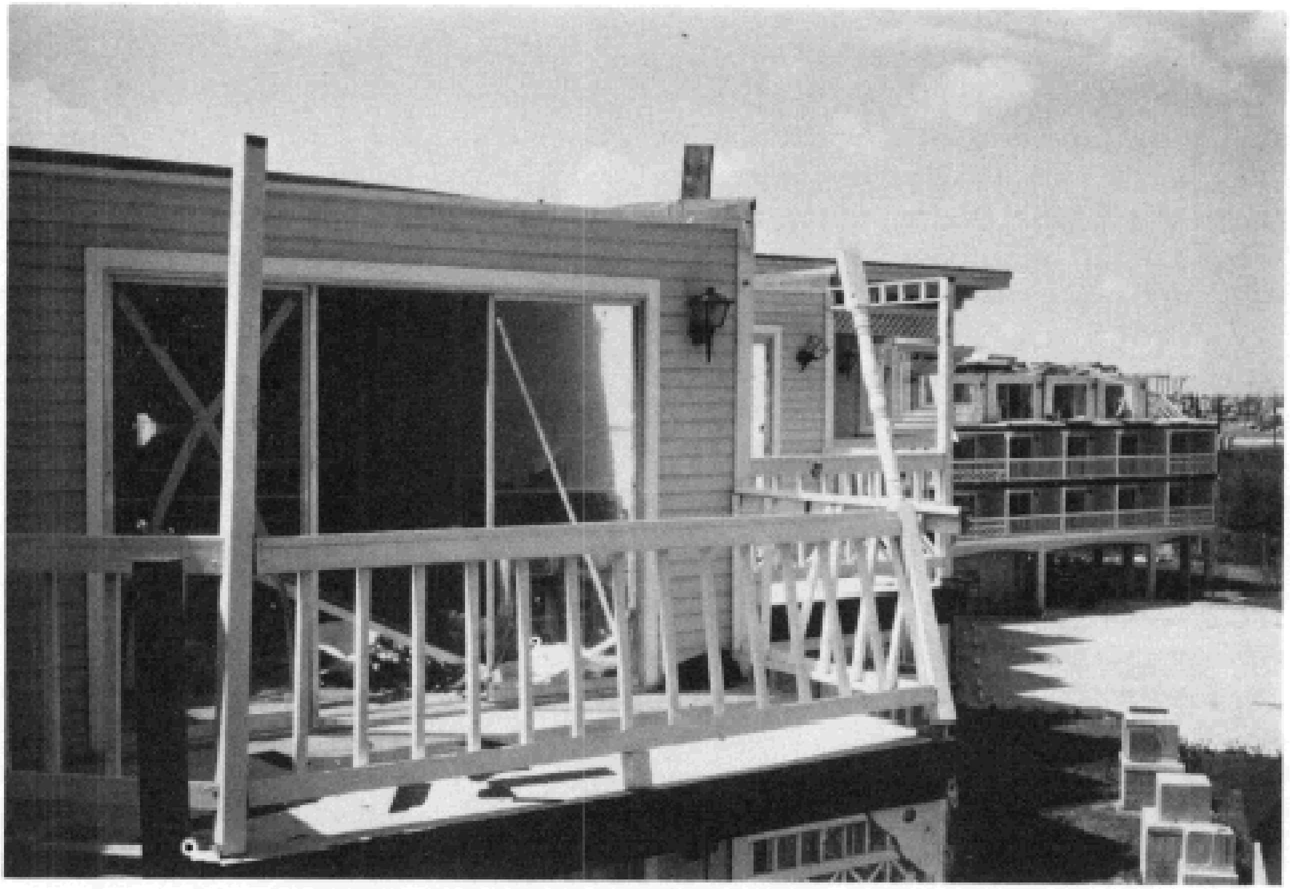
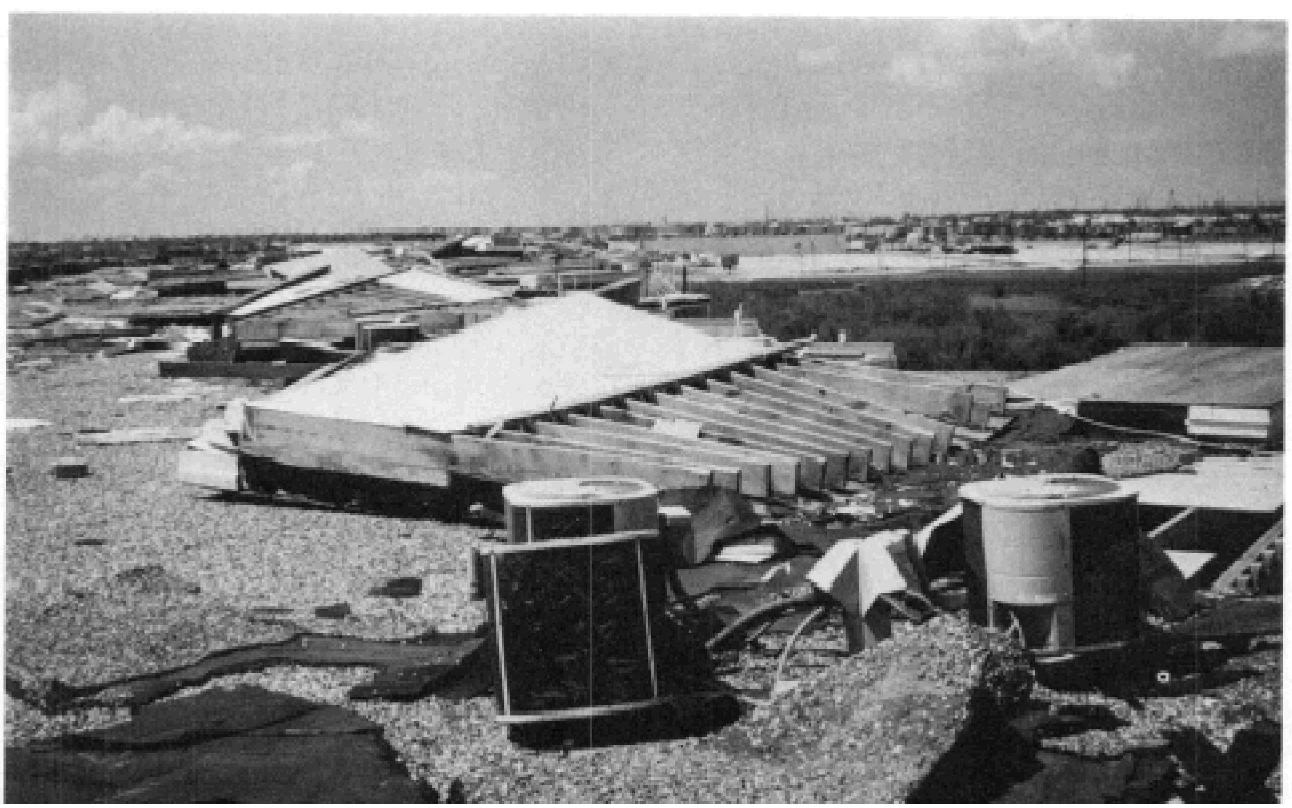


FIGURE 4.30 Closeup of a damaged unit in the Victoria Hotel.



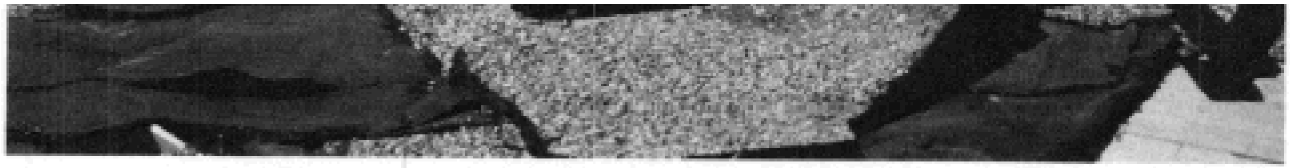
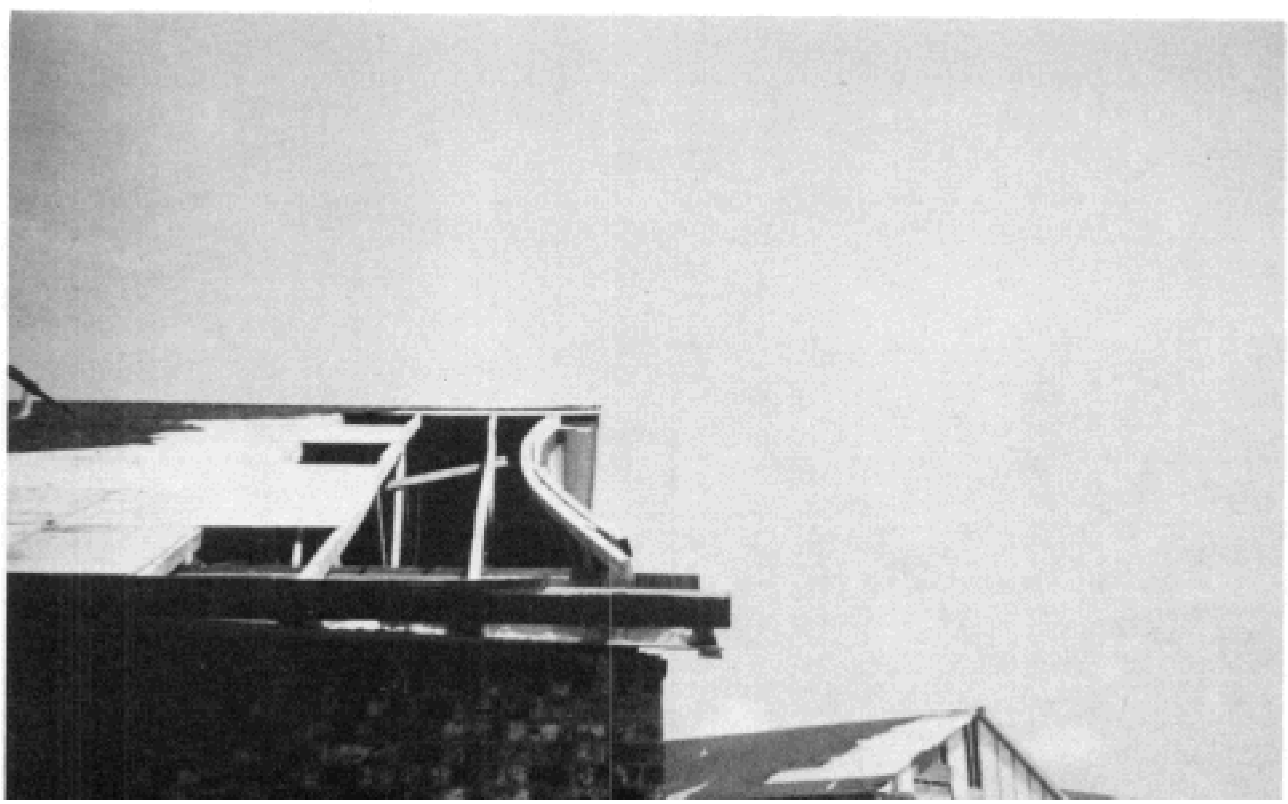


FIGURE 4.31 General view of the roof of the Victoria Hotel, showing damaged overhangs that landed on the roof.

Fig 4-32 and Fig 4-33 below Go Back

FIGURE 4.32 Roof damage to apartments near the seawall.



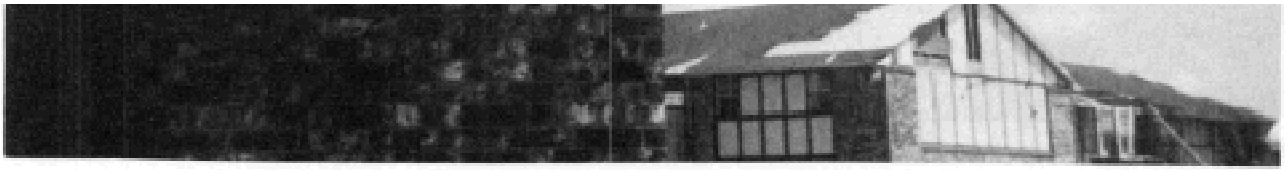


FIGURE 4.33 Damage to a roof truss caused by lack of bracing between trusses.

Fig 4-34 and 4-35 below Go Back

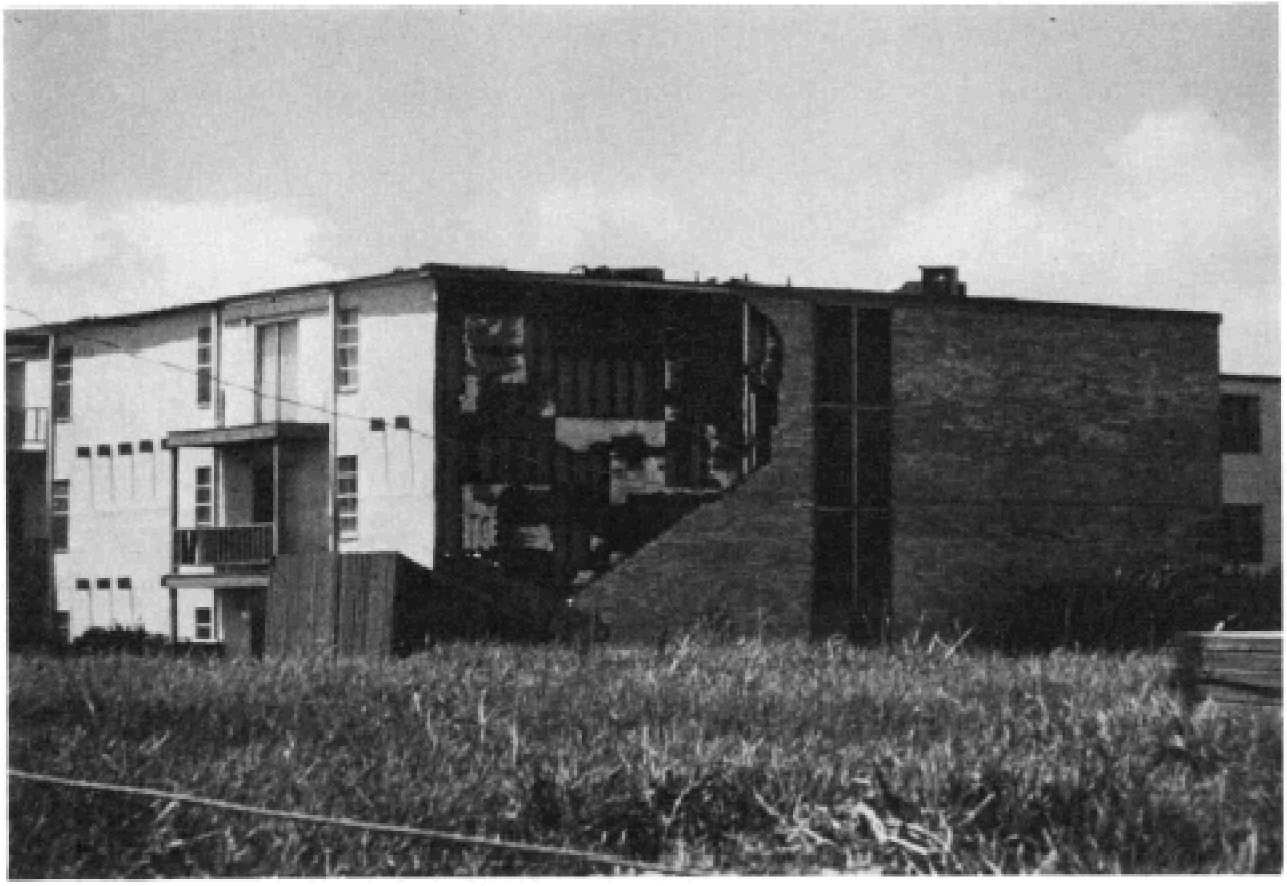
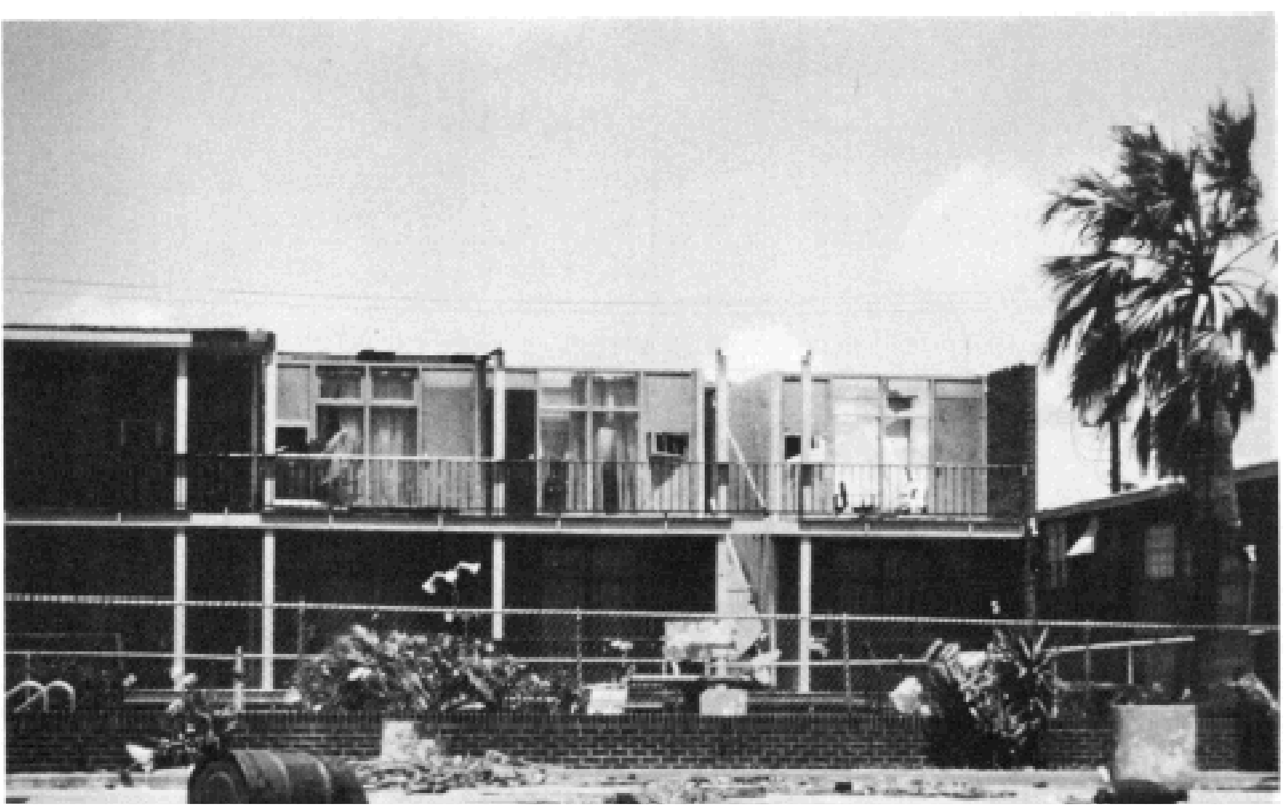


FIGURE 4.34 Failure of veneer brick walls due to lack of ties.



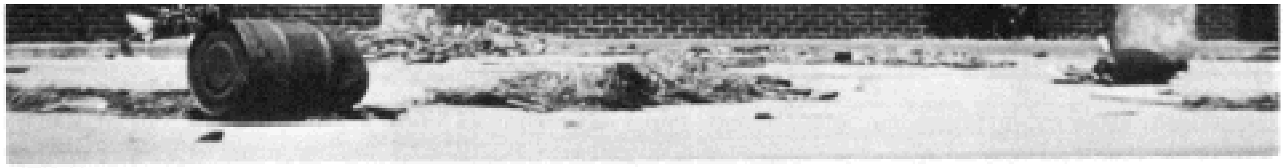


FIGURE 4.35 Partial loss of roof at a motel.

Fig 4-36 and 4-37 below Go Back

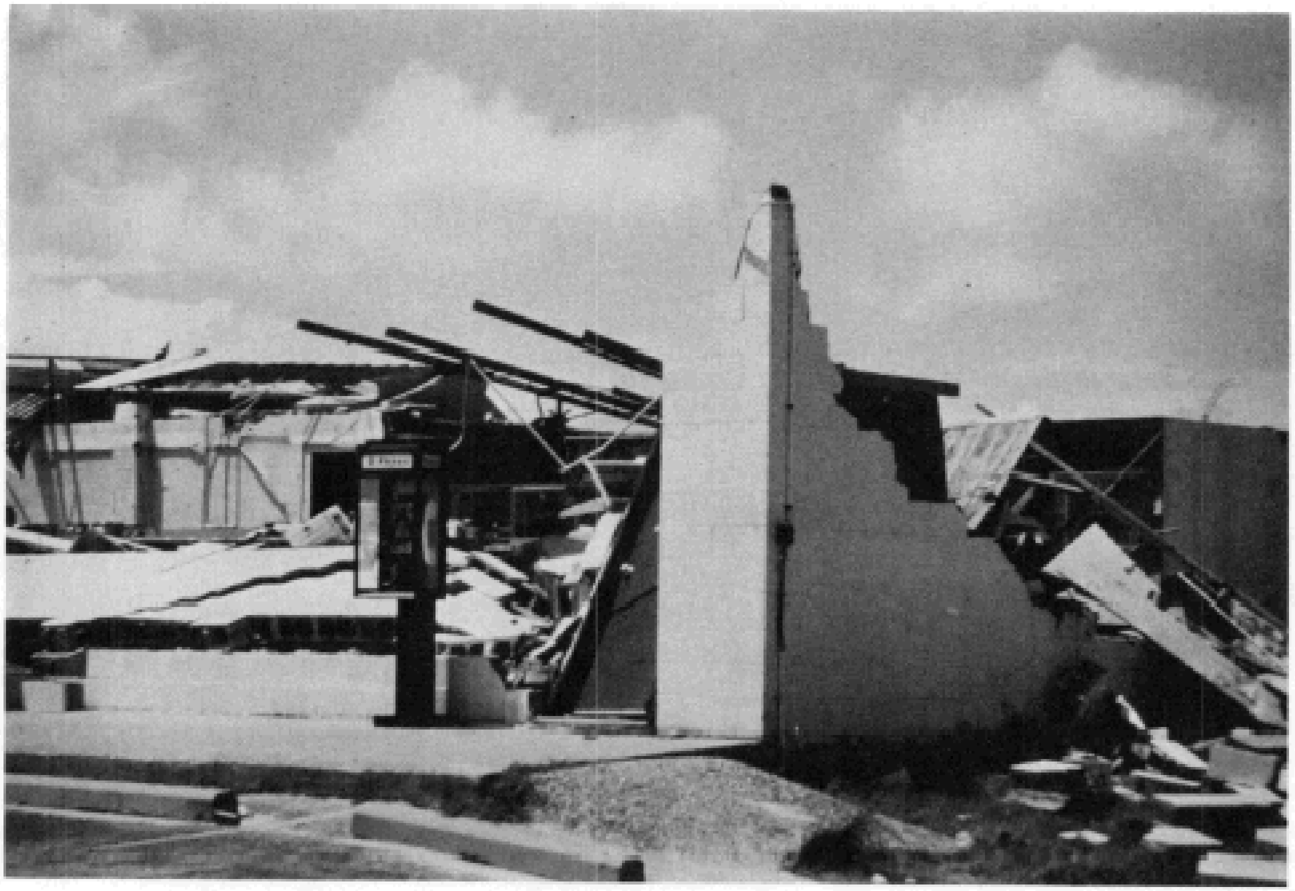
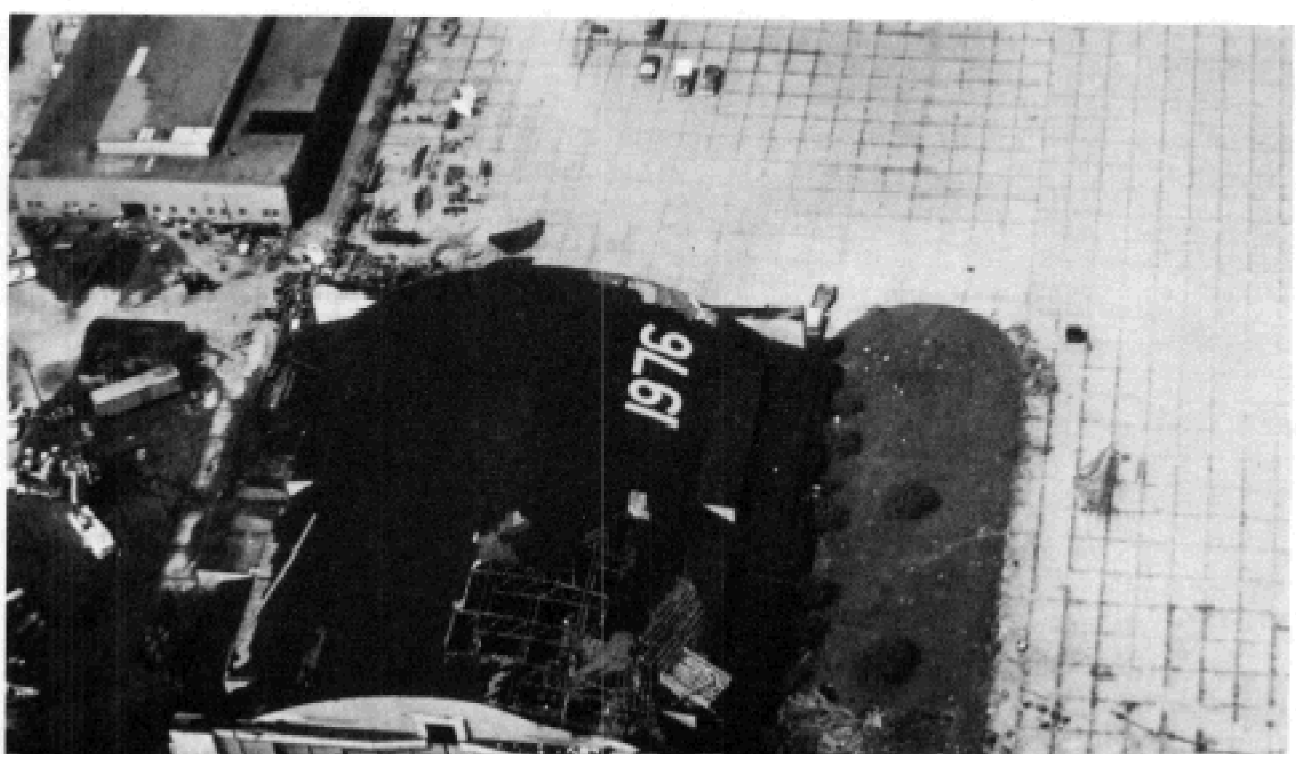


FIGURE 4.36 Typical example of the failure of one of many convenience stores.



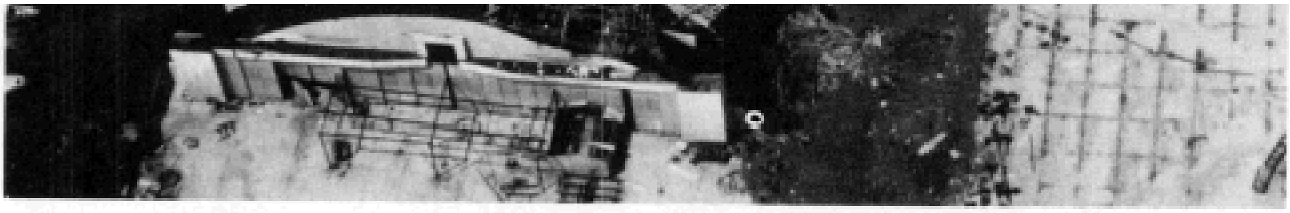


FIGURE 4.37 Wind damage to the roof of a hangar at Galveston Airport.

Go Back

FIGURE 4.38 Damaged hangars and small aircraft at Galveston Airport.

Fig 4-39 and 4-40 below [Go Back]

FIGURE 4.39 Example of a roof failure of a house in Terramar Beach.

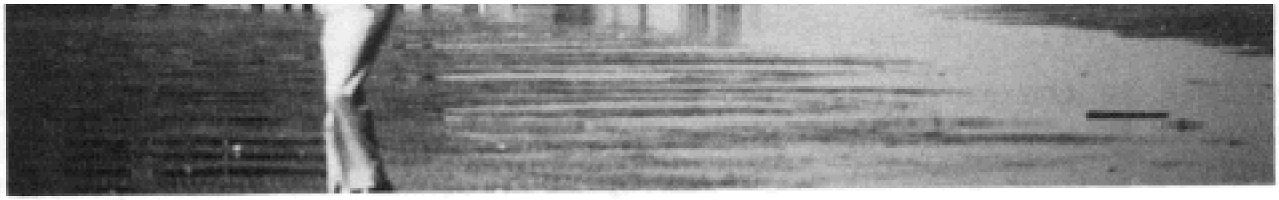


FIGURE 4.40 General view of damaged houses along Terramar Beach.

Go Back

FIGURE 4.4 Closeup of damaged glass on the southeast face of the Allied Bank Building.

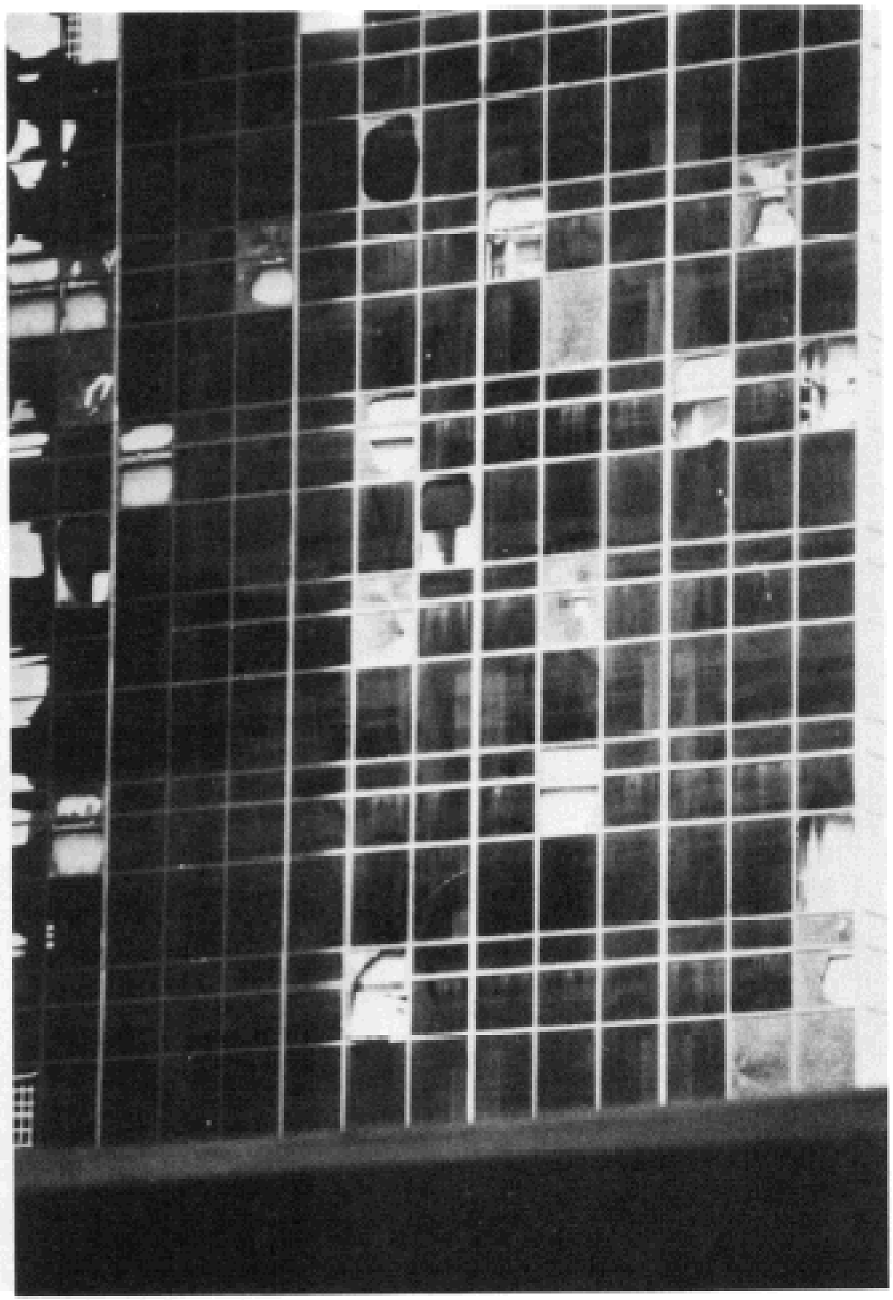


Fig 4-41 and 4-42 below Go Back

FIGURE 4.41 Example of overall collapse of a house and supporting structure.

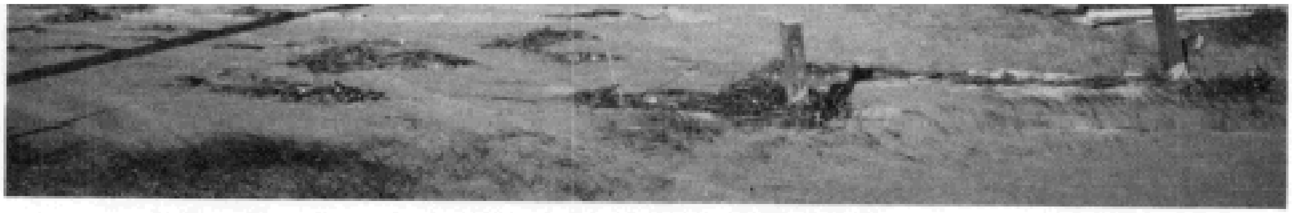


FIGURE 4.42 Typical example of partial collapse of a large house in Terramar Beach.

Fig 4-43 and 4-44 below [Go Back]

FIGURE 4.43 Example of a superstructure blown away by the wind. A mound of lumber, furniture, and appliances is in the backyard of the house.

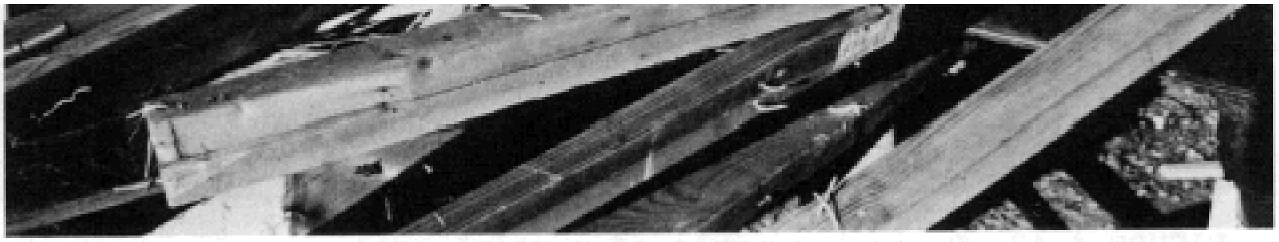


FIGURE 4.44 Details of toe nail connections.

Fig 4-45 and Fig4-46 below Go Back

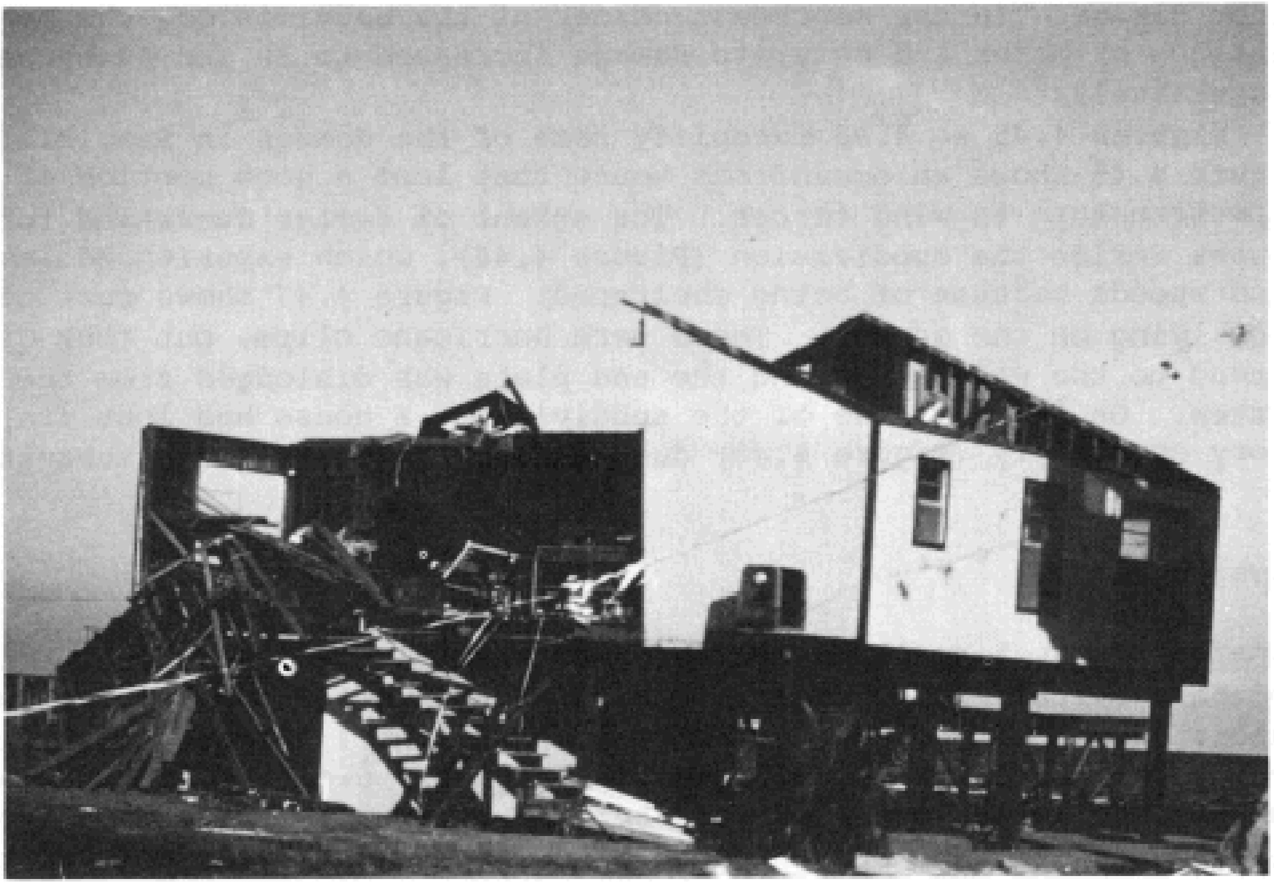
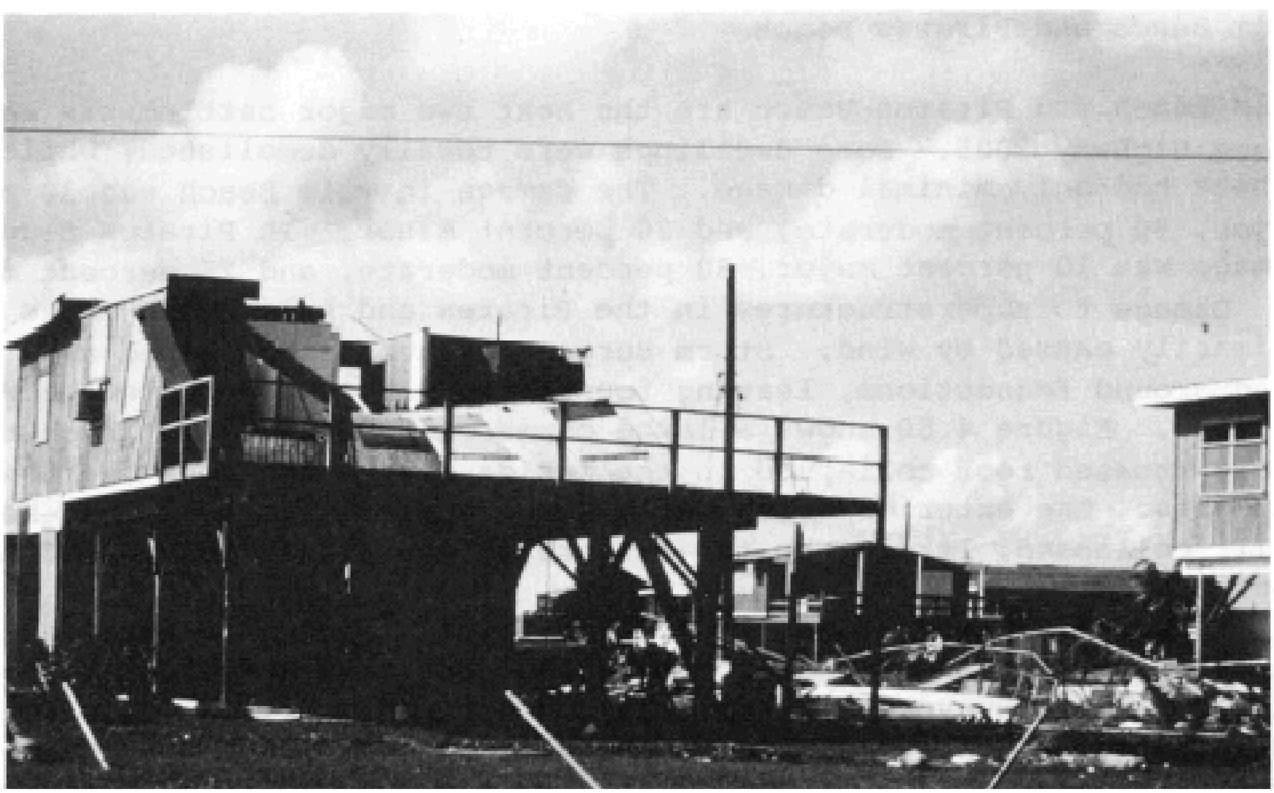


FIGURE 4.45 Damaged house fronting the Gulf in Sea Isle.



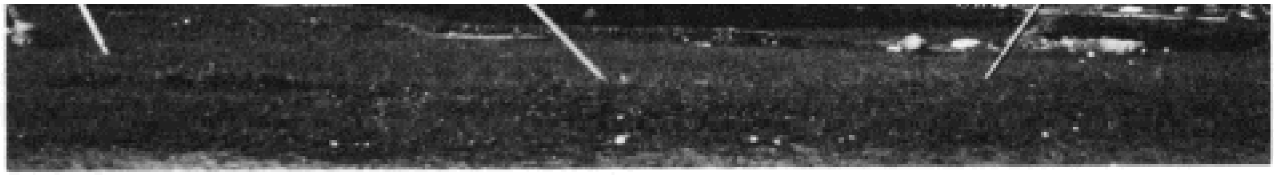


FIGURE 4.46 Damaged house in the second block from the coast in Sea Isle.

Fig 4-47 and 4-48 below Go Back

FIGURE 4.47 Details of end plate connections with rafters and hurricane clips.

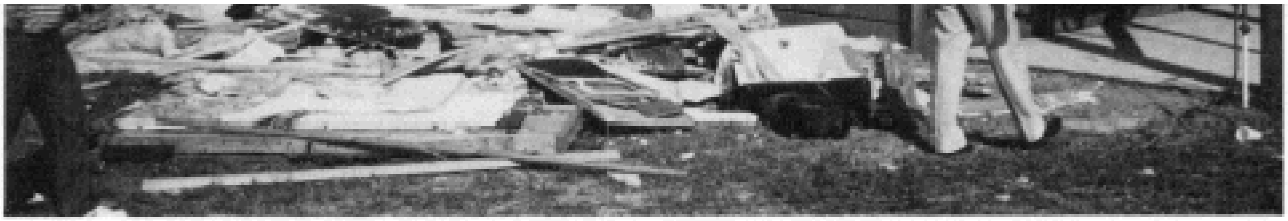


FIGURE 4.48 Typical example of poor connections between sub-systems.

Fig 4-49 and 4-50 below Go Back

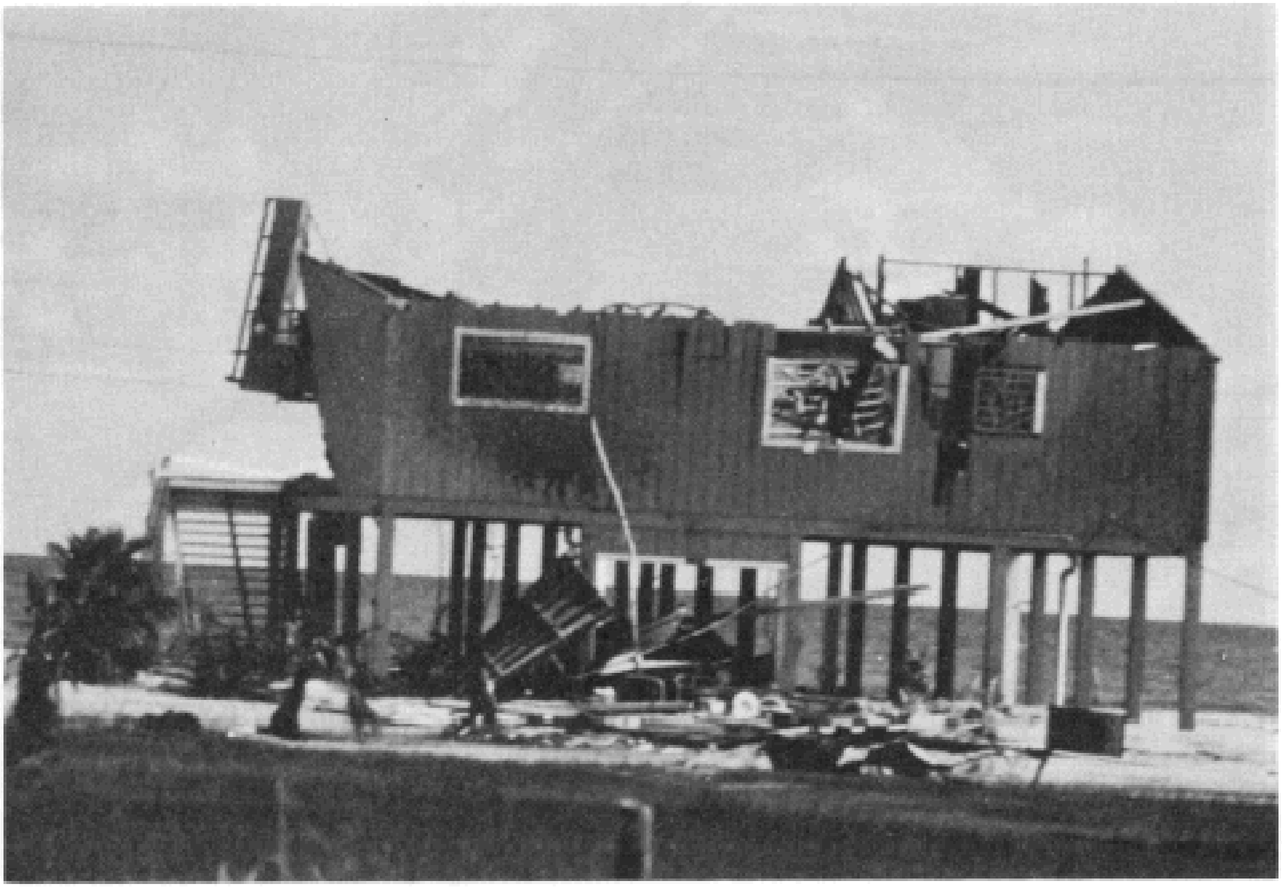


FIGURE 4.49 Damaged house in Jamaica Beach.

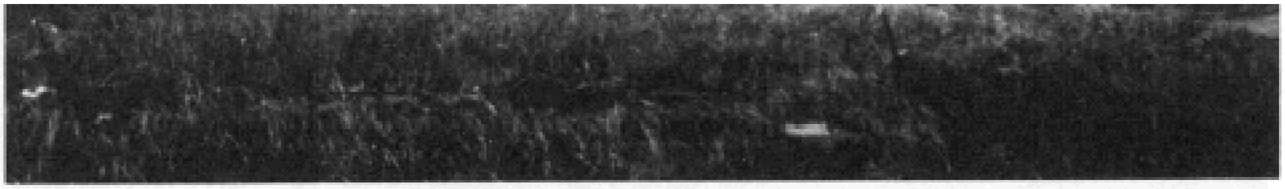


FIGURE 4.50 Damage to a large commercial warehouse building.

Go Back

FIGURE 4.5 Glass damage to the northeast face of the InterFirst Tower.

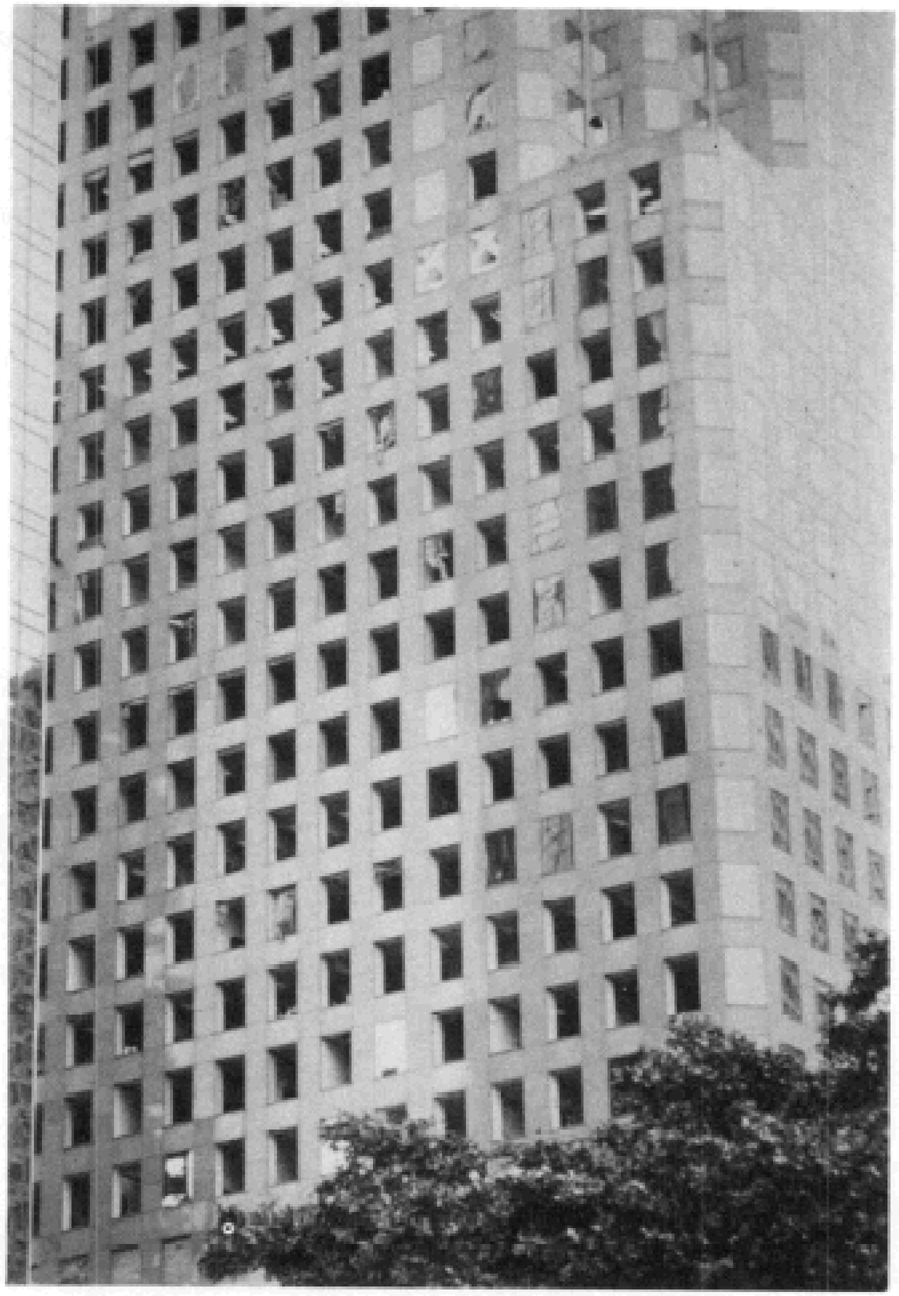


Fig 4-51 and 4-52 below Go Back

FIGURE 4.51 Example of a well-constructed house that performed very well except for erosion around the foundation.

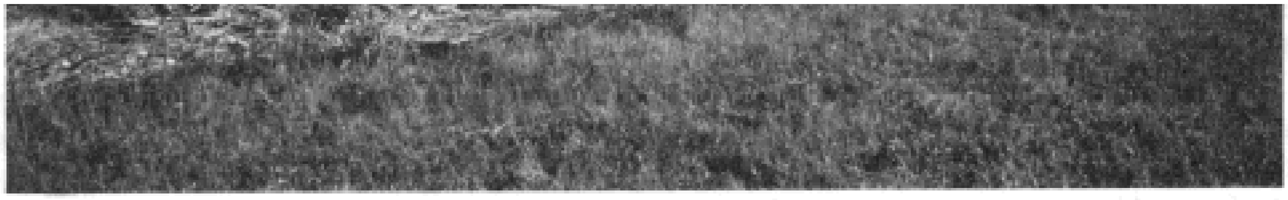
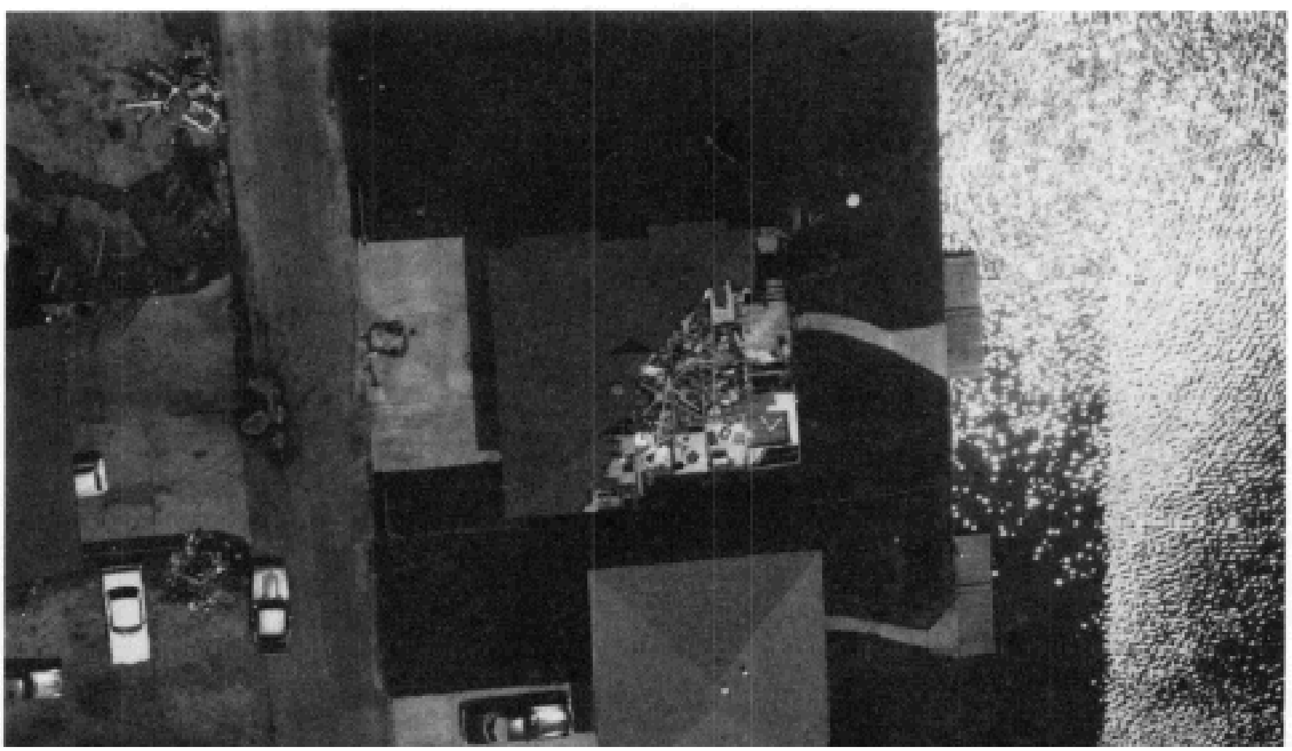


FIGURE 4.52 Damage to the roof and erosion around foundations of condominium units on the west side of San Luis Pass.

Fig 4-53 and 4-54 below [Go Back]

FIGURE 4.53 General view of a modular condominium project that experienced damage from wind and storm surge.



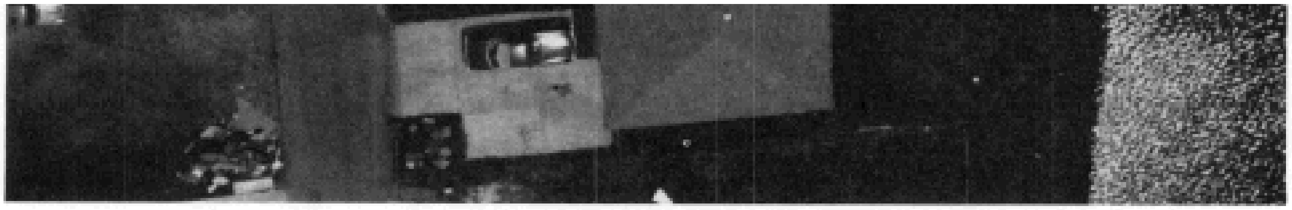


FIGURE 4.54 Aerial view of roof damage.

Fig 4-55 and 4-56 below Go Back

FIGURE 4.55 Damage to groin in front of the Galveston seawall.

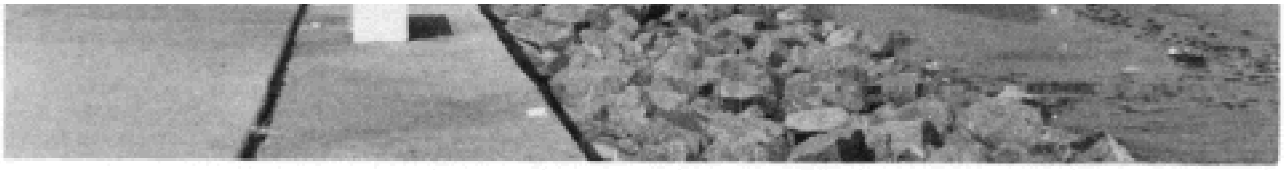
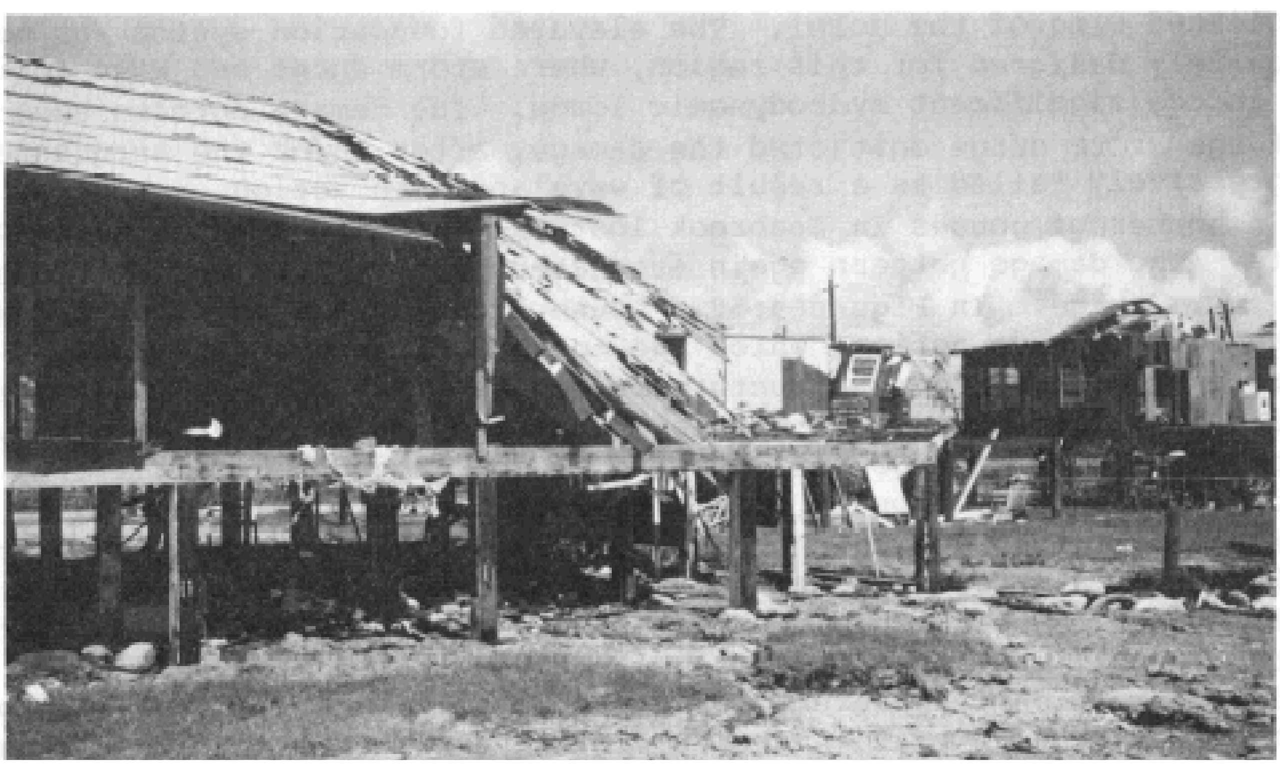


FIGURE 4.56 Galveston seawall and groin.

Fig 4-57 and 4-58 below Go Back

FIGURE 4.57 An elevated motel transported off its foundation by the storm surge.



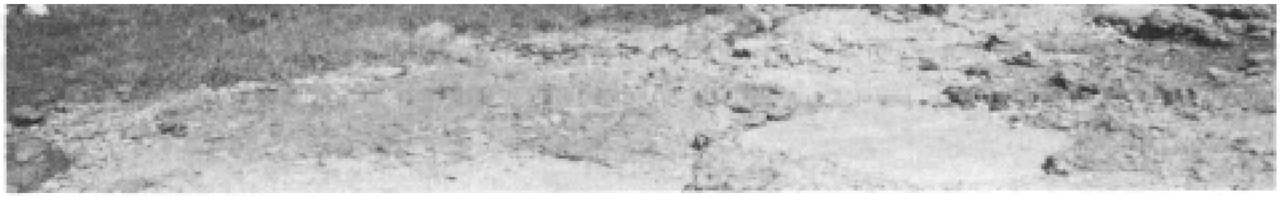
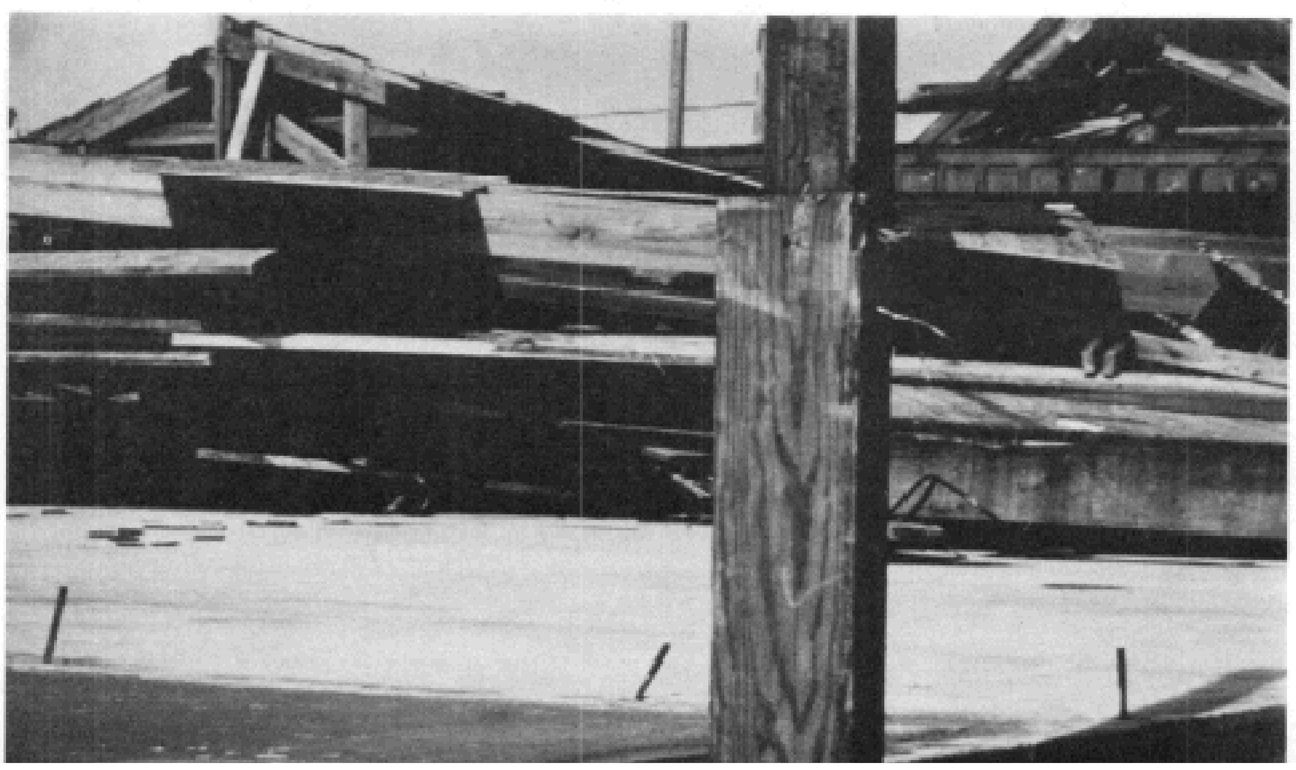


FIGURE 4.58 Bayfront house with a collapsed roof.

Fig 4-59 and 4-60 below Go Back

FIGURE 4.59 Failure of the roof and brick veneer wall of a condominium.



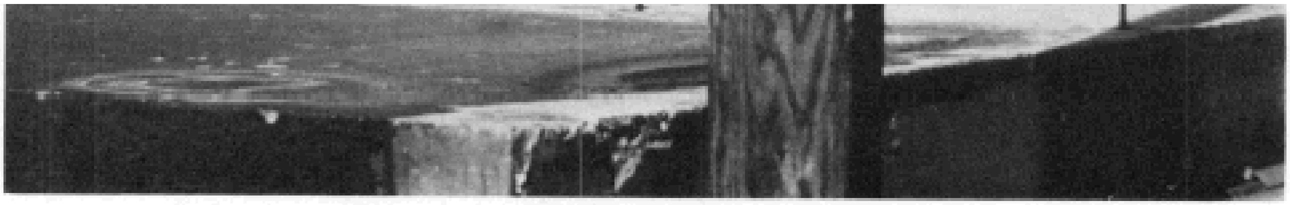


FIGURE 4.60 House washed away from its foundation slab by storm surge.

Go Back

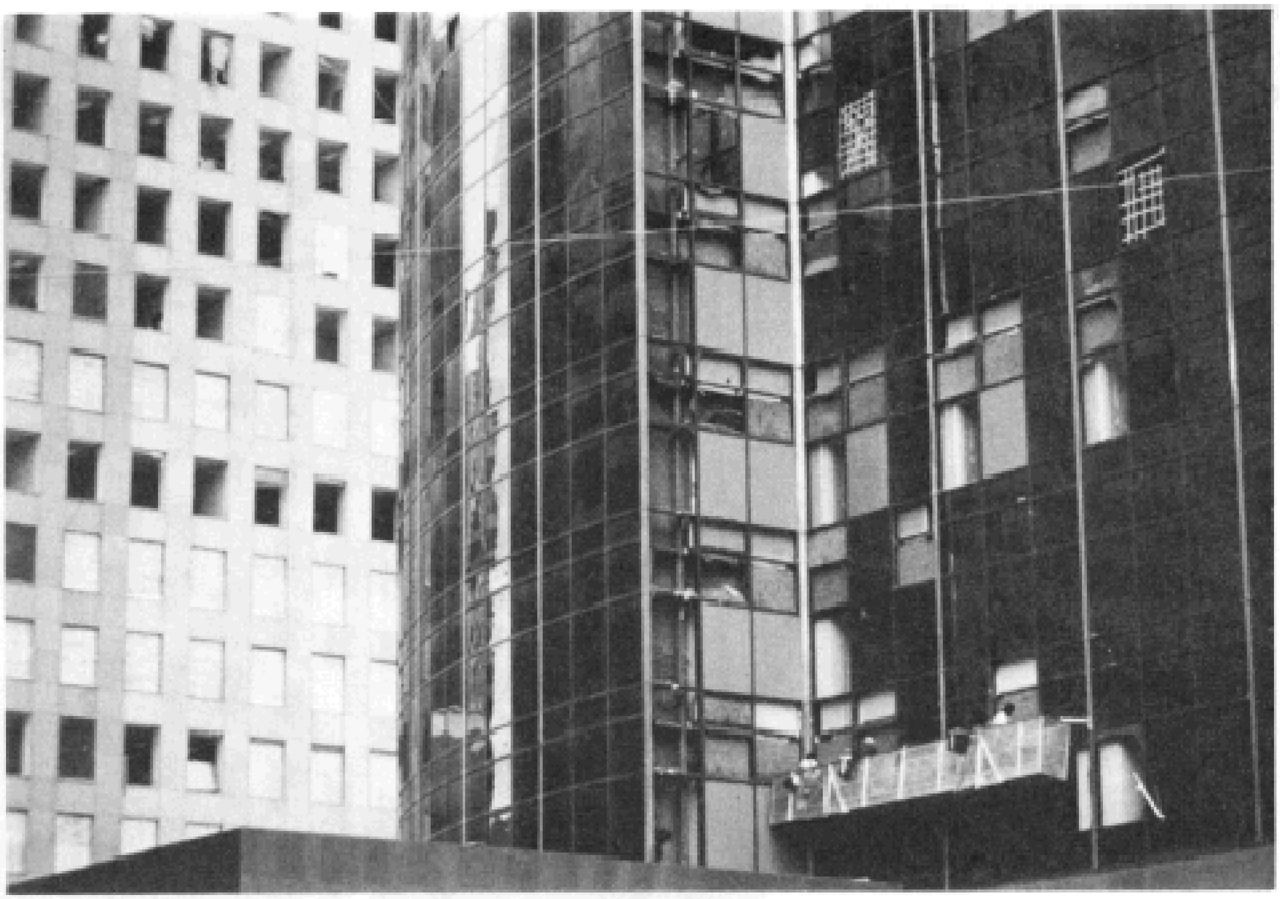


FIGURE 4.6 Closeup of damaged glass on the Allied and Inter-First towers.

Fig 4-61 and 4-62 below   Go Back

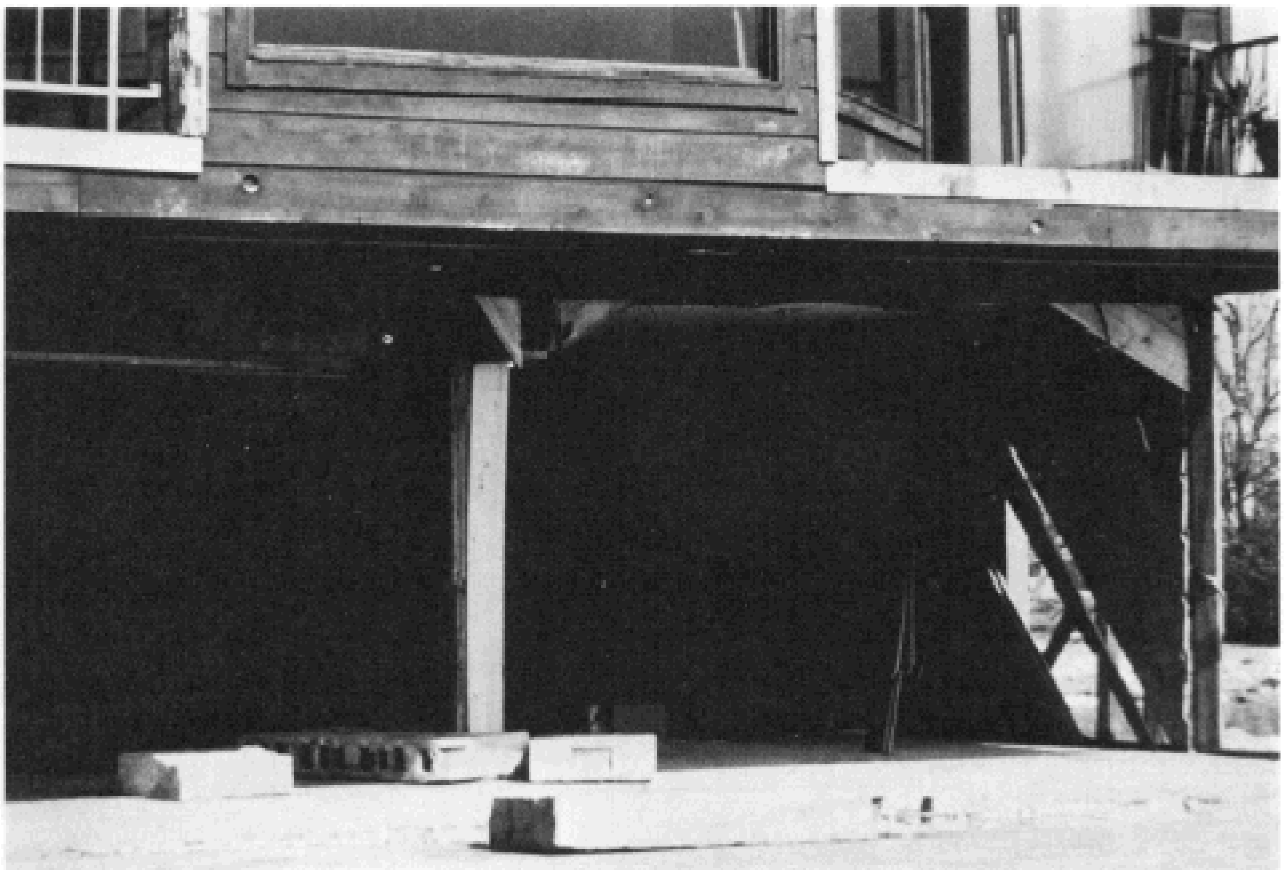
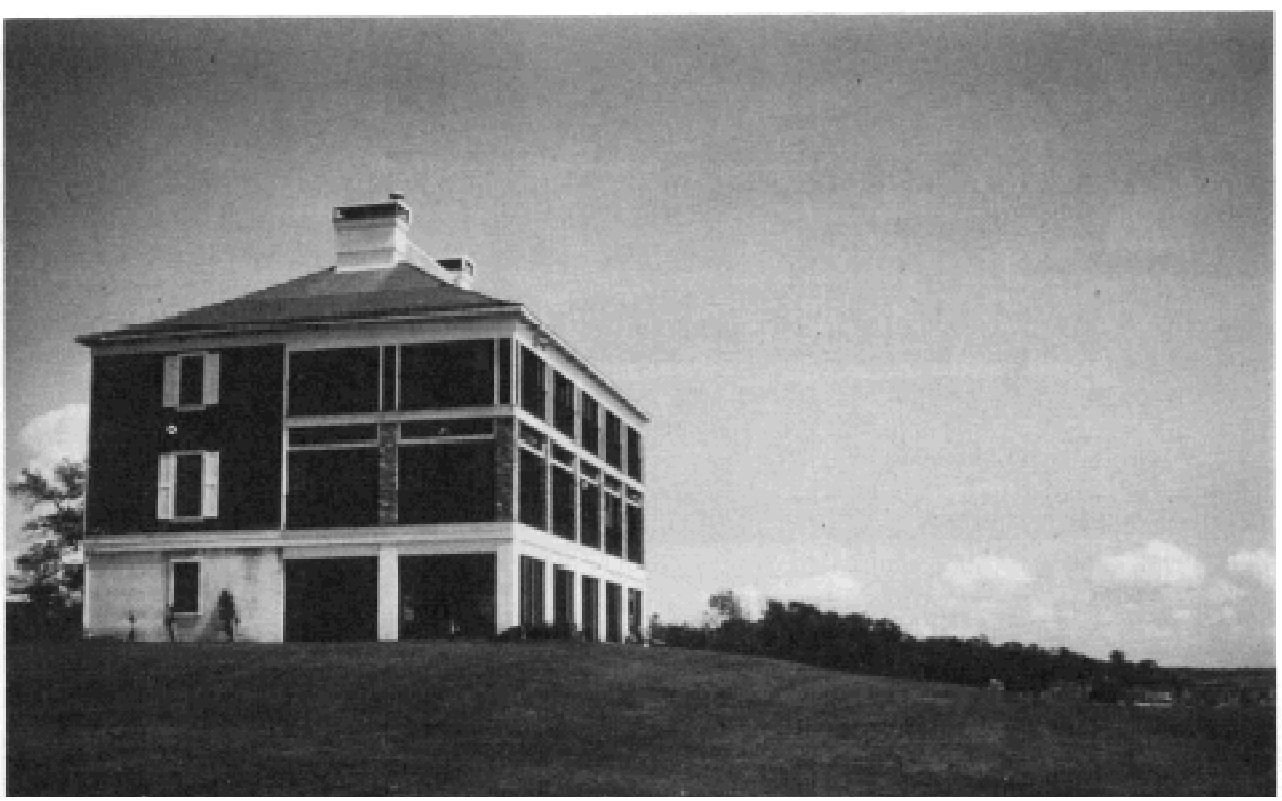


FIGURE 4.61 Damage to a grade-level enclosure.



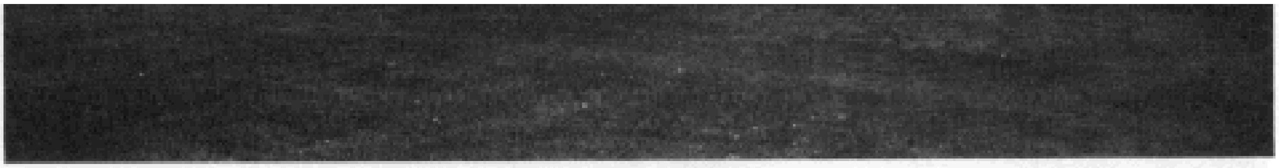


FIGURE 4.62 This mansion survived the storm very well.

Go Back

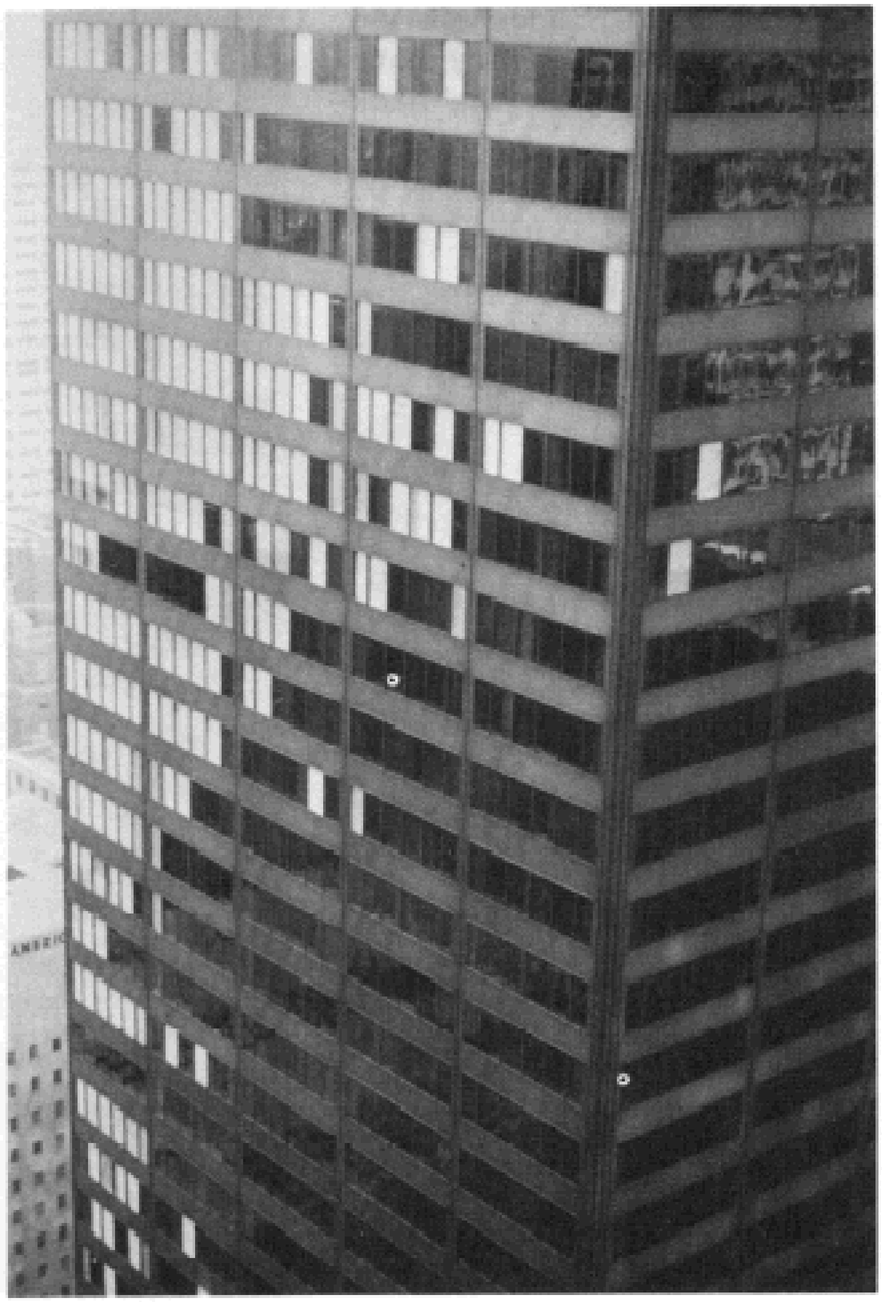
FIGURE 4.63 Roof damage to a condominium in Texas City.

Go Back

FIGURE 4.7 Window damage to the Hyatt Regency Hotel (the building in the background).

Go Back

FIGURE 4.8 Closeup of glass damage to the Milam Building.



Go Back

FIGURE 4.9 Glass damage to the northeast face of the Entex Building.

Fig 5-1 and 5-2 below Go Back

FIGURE 5.1 Typical washout of shoulder on San Luis Pass Road, Follets Island.

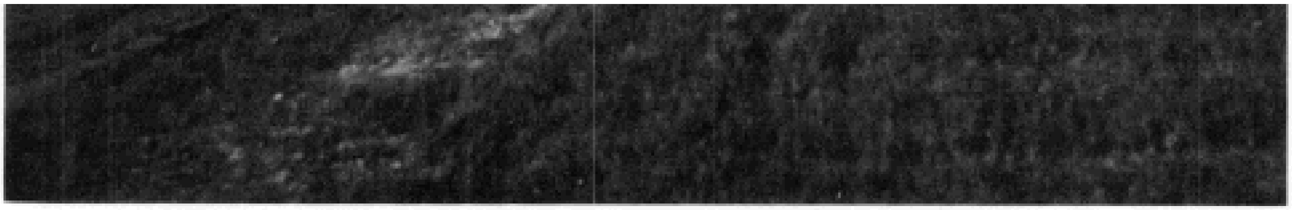


FIGURE 5.2 Typical undercut of roadbed on San Luis Pass Road, Follets Island.

Go Back

FIGURE 5.3 Total washout of shoulder and road on San Luis Pass Road, Follets Island.

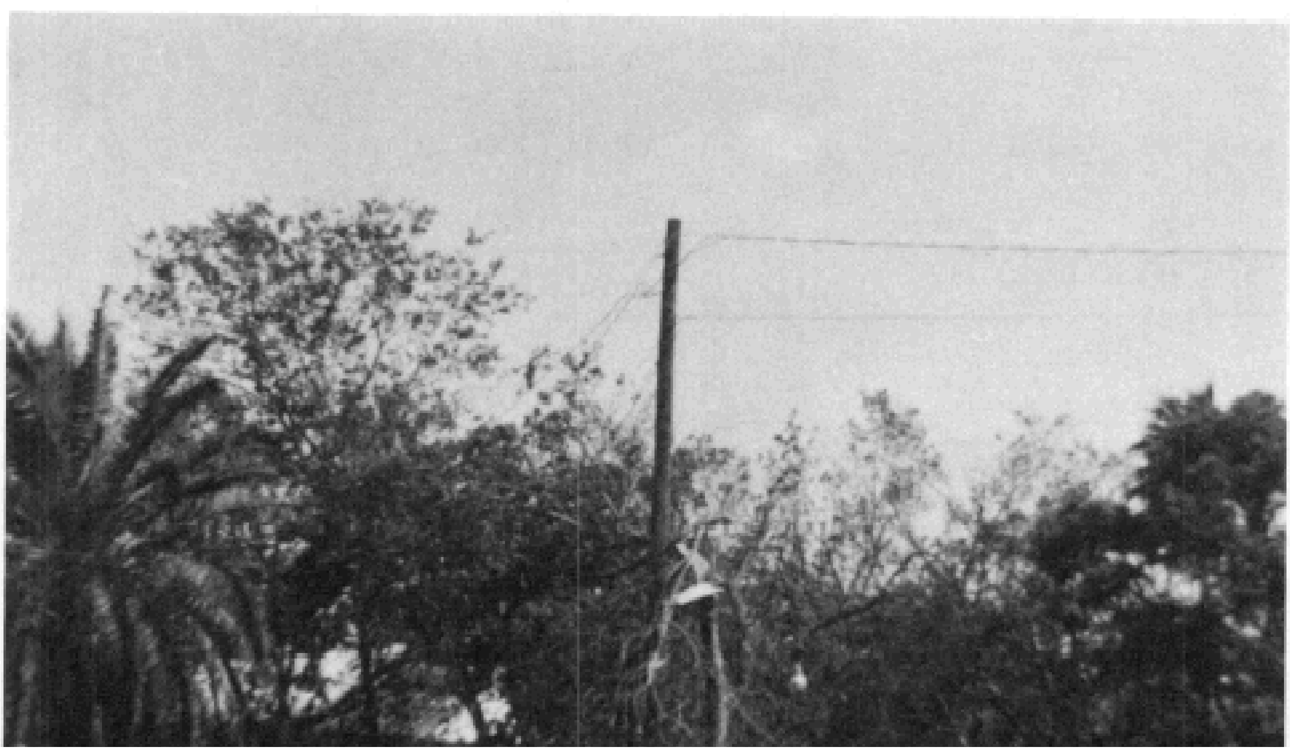
Fig 5-4 and 5-5 below Go Back

FIGURE 5.4 Typical failure of transformer pole on East Beach, Galveston Island.

FIGURE 5.5 Typical failure of utility pole on East Beach, Galveston Island.

Fig 5-6 & 5-7 below Go Back

FIGURE 5.6 Failure of primary power pole near Highway 146 south of Bay City.



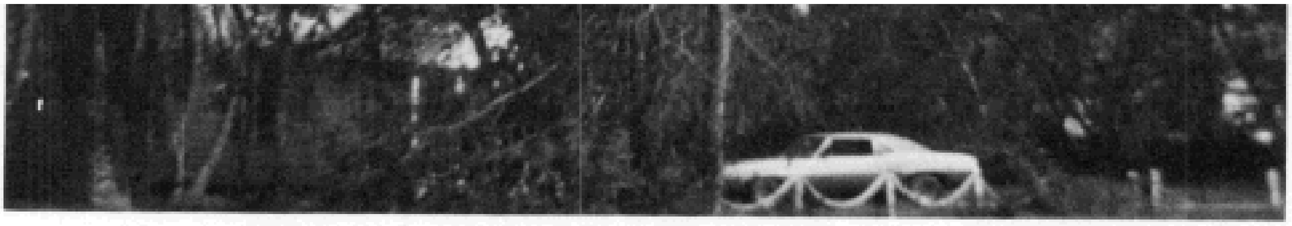


FIGURE 5.7 Typical failure of utility line caused by fallen trees in Seabrook.

Go Back

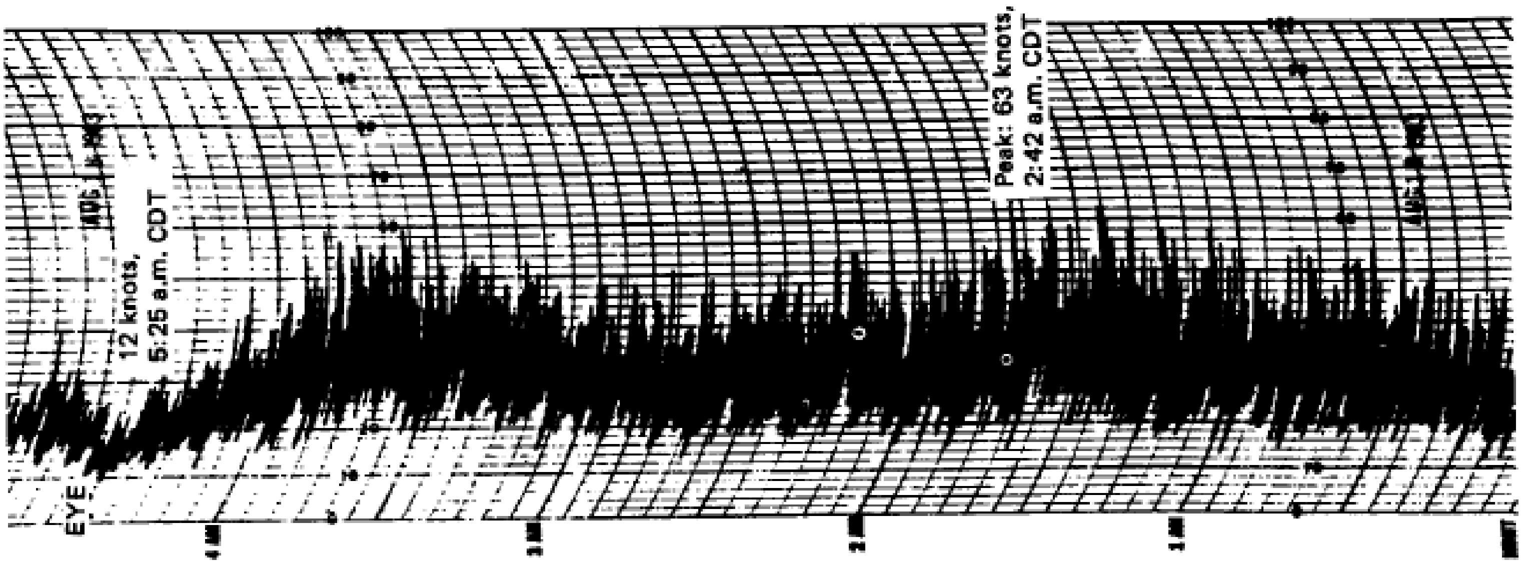


FIGURE 2.10A Anemometer record from Alvin NWS office illustrating wind regime in Hurricane Alicia near and following landfall (direction sensor was inoperable).

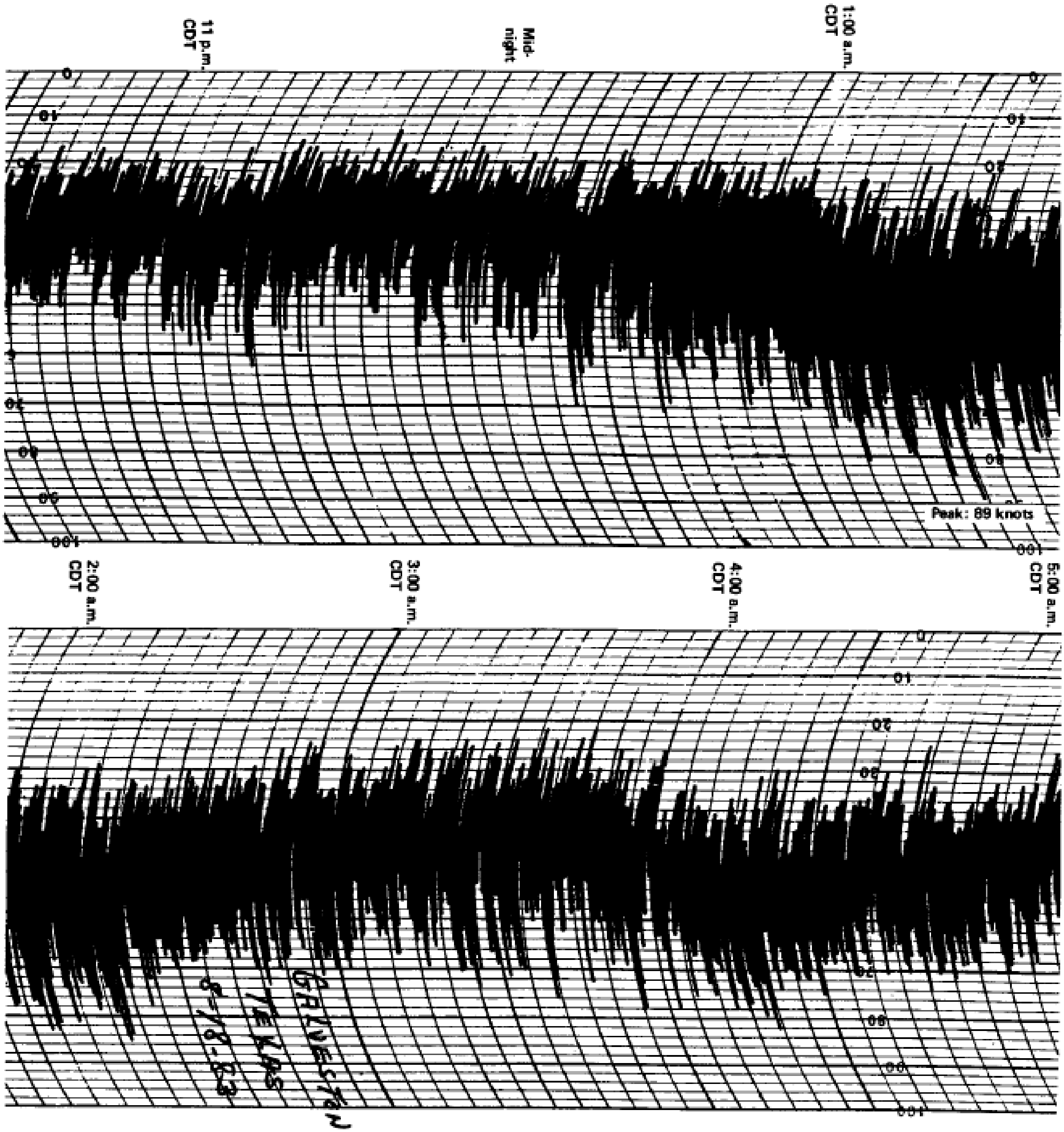
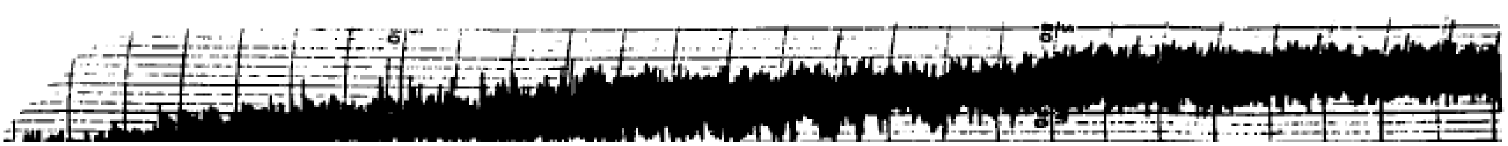


FIGURE 2.10B Anemometer record from Galveston NWS office illustrating wind regime in Hurricane Alicia near and following landfall.



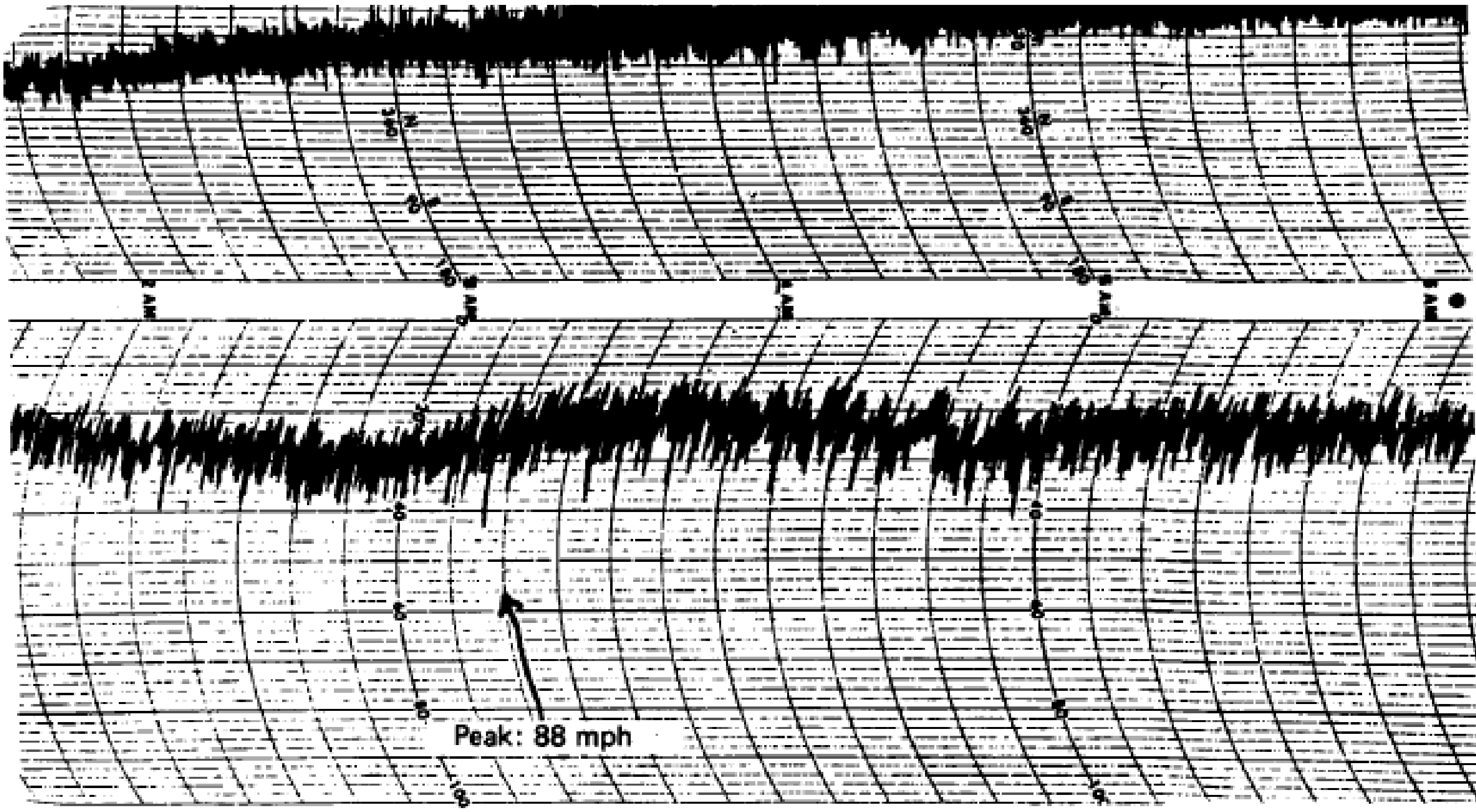


FIGURE 2.10C Anemometer record from Dow Chemical Plant A near Freeport illustrating wind regime in Hurricane Alicia near and following landfall.

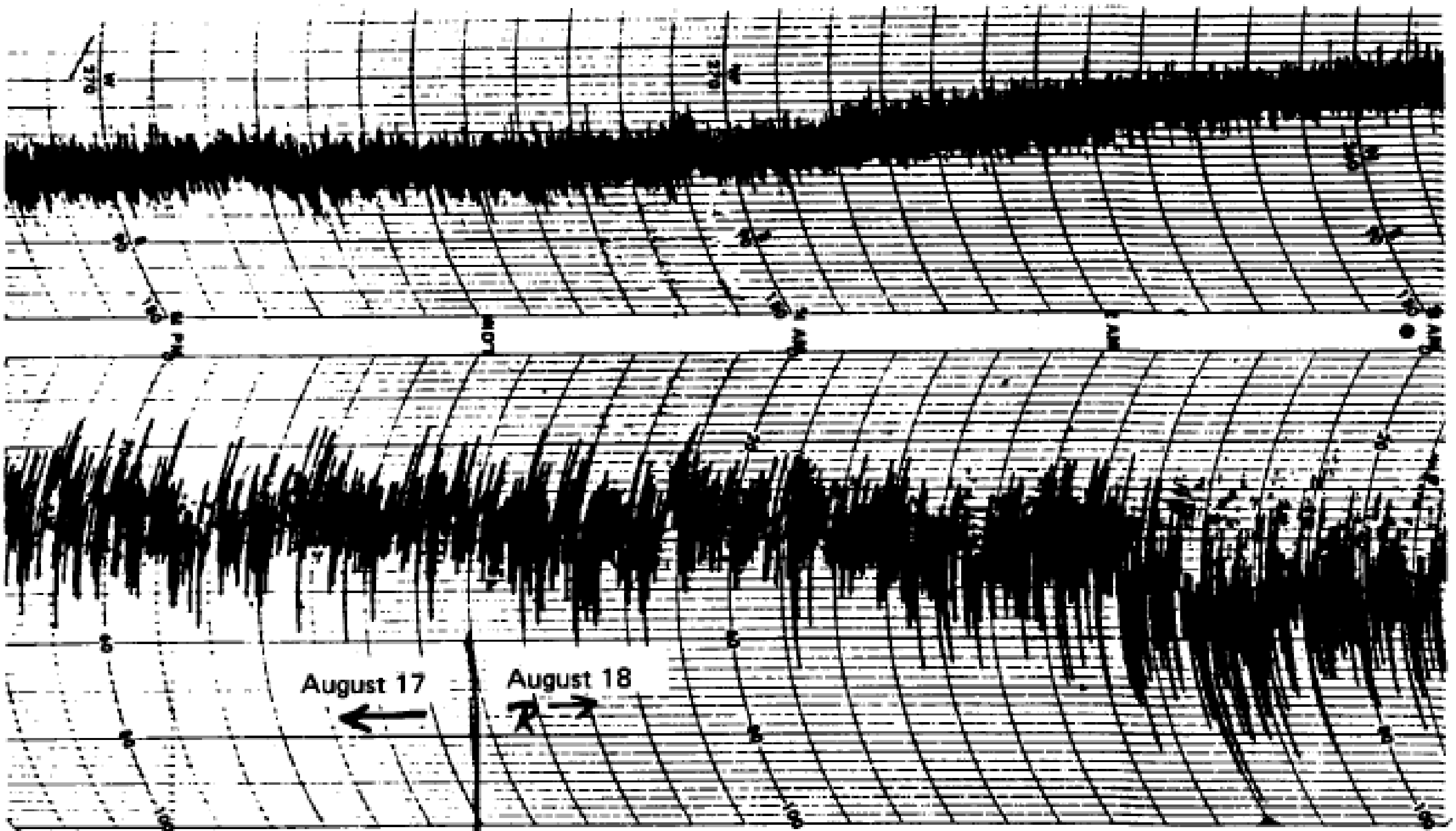


FIGURE 2.10D Anemometer record from Dow Chemical Plant B near

FIGURE 2.10D Anemometer record from Dow Chemical Plant B near Freeport illustrating wind regime in Hurricane Alicia near and following landfall.

Go Back

Go Back

FIGURES 2.11A-2.11B Aerial damage photographs taken from a NOAA helicopter at 1,000 ft on August 25, 1983.

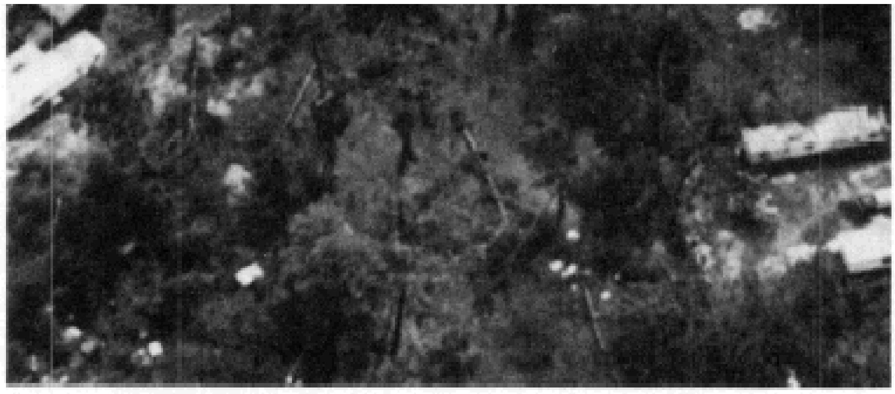
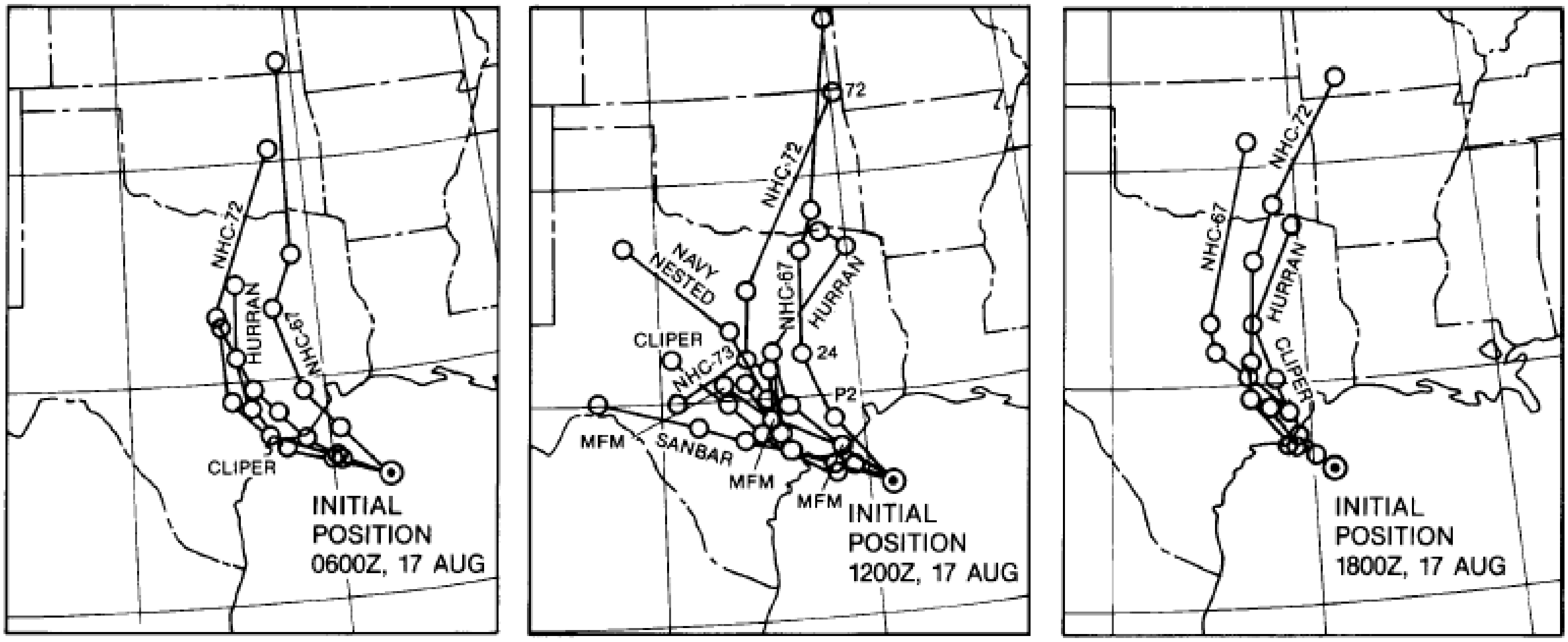


FIGURE 2.11C Aerial damage photograph taken from a NOAA heli-copter at 1,000 ft on August 25, 1983.

Go Back

[Go Back]



FIGURES 2.12A-2.12C Objective guidance model plots run operationally for NHC forecasters of Alicia's track, with initial eye positions at 0600Z, 1200Z, and 1800Z on August 17 (1:00 a.m., 7:00 a.m., and 1:00 p.m. CDT, August 17), respectively. Model track forecasts are typical for hurricanes moving over the northern Gulf of Mexico. Source: National Hurricane Center.

Go Back

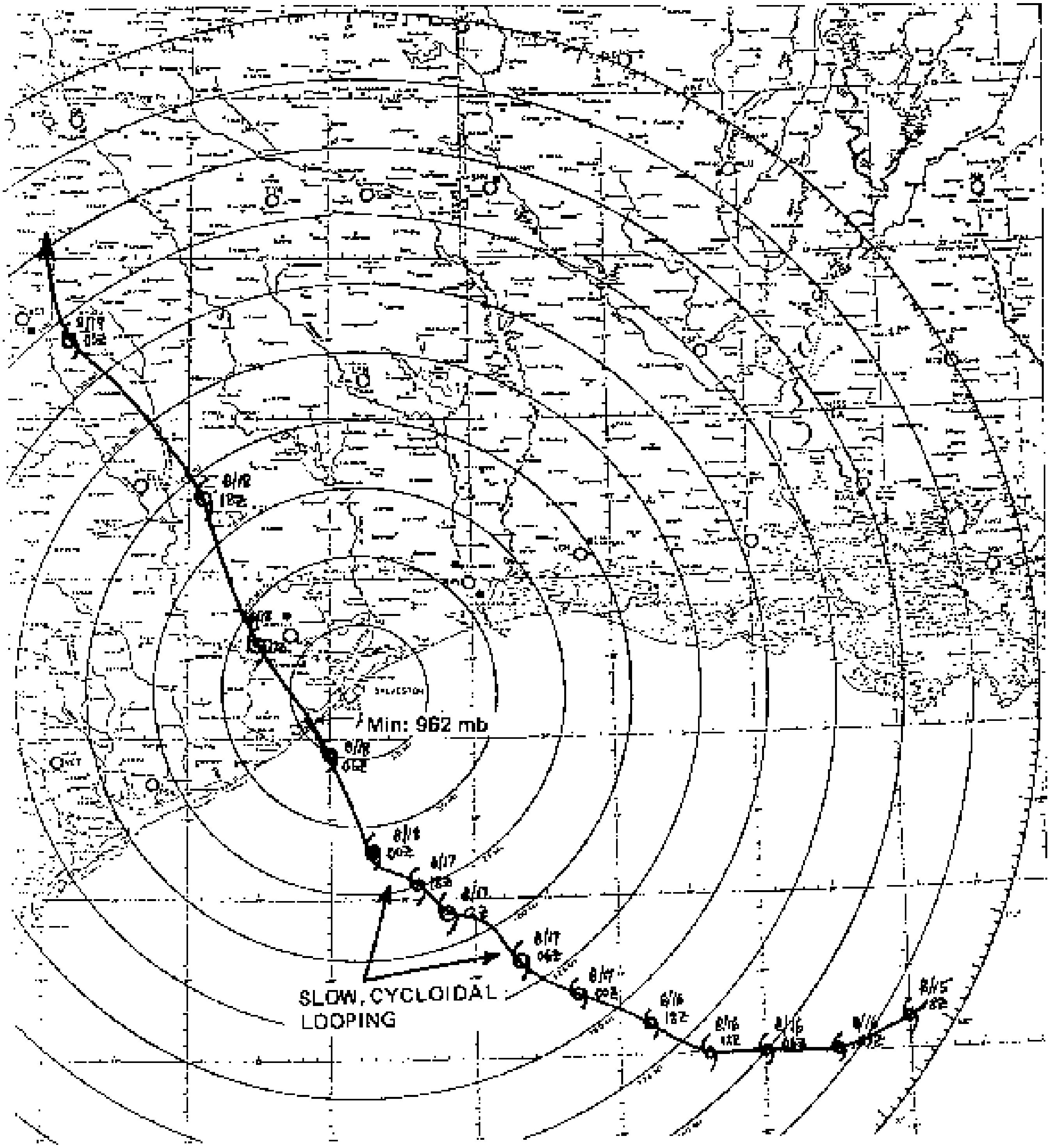


FIGURE 2.3A Preliminary track of Hurricane Alicia from earliest depression stage (the first confirmed closed surface circulation) through tropical storm and hurricane stages to after landfall. Source: R. C. Sheets, National Hurricane Center.

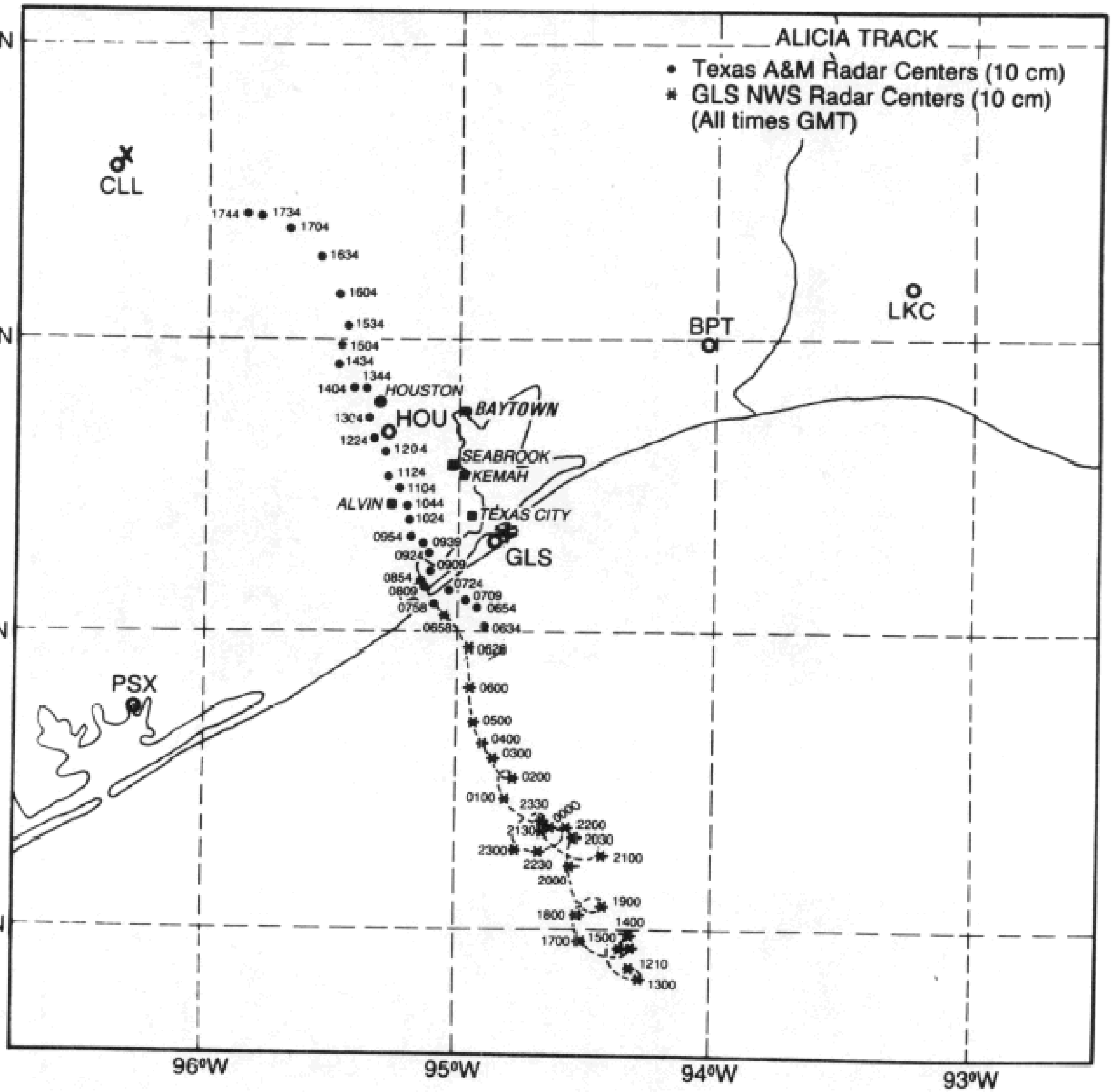


FIGURE 2.3B Detailed final track of Alicia during the approximately 6 hours surrounding landfall. Positions are derived from the 10-cm radar data from the Texas A&M University and Galveston radars. Source: Frank Marks, National Oceanic and Atmospheric Administration.

Go Back

Go Back

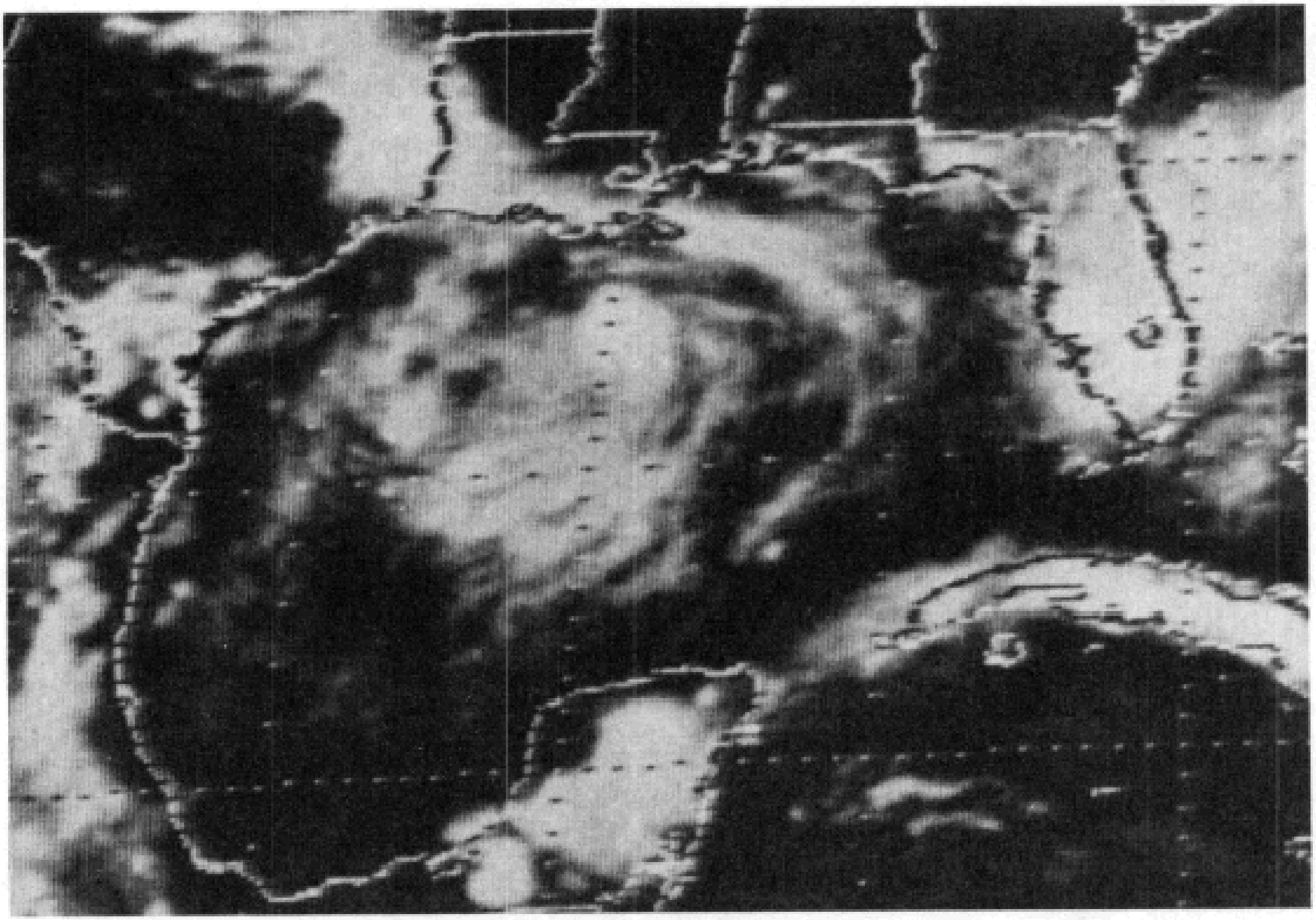
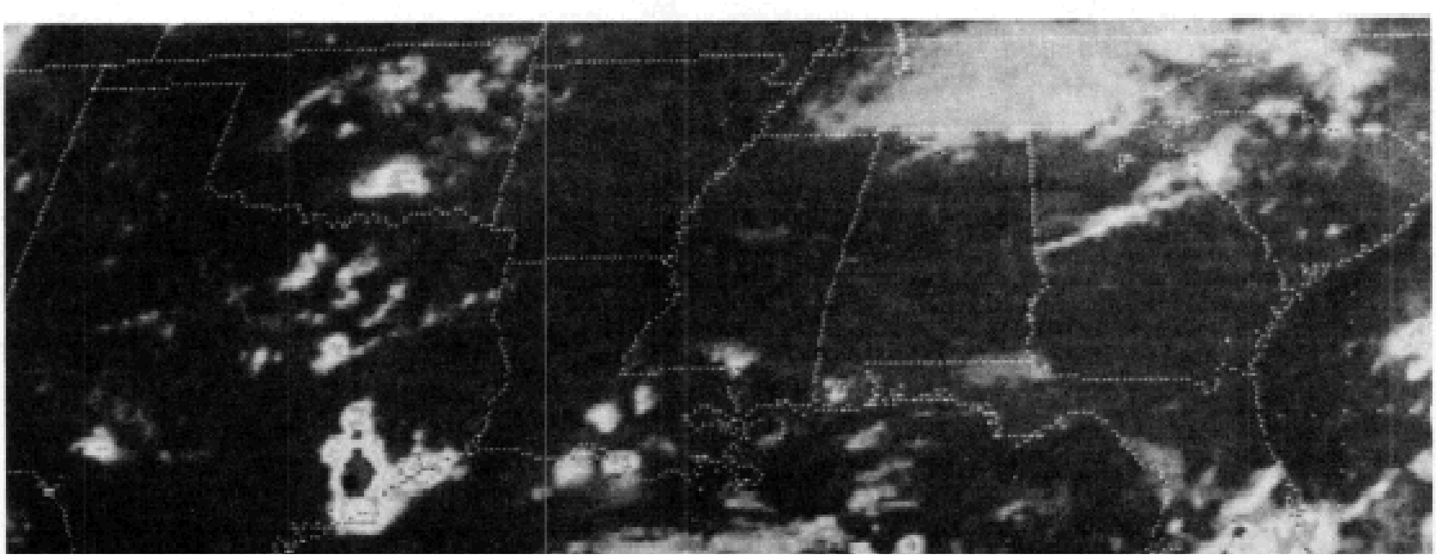


FIGURE 2.4A GOES infrared satellite photograph at 0000Z (7:00 p.m. CDT, August 14, 1983). Horizontal resolution is 3 to 5 km. Source: National Weather Service.



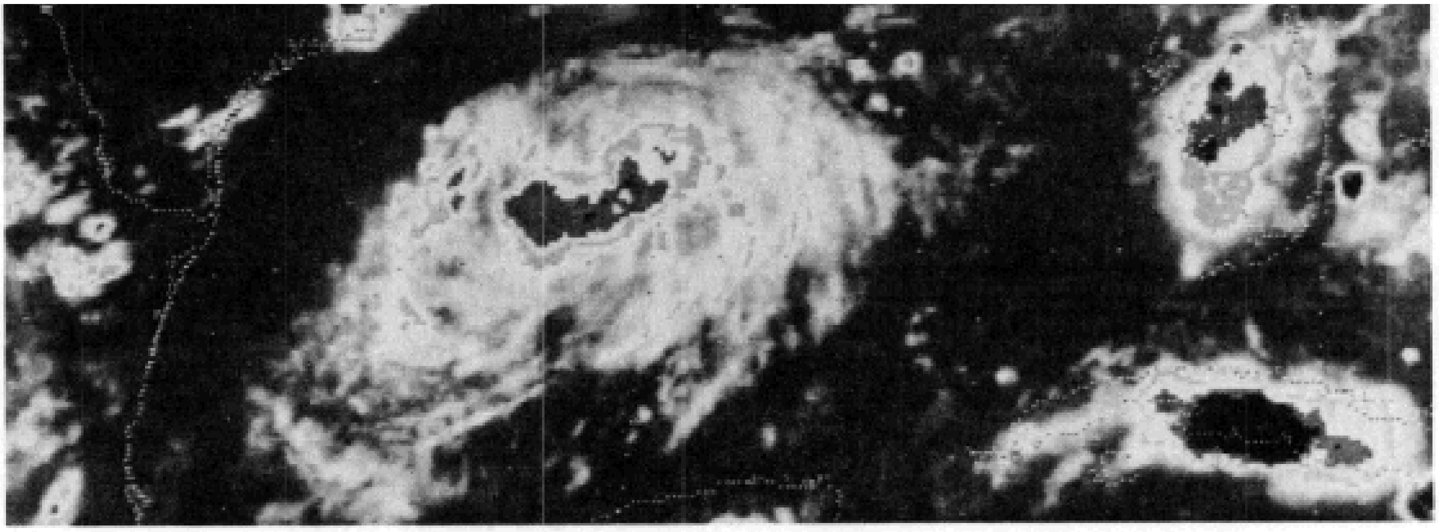


FIGURE 2.4B GOES infrared satellite photograph at 0000Z (7:00 p.m. CDT, August 15, 1983). Horizontal resolution is 3 to 5 km. Source: National Weather Service.

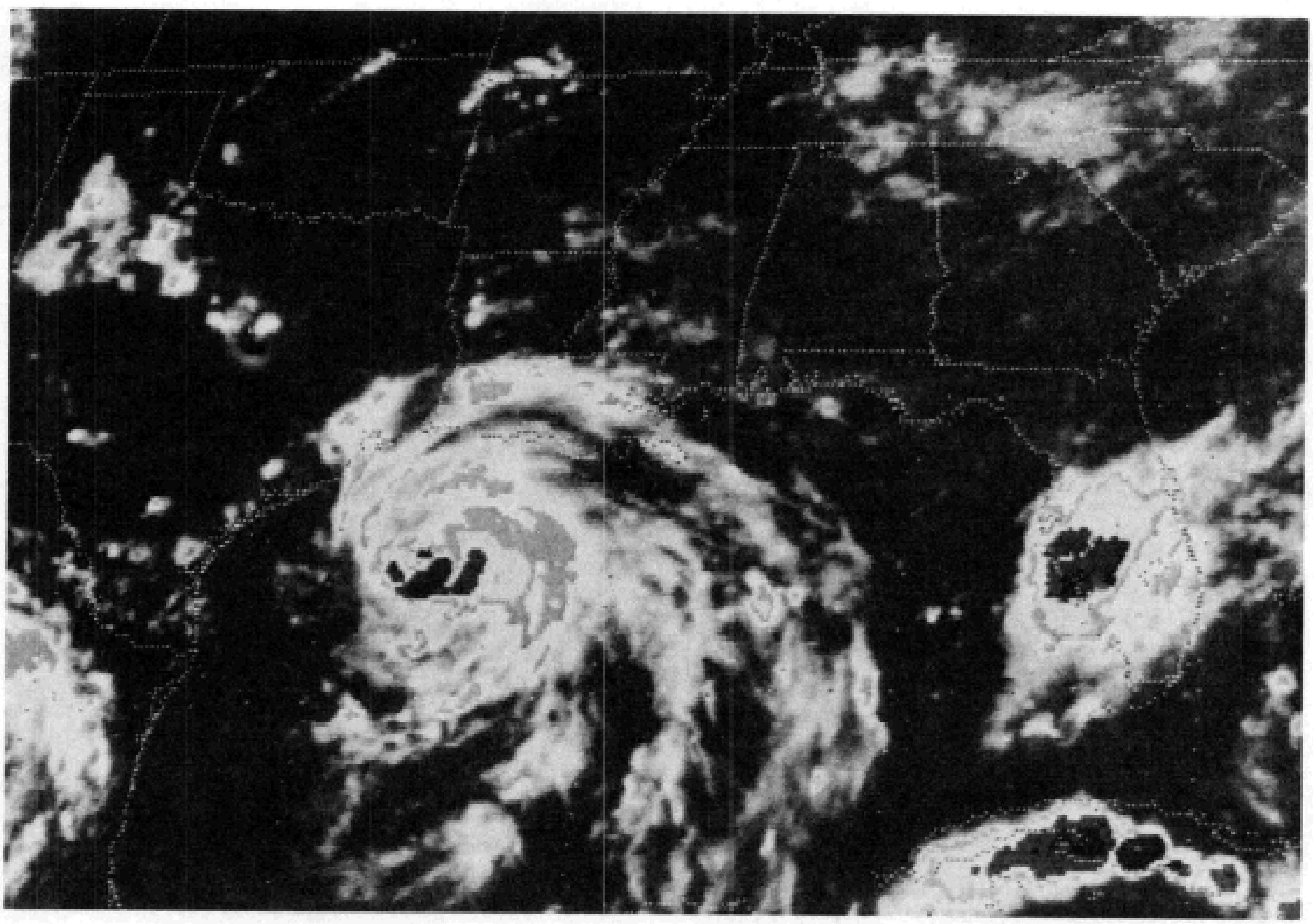


FIGURE 2.4C GOES infrared satellite photograph at 0000Z (7:00 p.m. CDT, August 16, 1983). Horizontal resolution is 3 to 5 km. Source: National Weather Service.

[illegible] Horizontal resolution is 3 to 5 km. Source: National Weather Service.

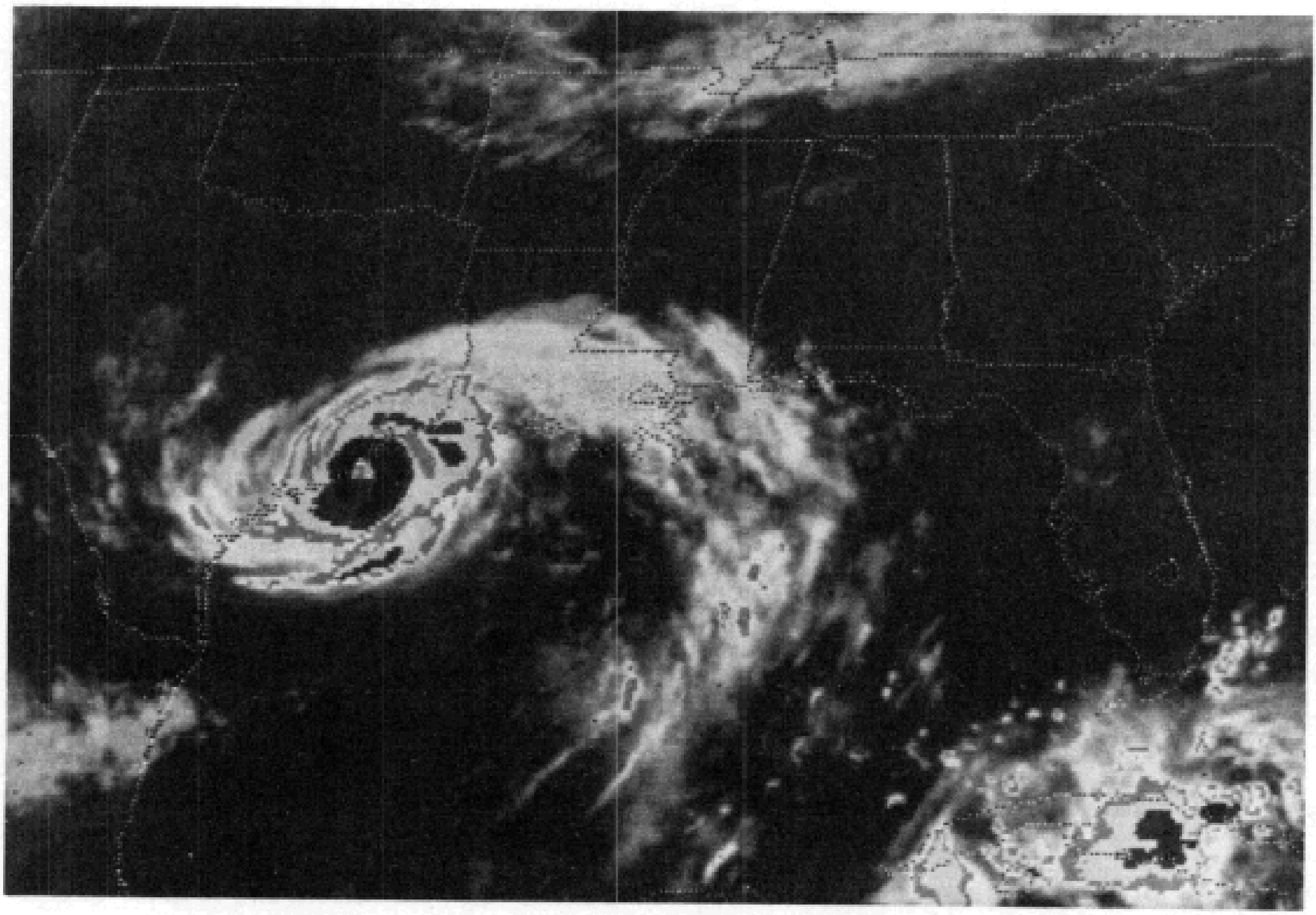
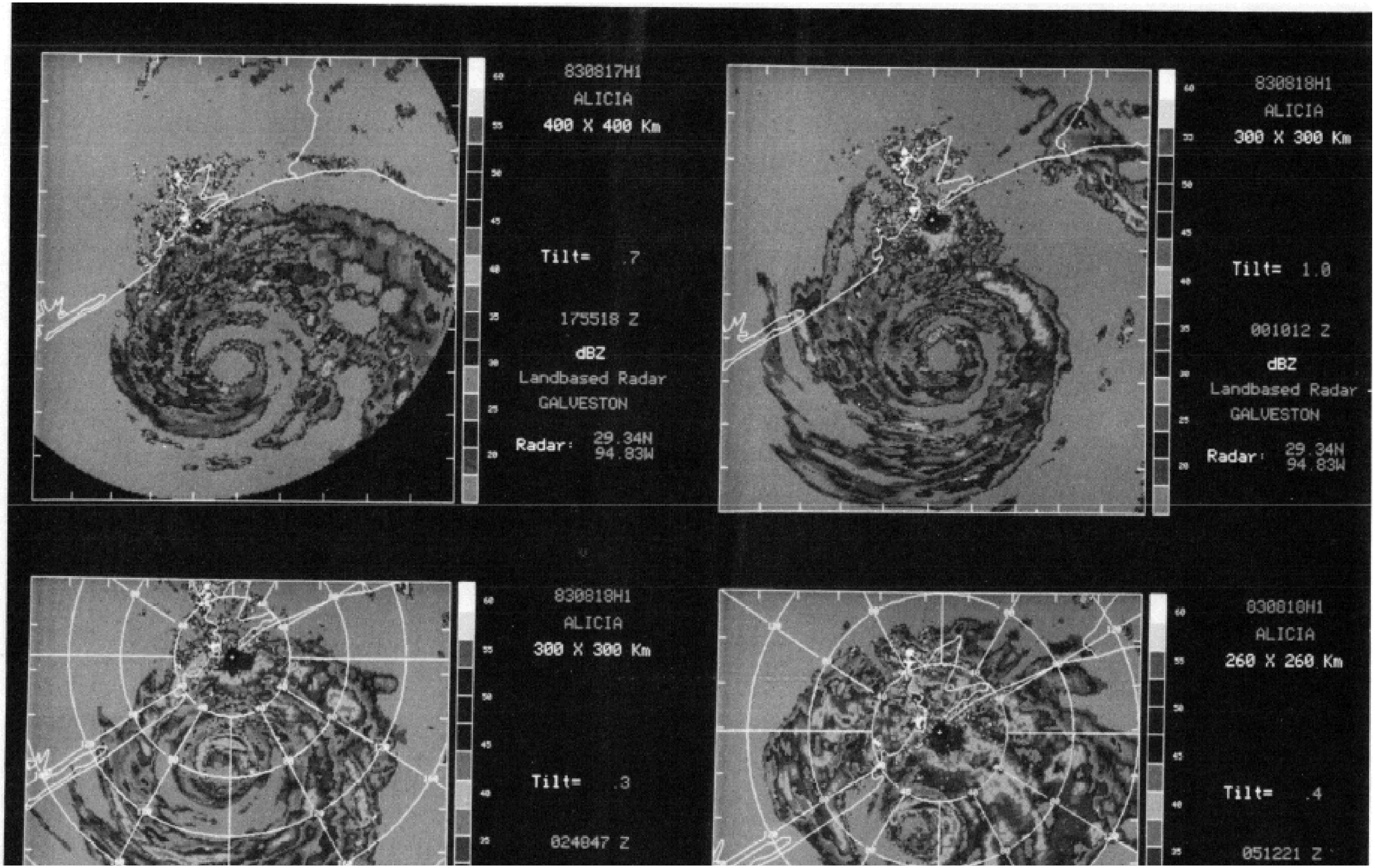


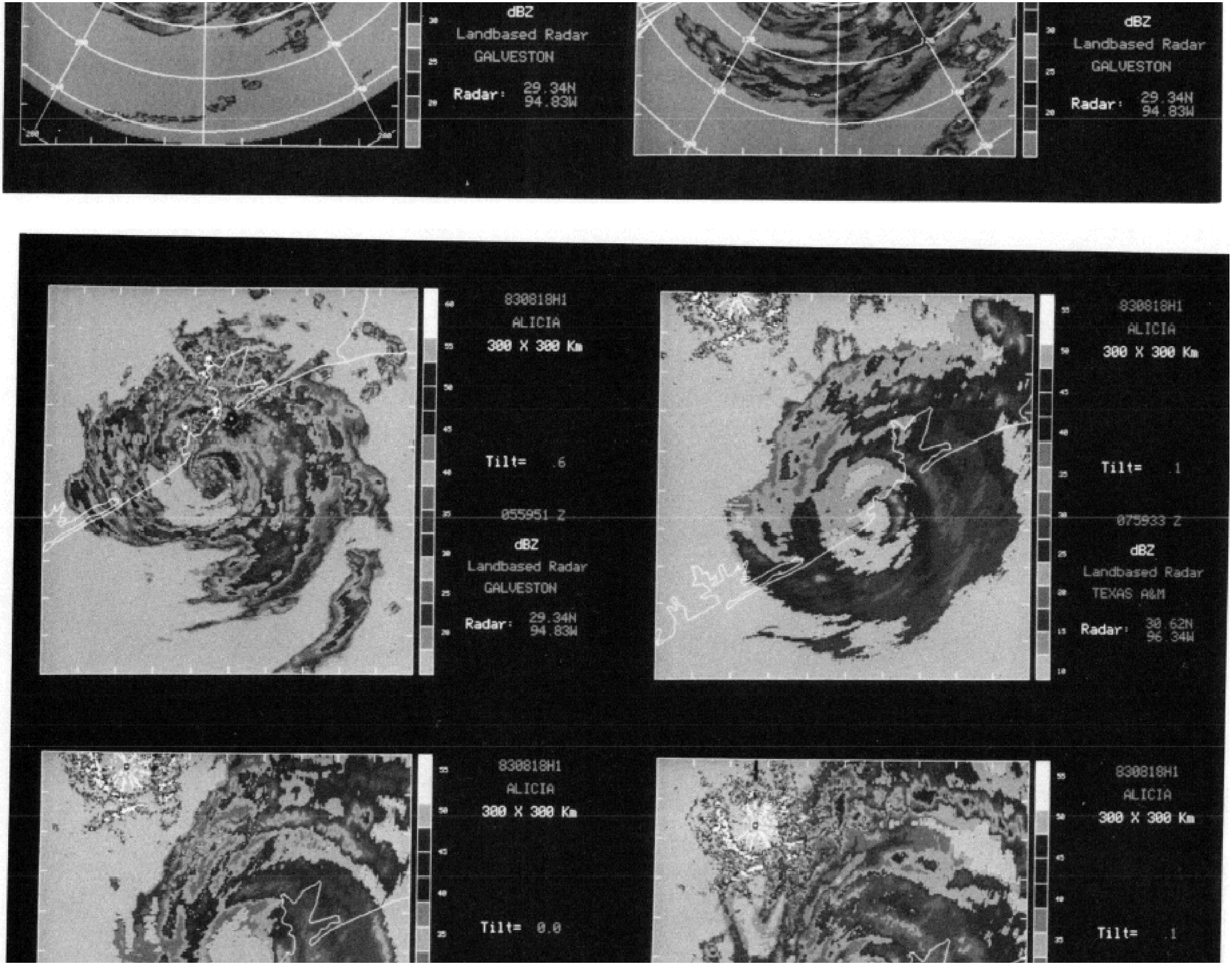
FIGURE 2.4D GOES infrared satellite photograph at 0000Z (7:00 p.m. CDT, August 17, 1983--near landfall). Horizontal resolution is 3 to 5 km. Source: National Weather Service.

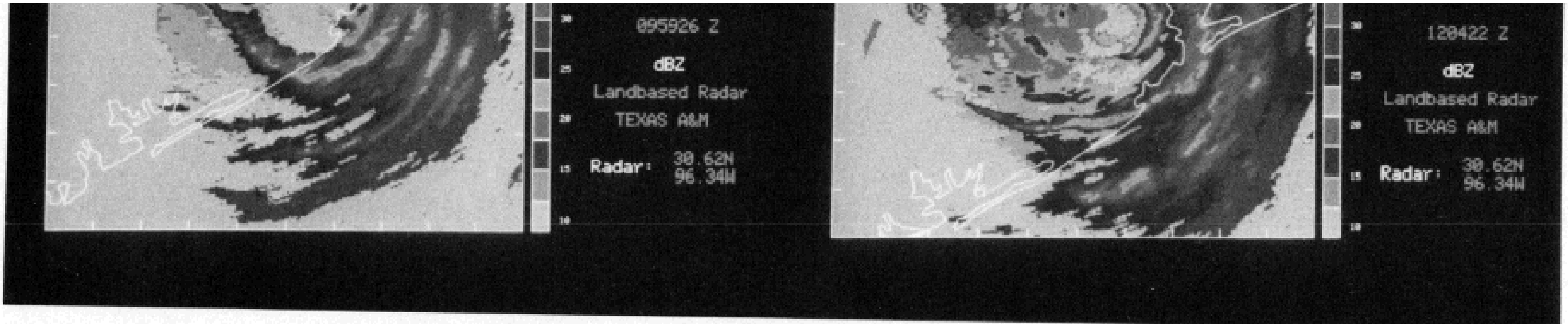
Go Back

Go Back

FIGURES 2.5A-2.5H Digitized, land-based, 10-cm radar maps shaded to echo reflectivity values in dbZ. Each map is 300 km by 300 km square. The first five are from the Galveston NWS radar and the last three are from the Texas A&M University radar. The sequence on each page is from upper left to upper right to lower left to lower right. Source: Frank Marks, National Oceanic and Atmospheric Administration.




dBZ
Landbased Radar
GALVESTON
Radar: 29.34N 94.83W
dBZ
Landbased Radar
GALVESTON
Radar: 29.34N 94.83W
830818H1
ALICIA
300 X 300 Km
Tilt= .6
055951 Z
dBZ
Landbased Radar
GALVESTON
Radar: 29.34N 94.83W
830818H1
ALICIA
300 X 300 Km
Tilt= .1
075933 Z
dBZ
Landbased Radar
TEXAS A&M
Radar: 30.62N 96.34W
830818H1
ALICIA
300 X 300 Km
Tilt= 0.0
830818H1
ALICIA
300 X 300 Km
Tilt= .1


095926 Z
dBZ
Landbased Radar
TEXAS A&M
Radar: 30.62N
96.34W
120422 Z
dBZ
Landbased Radar
TEXAS A&M
Radar: 30.62N
96.34W

Go Back

Go Back

FIGURE 2.6A (Below) - Composite of sustained flight-level winds through Hurricane Alicia before landfall measured by NOAA research aircraft along flight tracks near 5,000 ft. Solid lines are stream lines and dashed lines are isotachs, both analyzed subjectively. Source: P. G. Black, National Oceanic and Atmospheric Administration.

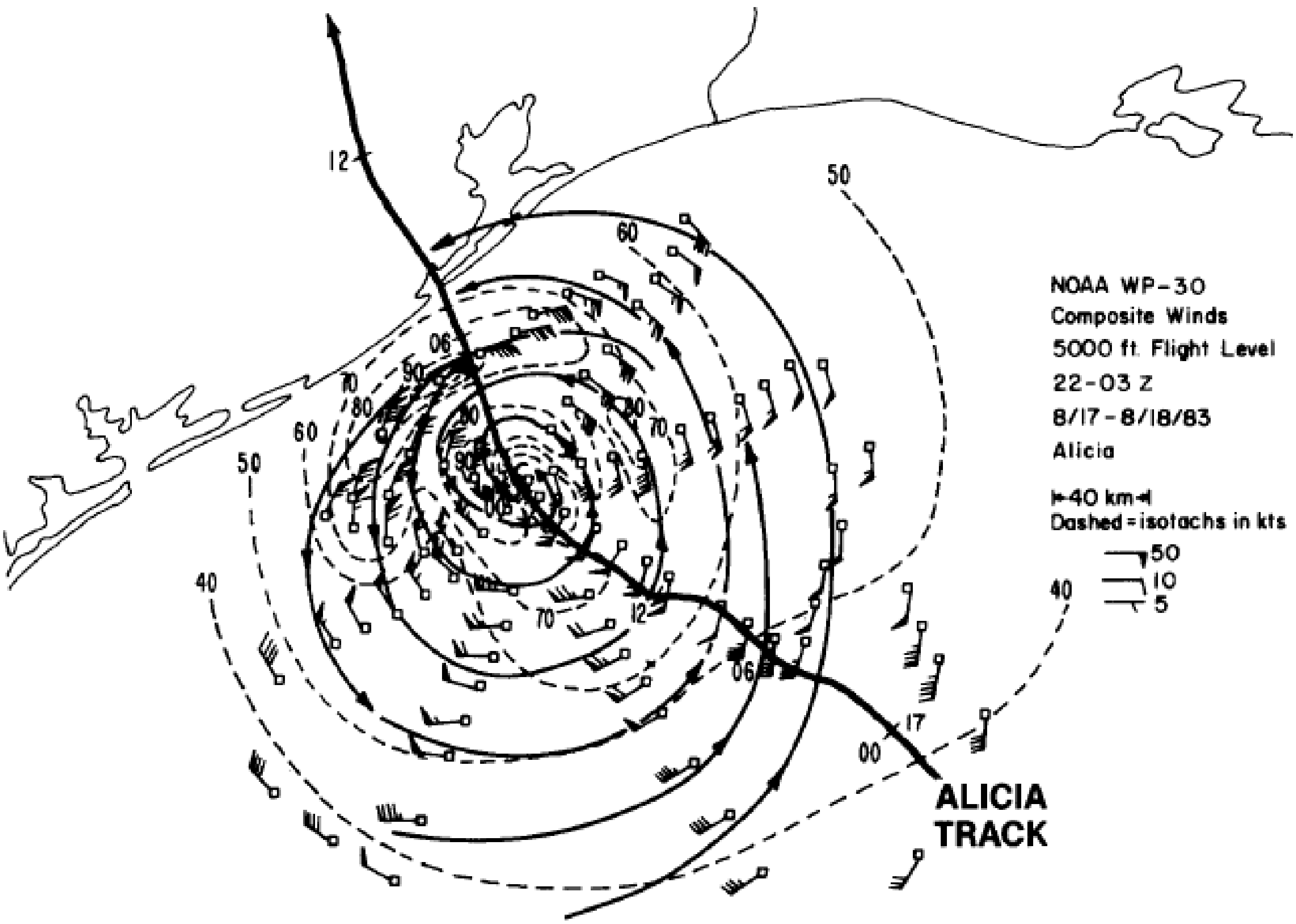


FIGURE 2.6B (Below) - Composite of sustained flight-level winds through Hurricane Alicia around landfall measured by NOAA research aircraft along flight tracks near 5,000 ft. Solid lines are stream lines and dashed lines are isotachs, both analyzed subjectively. Source: P. G. Black, National oceanic and Atmospheric Administration.

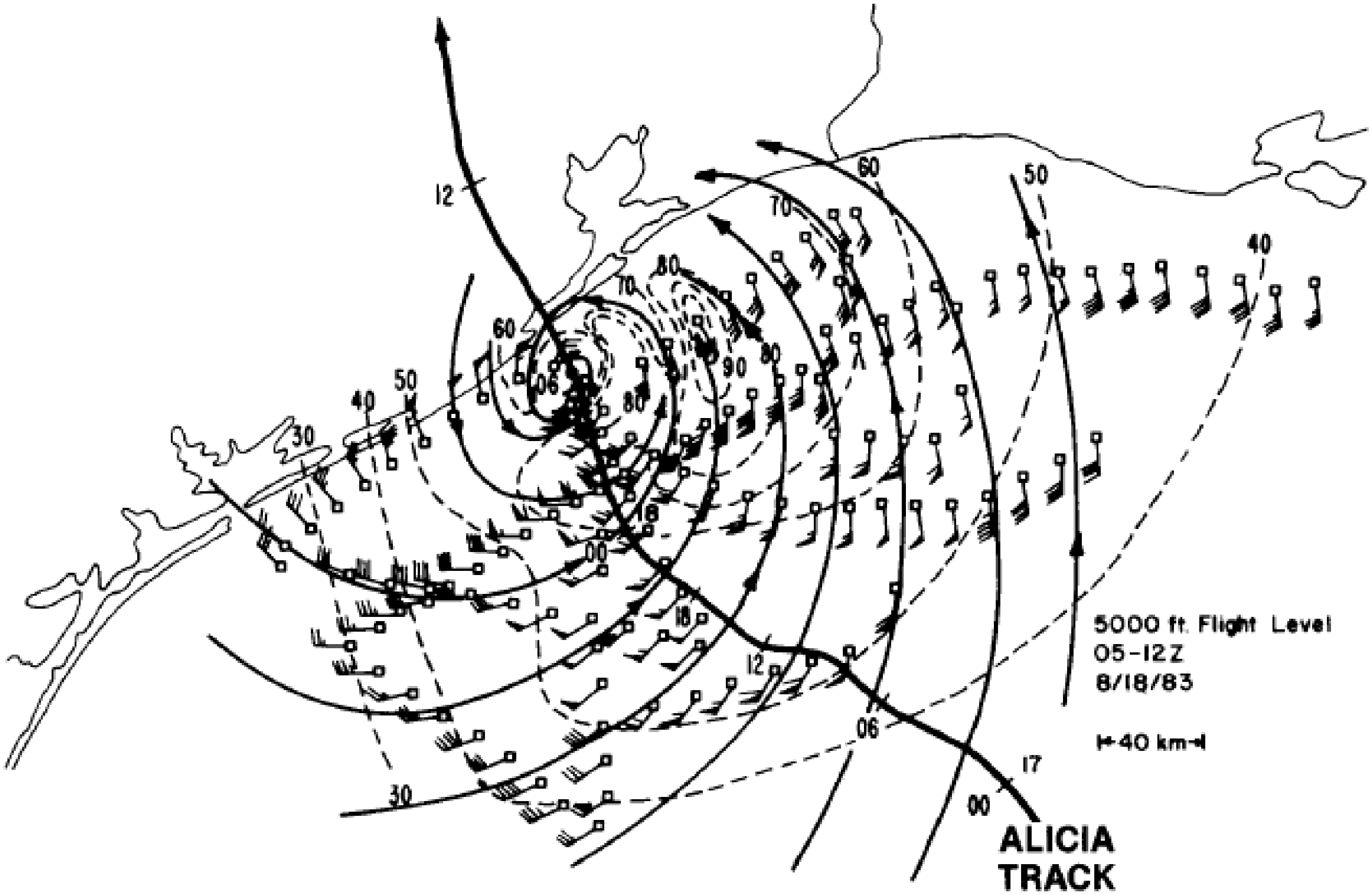
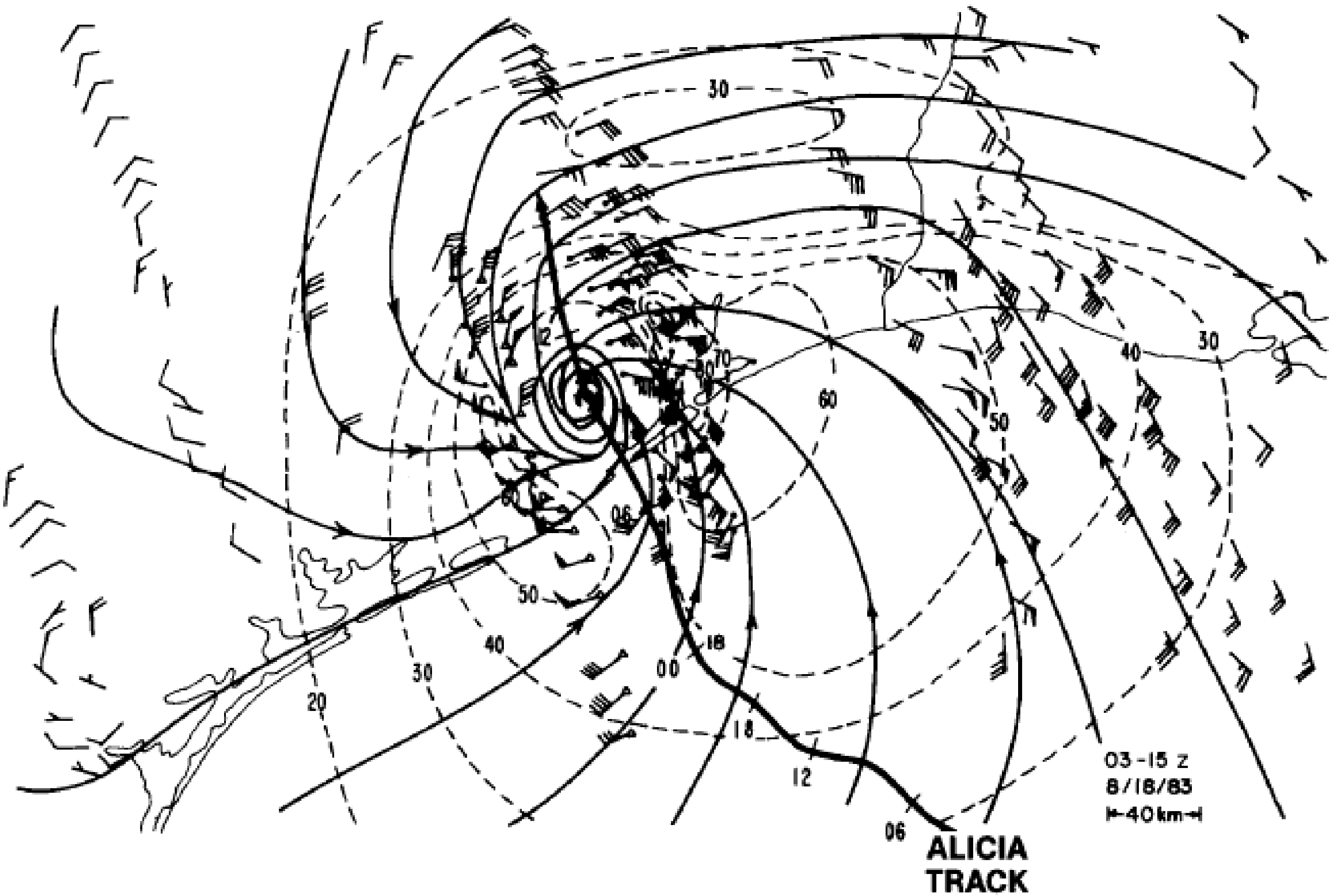


FIGURE 2.6C (Below) - Composite of sustained flight-level winds through Hurricane Alicia after landfall measured by NOAA research aircraft along flight tracks near 5,000 ft. Solid lines are stream lines and dashed lines are isotachs, both analyzed subjectively. Source: P. G. Black, National Oceanic and Atmospheric Administration.


30
30
40
50
60
70
80
12
06
60
50
40
30
20
18
00
18
12
06
03-15 Z
8/18/83
40 km
ALICIA
TRACK

Go Back

Go Back

FIGURE 2.7A (Below) Radial profile of horizontal sustained winds (solid line) measured by NOAA research aircraft from Alicia's eye to the northeast. Dashed line shows D values, which are a measure of the departure of the surface pressure from the general environmental mean. Source: P. G. Black, National Oceanic and Atmospheric Administration.

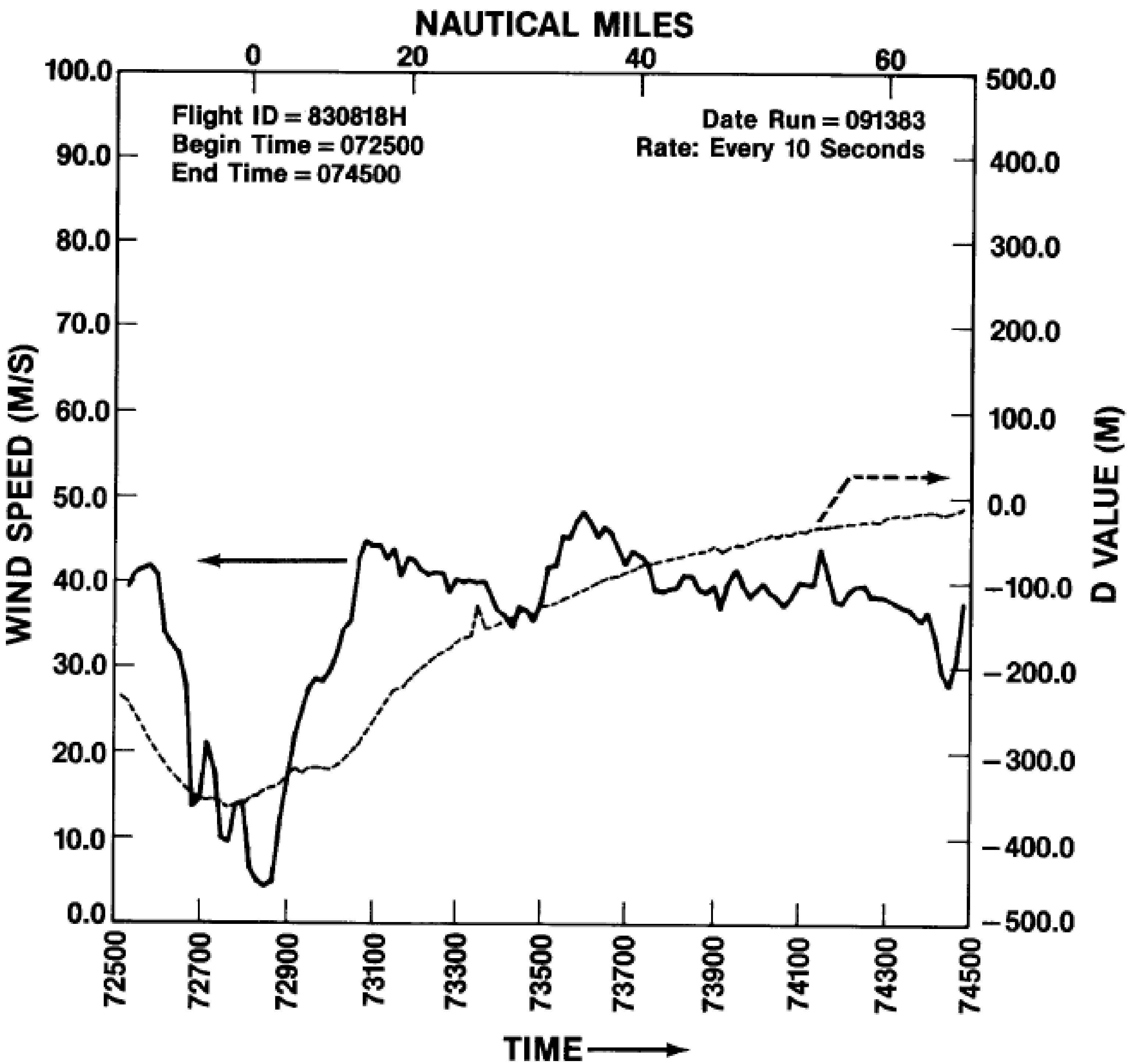
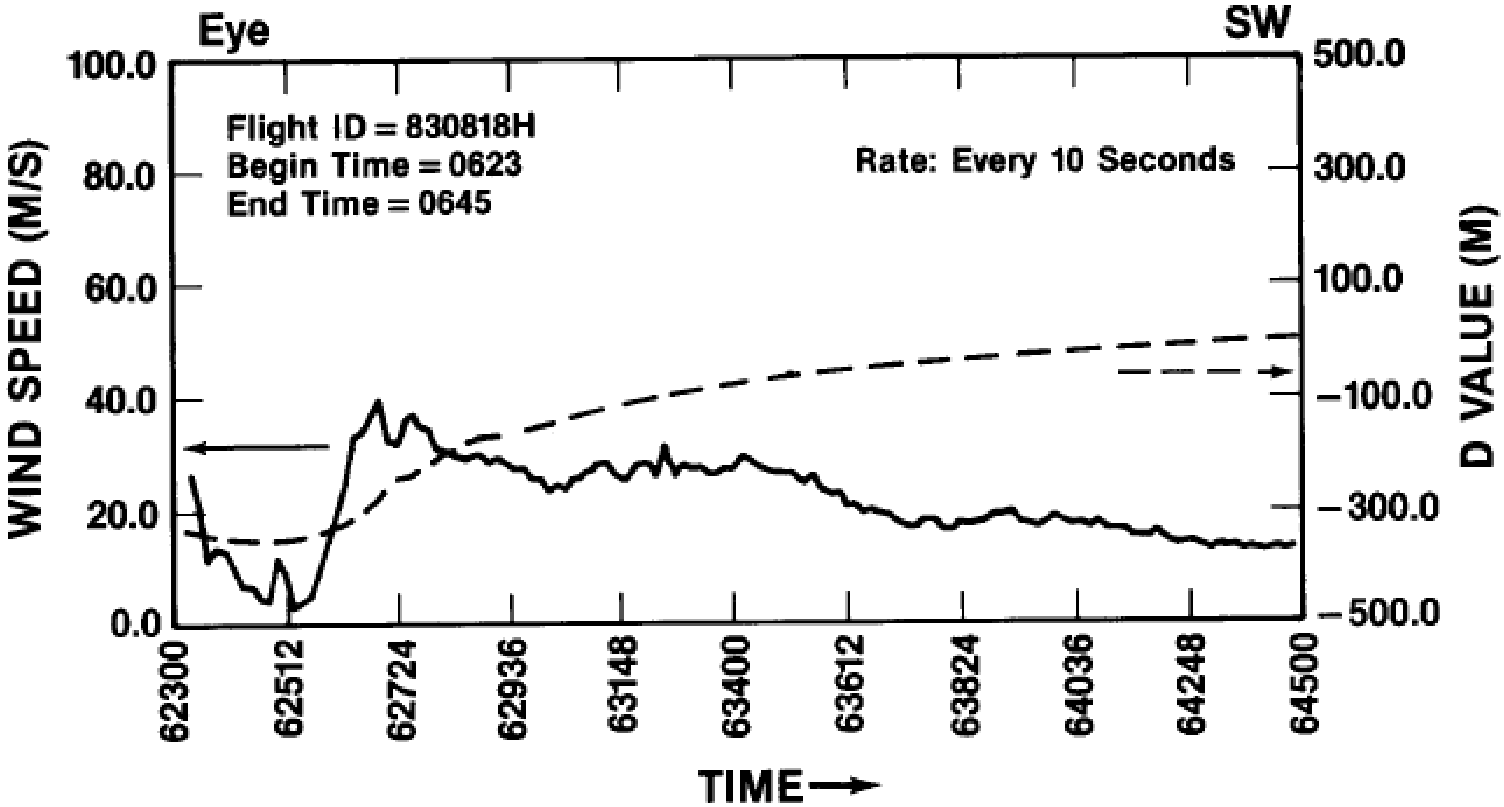


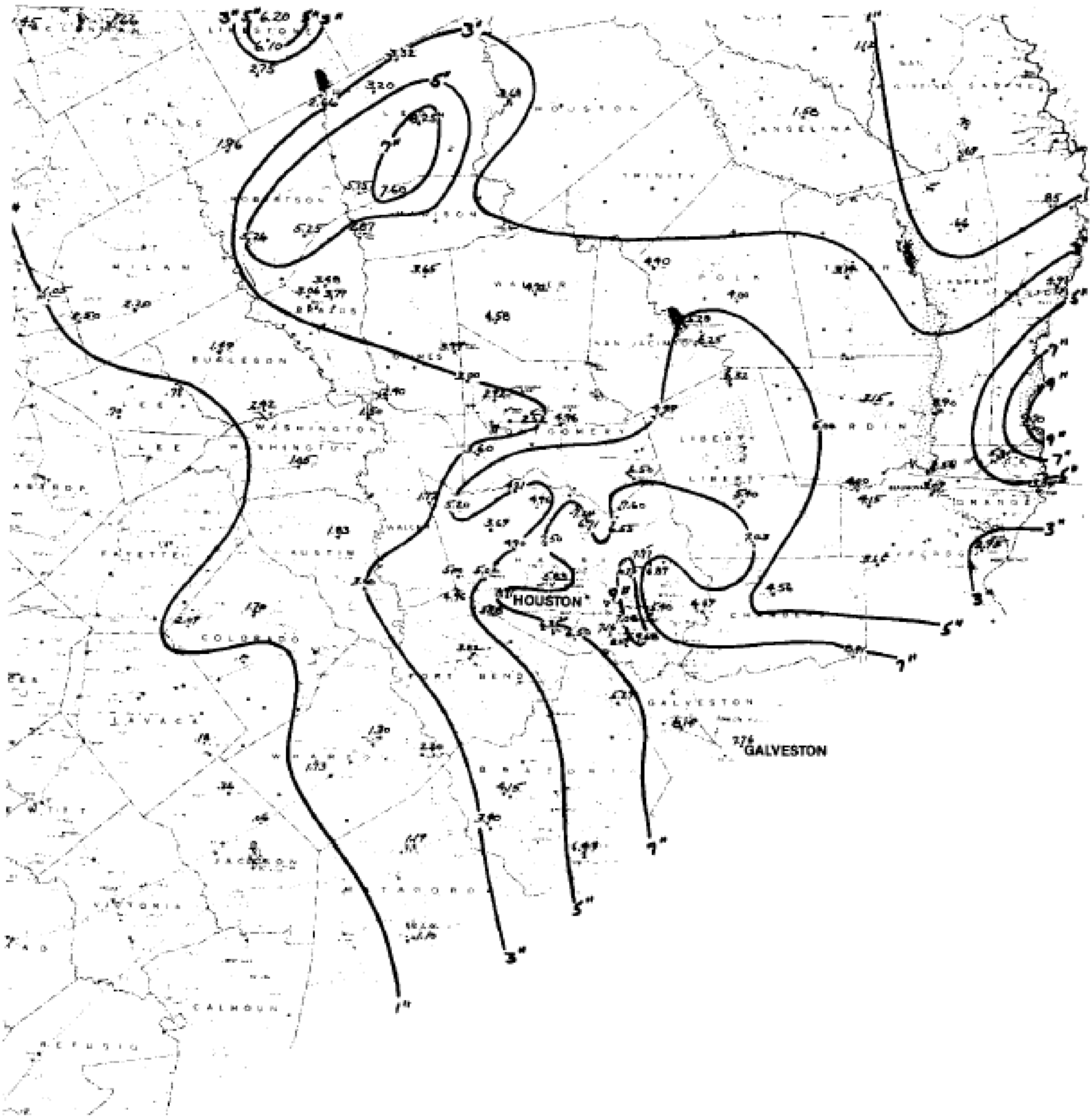
FIGURE 2.7B (below) Radial profile of horizontal sustained winds (solid line) measured by NOAA research aircraft from Alicia's eye to the southwest. Dashed line shows D values, which are a measure of the departure of the surface pressure from the general environmental mean. Source: P. G. Black, National oceanic and Atmospheric Administration.


Eye
SW
Flight ID = 830818H
Begin Time = 0623
End Time = 0645
Rate: Every 10 Seconds
WIND SPEED (M/S)
D VALUE (M)
100.0
80.0
60.0
40.0
20.0
0.0
500.0
300.0
100.0
−100.0
−300.0
−500.0
62300
62512
62724
62936
63148
63400
63612
63824
64036
64248
64500
TIME

Go Back

Go Back

FIGURE 2- 8 Preliminary analysis of total two-day rainfall accumulations from Hurricane Alicia for August 18-19, 1983. Isohyets are analyzed in inches. Source: George Kush, NWS San Antonio.



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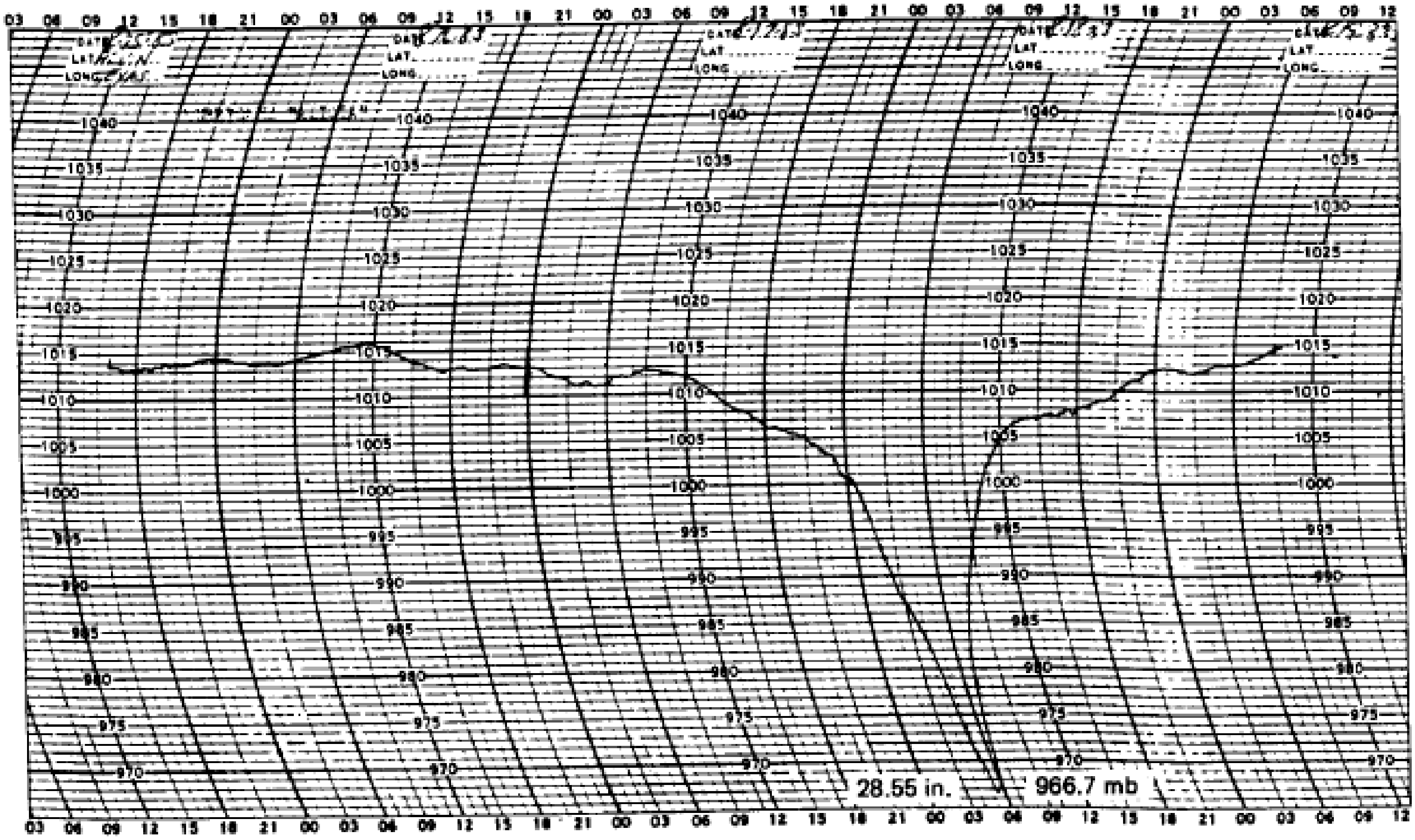
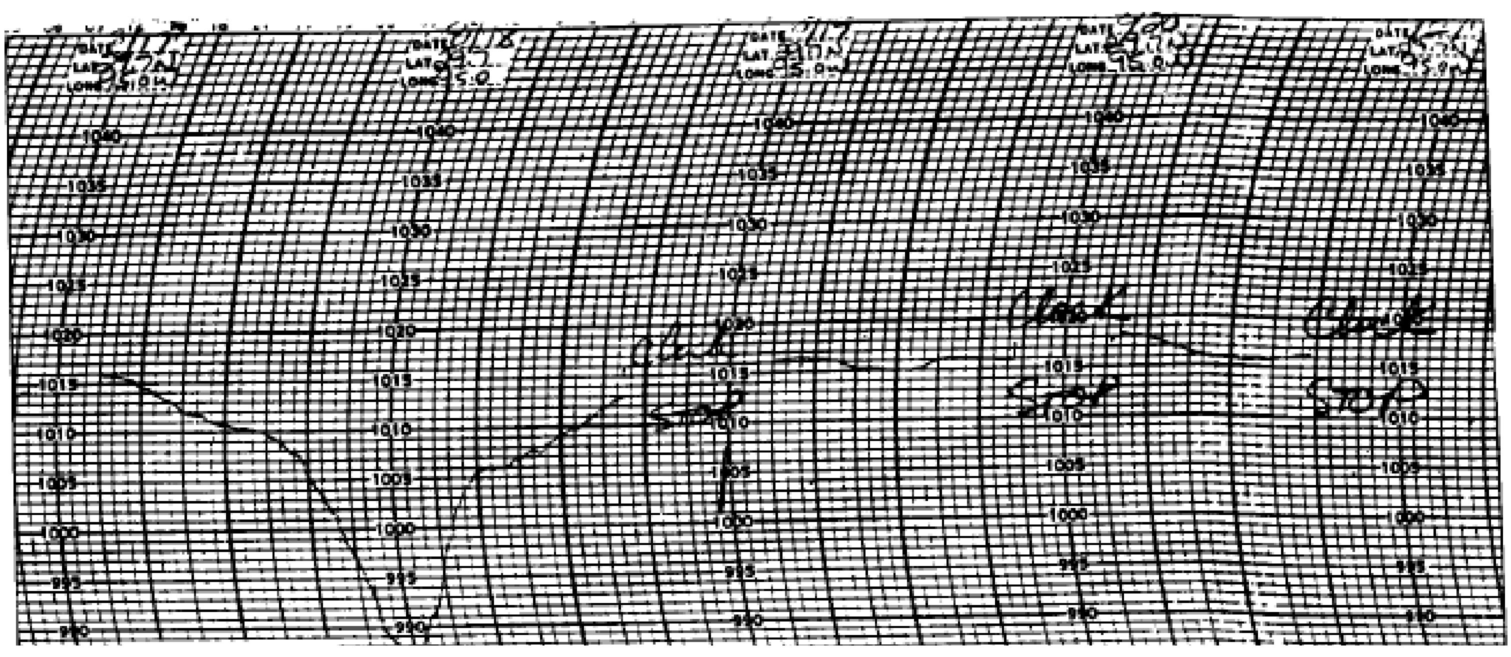


FIGURE 2.9A Surface microbarograph trace from NWS Alvin (in eye). The minimum pressure of 966.7 mb occurred at 5:25 a.m. CDT August 18.



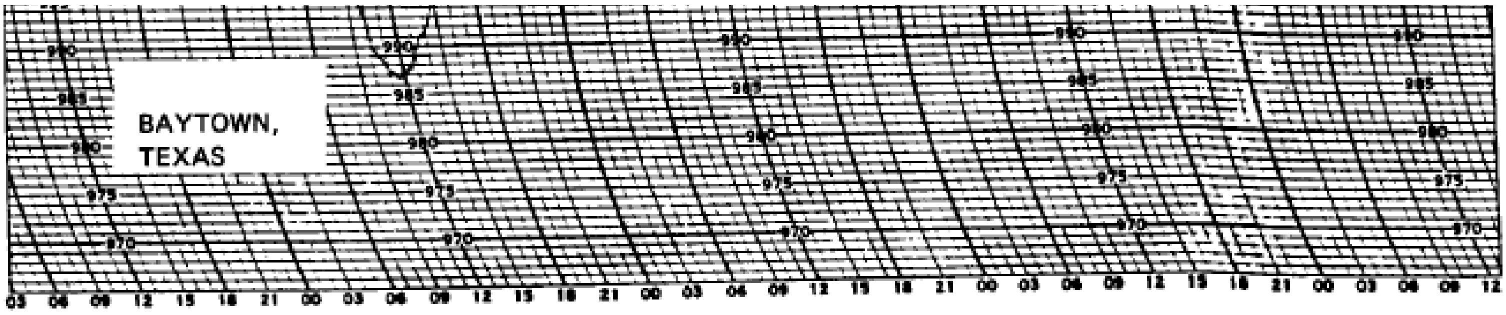


FIGURE 2.9B Surface microbarograph trace from Baytown (east of eye).

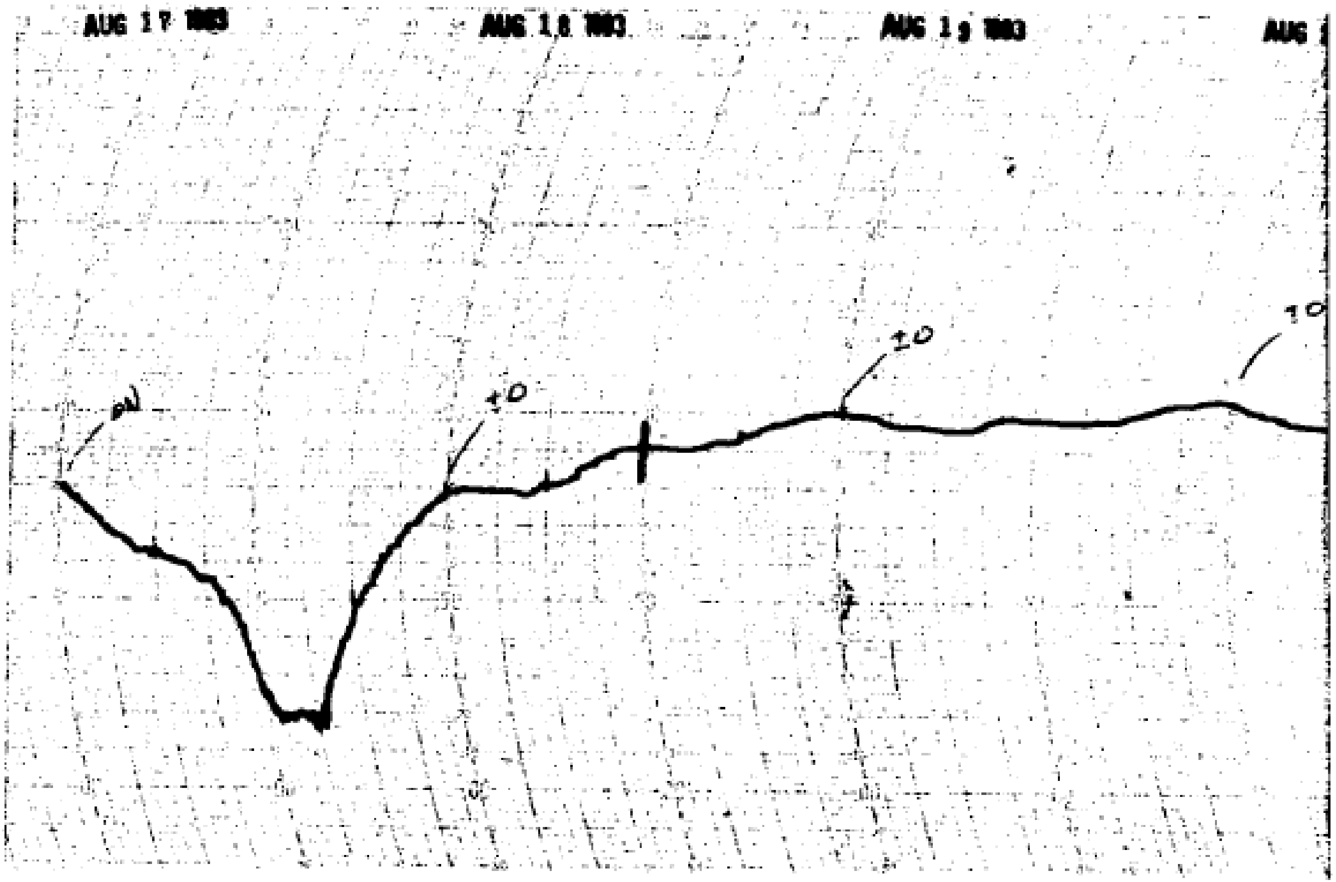
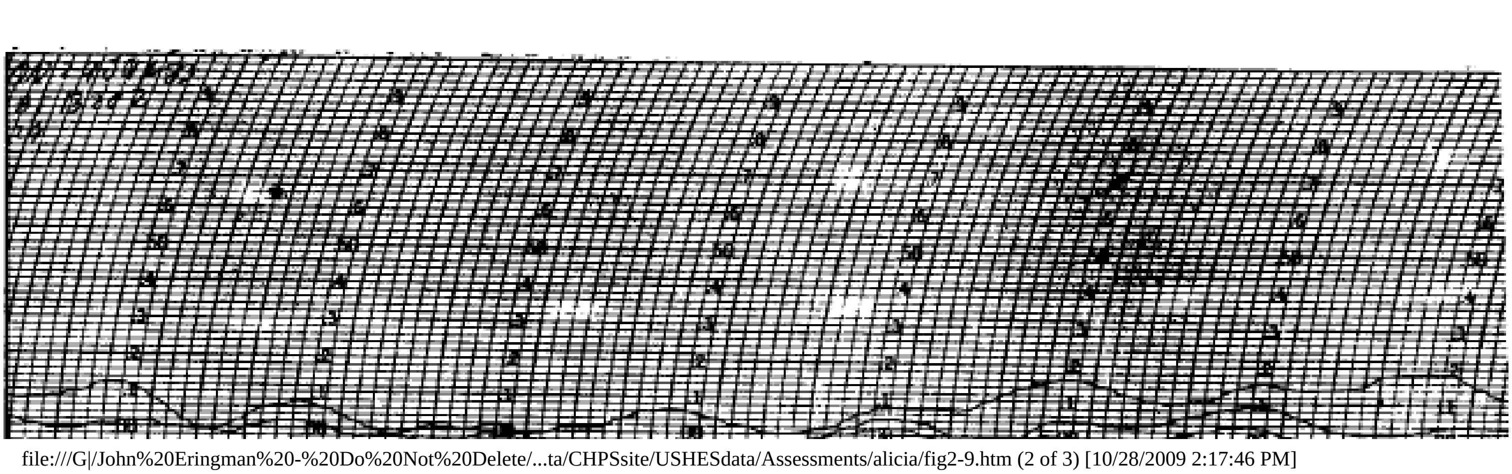


FIGURE 2.9C Surface microbarograph trace from NWS Galveston (east of slow-moving and looping eye). The pressure at the beginning of the trace is 29.97 in.



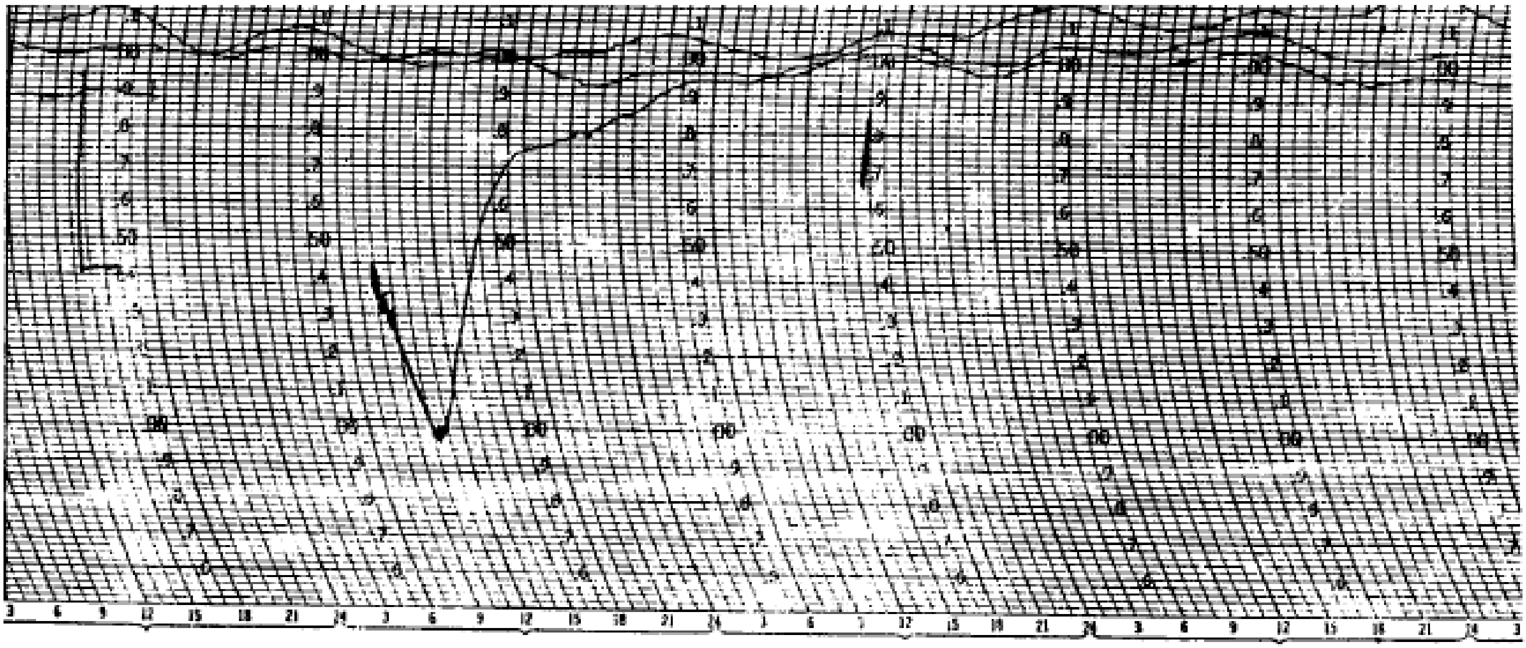


FIGURE 2.9D Surface microbarograph trace from Ellington Air Force Base (perhaps briefly in eye).

Go Back Fig. 3-1 below

FIGURE 3.1 Debris line on bay (north) side of the foredune on Follets Island about 1-1/2 miles east of San Luis Pass.

Go Back Fig. 3-2 below

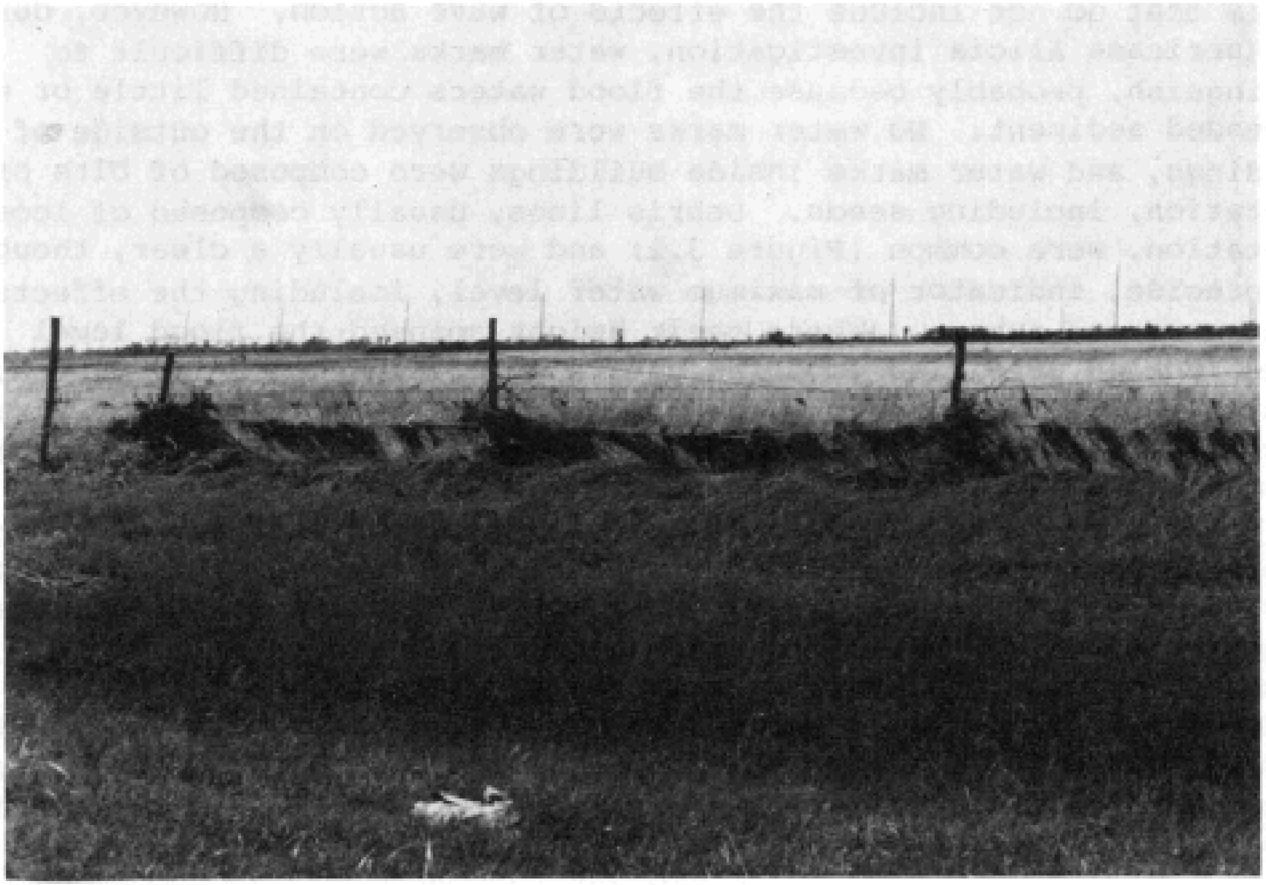


FIGURE 3.2 Debris on barbed wire fence about 1/2 mile west of Eight Mile Road on western Galveston Island.

Go Back

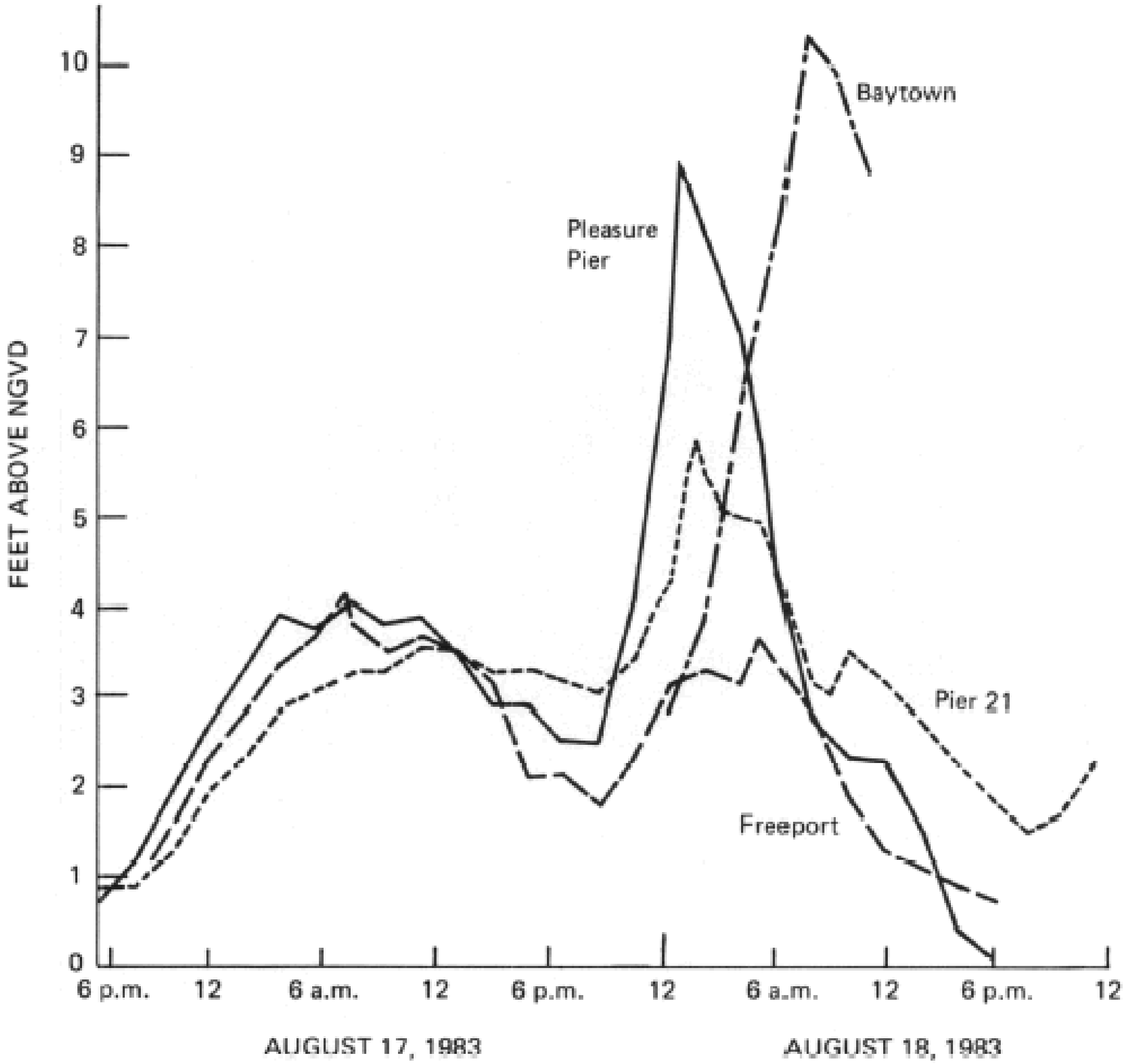


FIGURE 3.3 Tides at Baytown, Pleasure Pier, Pier 21, and Freeport during Hurricane Alicia. The reference level for Baytown is mean sea level, and times are in Central Daylight Time.

Fig 3-4 & 3-5 below Go Back

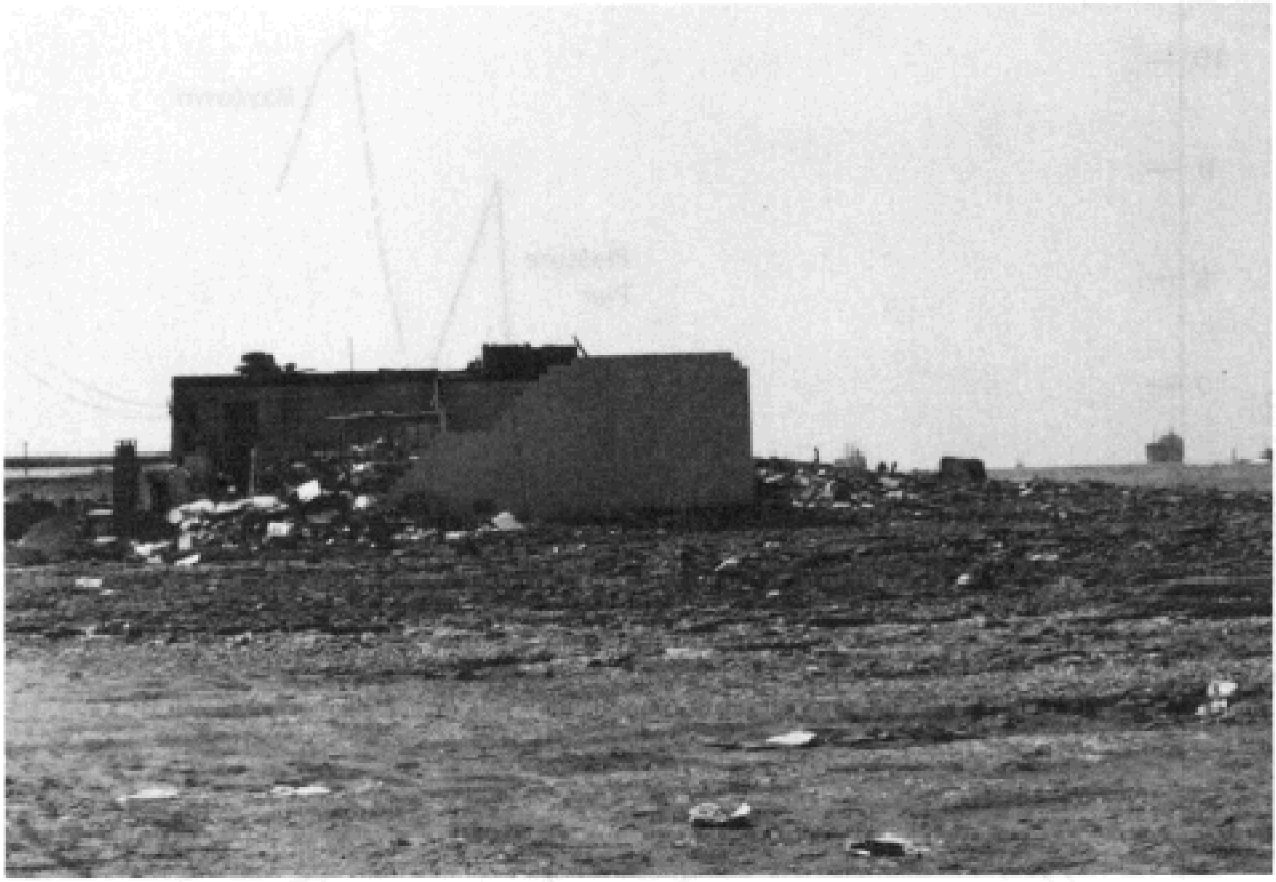
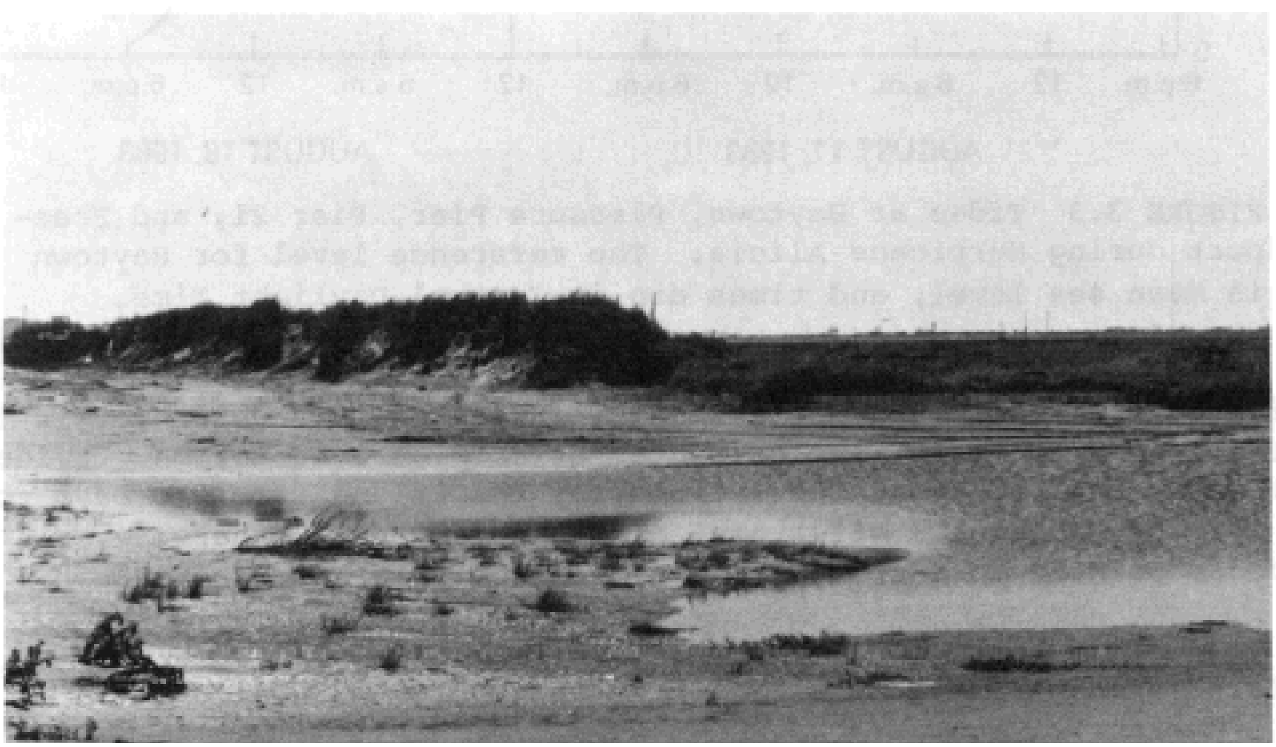


FIGURE 3.4 Scour and building damage near the intersection of the Galveston seawall and the west jetty of Galveston Inlet.



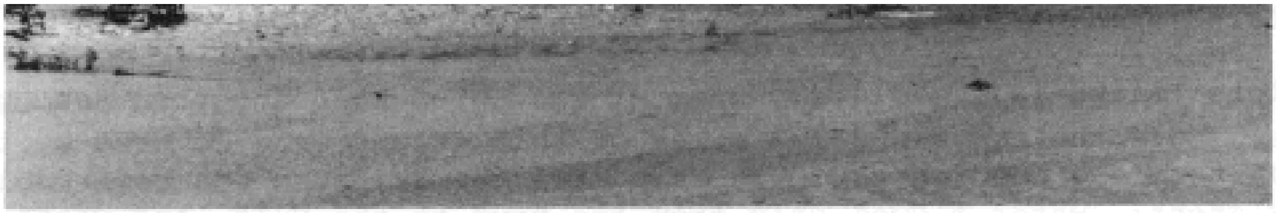


FIGURE 3.5 Front of scour channel and frontal dune on East Beach showing dune erosion. Scour channel was caused by flow confined between the dune and an adjacent beachfront condominium.

Go Back

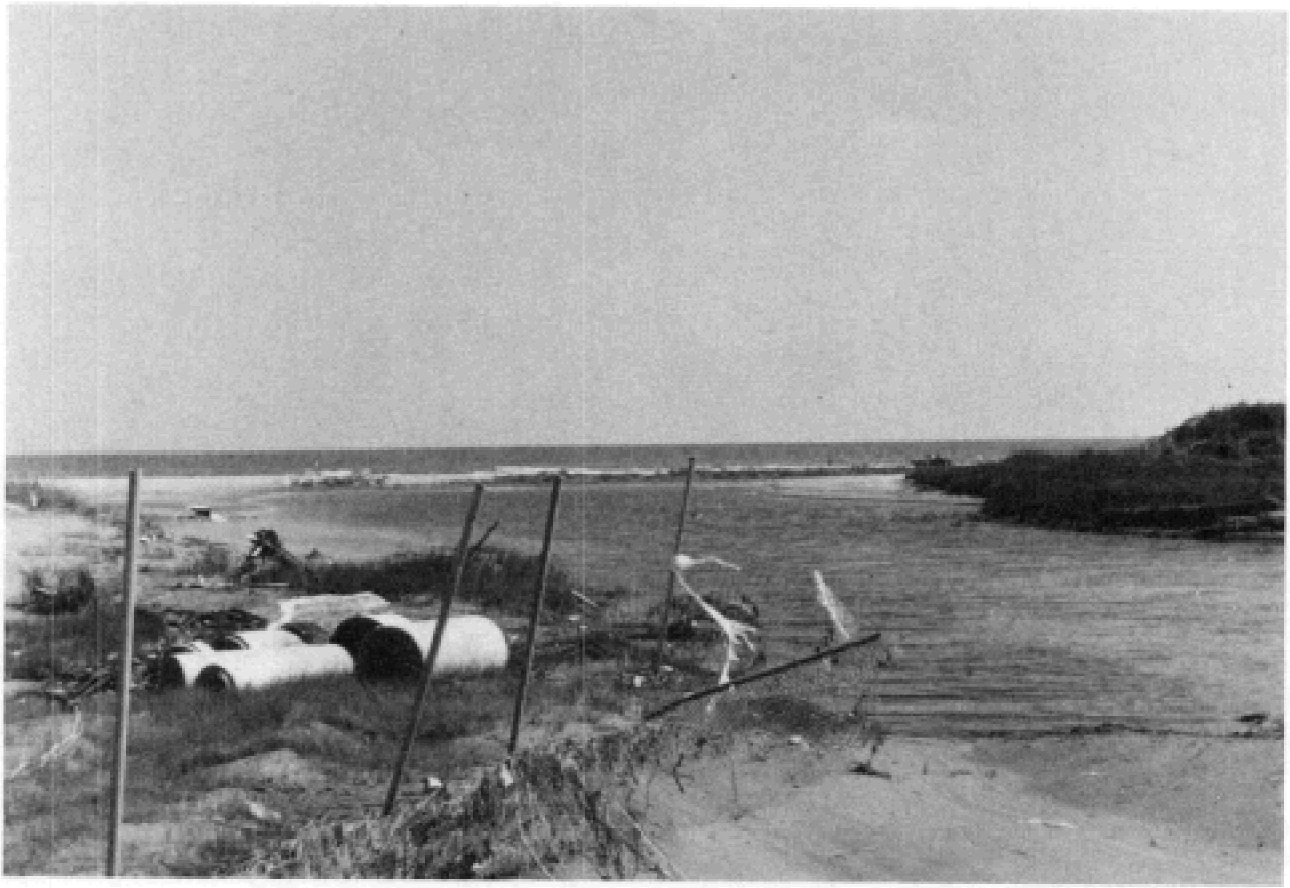


FIGURE 3.6 Landward end of the scour channel shown in Figure 3.5.

Fig 3-7 & 3-8 below Go Back

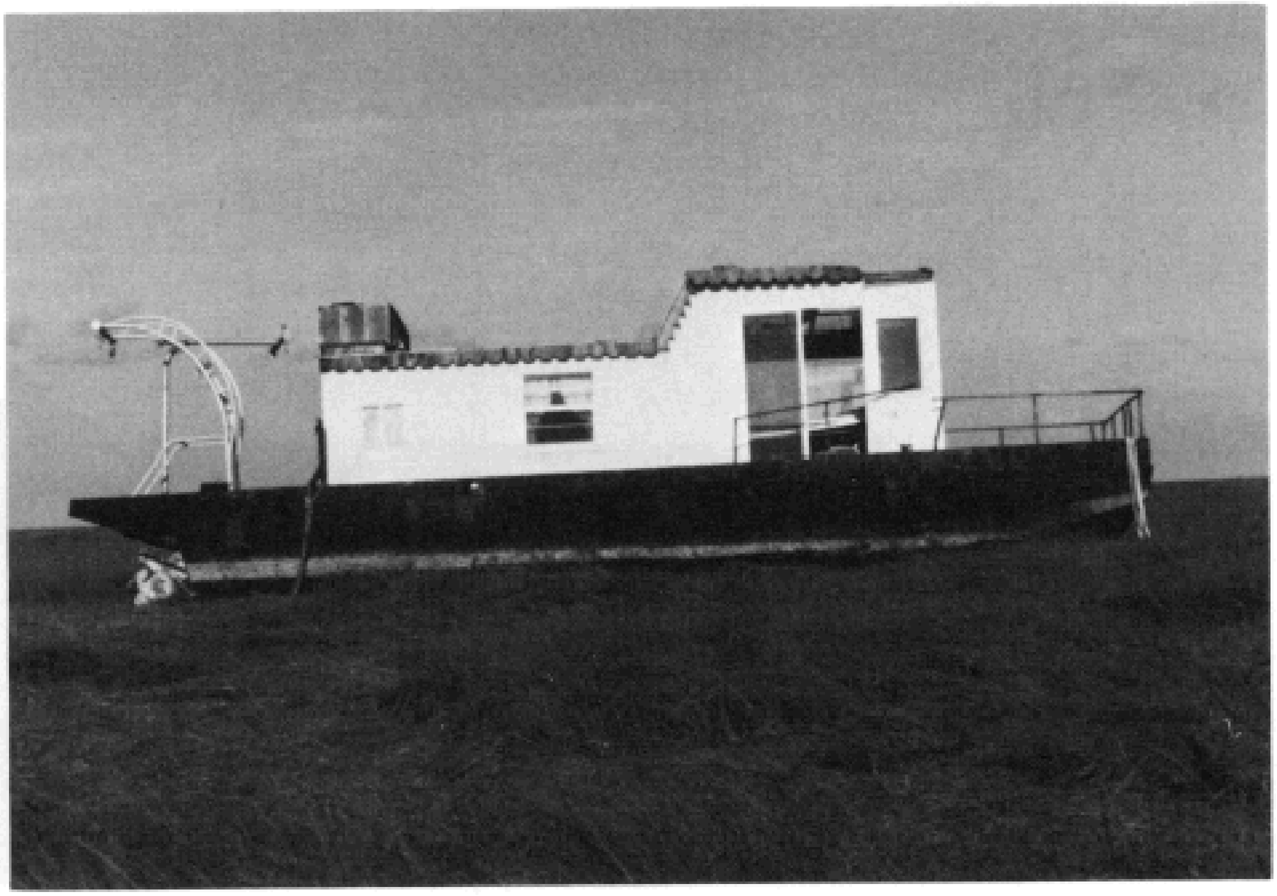


FIGURE 3.7 Houseboat grounded between the highway and the Gulf about 4-1/2 miles west of San Luis Pass on Follets Island. Note fresh barnacles on the bottom of the boat.

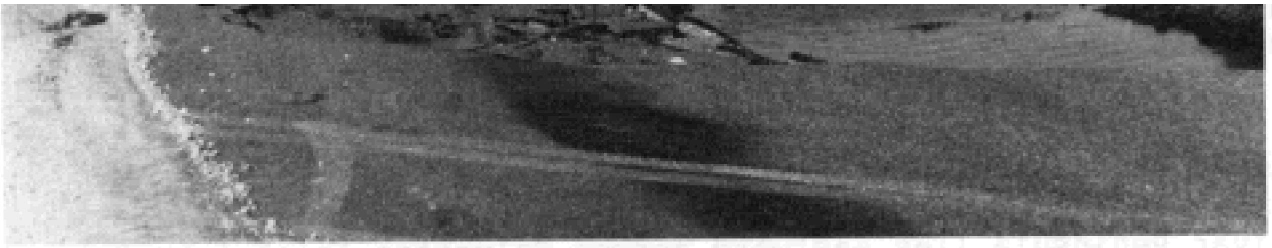


FIGURE 3.8 Washout channel looking south toward the Gulf about 7 miles west of San Luis Pass on Follets Island.

Go Back

Go Back

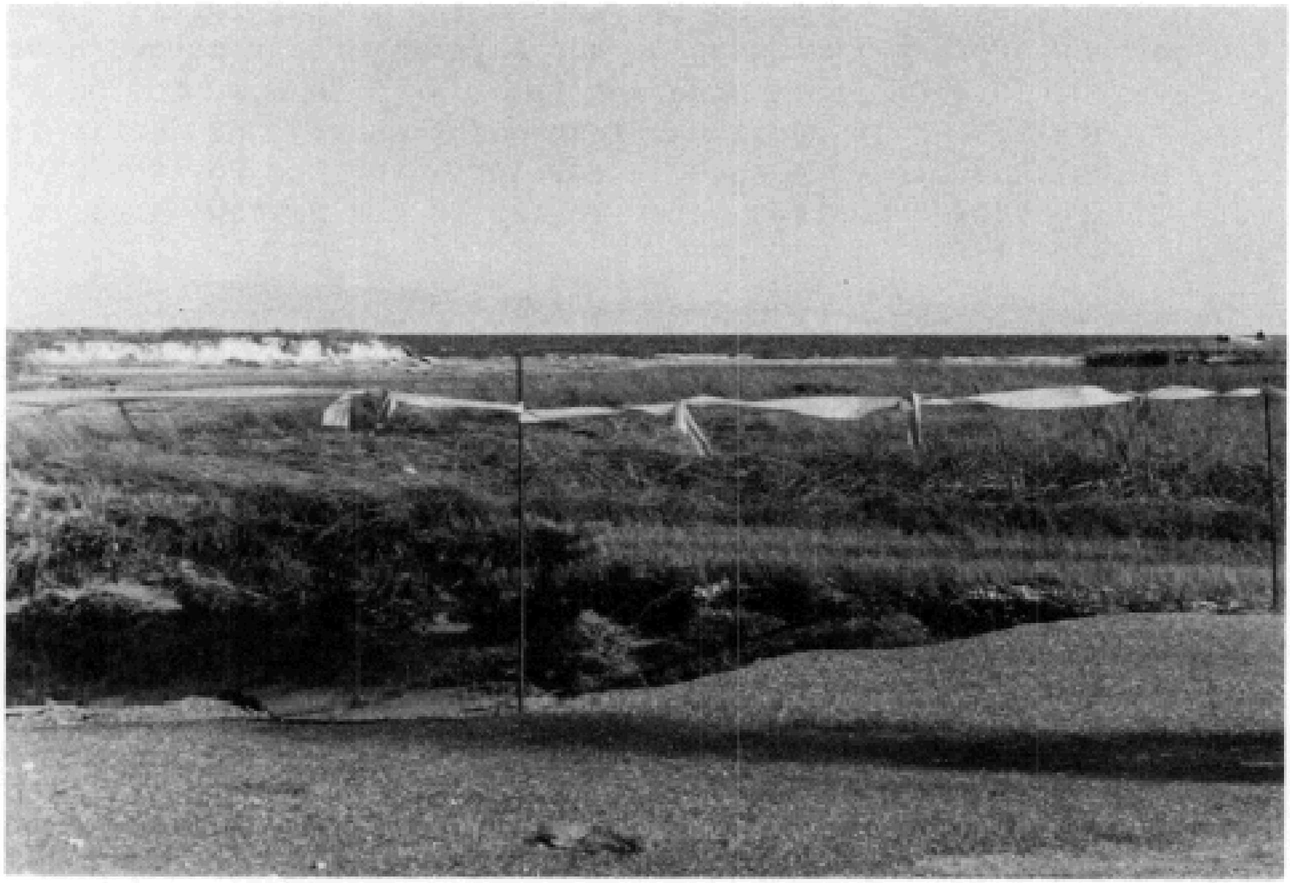


FIGURE 3.9 Portion of the channel shown in Figure 3.8 looking toward the Gulf. Note dune erosion in the vicinity of the beach.

Table 6-8 and Table 6-9 below Go Back

TABLE 6.8 Estimates of Losses from Hurricane Alicia in Galveston, Harris, Brazoria, and Chambers Counties

Type of Loss	Value (millions of dollars)
Residential	100 (9,500 structures)
Commercial	9 (300 structures)
Industrial	4
Public Facilities	1
Roads and Highways	1
Utilities	60
Vehicles	19 (6,250 vehicles)
Agriculture	51
Marine	10
Total	250

SOURCE: U.S. Army Corps of Engineers, 1983.

TABLE 6.9 Housing Units Damaged or Destroyed by Hurricane Alicia

	Destroyed	Minor Damage
Single-family homes	1,209	12,472
Mobile homes	455	1,034
Multifamily units (apartments, etc.)	633	2,857

SOURCE: Interagency Hazard Mitigation Team, 1983.

Go Back

TABLE 3.1 Changes in Shoreline Features from High Island Westward to Freeport Inlet

Location	Distance from Storm Center (miles)	Change in Water Line* (ft)	Change in Vegetation Line* (ft)	Erosion of Vegetation Line (ft)	Overwash (ft)
High Island	55.5	-38	18	--	--
	53.5	-92	24	--	--
	52.6	23	26	26	0
	50.7	32	193	--	--
	49.4	49	250	--	--
	48.4	-9	146	--	--
Rollover Pass	48.2				
	47.7	-21	208	--	--
Caplen	46.7				
	46.4	118	208	--	--
	45.0	-22	136	55	81
	43.6	-62	86	--	--
	42.0	101	116	--	--
Crystal Beach	39.1	62	67	16	51
	37.1	21	31	15	16
Flake	35.3				
	34.8	-18	92	62	30
The Galveston seawall extends from 18.9 miles to 28.5 miles.					
	17.9	13	238	134	104
	16.9	102	171	161	10
	15.9	91	210	75	135
	14.7	128	156	80	76
	13.1	151	177	152	25
State Park	12.3				
Jamaica Beach	11.4	166	233	65	16
	11.1	127	194	107	87
	10.0	144	164	--	--
	8.7	108	61	61	0
	8.3	108	70	70	0
	7.5	48	114	73	41
	6.5	145	145	--	--
Sea Isle	6.1				
	5.7	77	138	--	--
	5.1	172	1,058		

	5.7	77	138	--	--
	5.1	172	1,058	--	--
	4.6	182	245	91	154
Bay Harbor	4.4				
	4.3	168	310	79	231
	2.9	166	141	89	52
	2.2	195	170	88	82
	1.6	110	146	28	118
San Luis Pass	0.0				
	2.1	-30	45	--	--
	3.5	-58	8	--	--
	5.5	-58	-21	--	--
	7.5	-51	--	--	--
	9.1	9	--	--	--
	1.2	-6	-11	--	--
	2.5	78	16	--	--
	3.4	-35	-4	--	--
Surfside Beach	13.9	-33	55	--	--
	14.5	-3	28	--	--
Freeport Inlet	14.7				

*Negative numbers indicate movement toward the Gulf.

Go Back

Go Back

TABLE 6.1 Summary of Selected Information from NHC Advisories

Time	Date	Status: Tropical Storm or Hurricane	Maximum Wind (mph)	Eye Pressure (mb)	Eye Latitude	Eye Longitude	Distance of Eye from Galveston or Corpus Christi (miles)	Direction of Eye from Galveston or Corpus Christi
5:00 p.m.	15	T	45	1004	27.2	91.3	375 (Corpus)	E (Corpus)
9:30 p.m.	15	T	45	1004	27.0	91.6	350 (Corpus)	E (Corpus)
5:00 a.m.	16	T	50	1004	27.0	92.5	300 (Corpus)	E (Corpus)
11:00 a.m.	16	T	65	1001	27.0	92.5	300 (Corpus)	E (Corpus)
2:00 p.m.	16	T	70	997	27.2	92.8	280 (Corpus)	E (Corpus)
5:00 p.m.	16	H	80	997	27.3	93.1	175	SE
8:00 p.m.	16	H	80	991	27.4	93.3	160	SE
11:00 p.m.	16	H	80	989	27.7	93.7	140	SE
2:00 a.m.	17	H	80	988	27.7	93.8	125	SE
5:00 a.m.	17	H	80	--	27.8	94.2	110	SSE
8:00 a.m.	17	H	80	--	28.0	94.5	90	SSE
11:00 a.m.	17	H	85	980	28.0	94.5	90	SSE
1:00 p.m.	17	H	100	974	28.1	94.6	85	SSE
5:00 p.m.	17	H	110	972	28.1	94.6	85	SSE
7:00 p.m.	17	H	110	969	28.3	94.6	70	SSE
9:00 p.m.	17	H	115	967	28.4	94.8	60	S
11:00 p.m.	17	H	115	966	28.5	94.9	55	S
1:00 a.m.	18	H	115	966	28.8	95.0	35	SSW
3:00 a.m.	18	H	115	963	29.1	95.2	west tip of island	--
5:00 a.m.	18	H	115	962	29.3	95.3	30	W

TABLE 6.1 (Cont.)

Time	Date	Direction of Movement	Forward Speed (mph)	Galveston Probability	Predicted Tide (ft)	Likely to Intensify	Dangerous	Predicted Rain (in.)	Tornadoes Mentioned
5:00 p.m.	15	W	5	17	--	yes	--	--	--
9:30 p.m.	15	W	6	18	--	yes	--	--	--
5:00 a.m.	16	W	6	19	--	yes	--	--	--
11:00 a.m.	16	W	--	21	--	yes	--	--	--
2:00 p.m.	16	WNW	5	--	--	yes	--	--	--
5:00 p.m.	16	WNW	5	36	--	yes	--	--	--
8:00 p.m.	16	WNW	5	--	--	yes	--	--	--
11:00 p.m.	16	WNW	5	46	4 to 6	yes	--	--	--
2:00 a.m.	17	WNW	5	--	4 to 6	yes	--	--	--
5:00 a.m.	17	WNW	5	51	6	possible	--	squalls	--
8:00 a.m.	17	WNW	5	--	6	possible	--	squalls	--
11:00 a.m.	17	WNW	5	--	6 to 8	possible	--	squalls	yes
1:00 p.m.	17	WNW	5	--	10	yes	yes	10 to 15	yes
5:00 p.m.	17	WNW	5	--	10	yes	yes	10 to 15	yes
7:00 p.m.	17	WNW	5	--	10	yes	yes	10 to 15	yes
9:00 p.m.	17	WNW	5	--	12	yes	yes	10 to 15	yes
11:00 p.m.	17	NW	5	--	12	yes	yes	10 to 15	yes
1:00 a.m.	18	NW	5	--	12	yes	yes	10 to 15	yes
3:00 a.m.	18	NNW	6	--	12	--	--	10	yes
5:00 a.m.	18	NW	7	--	12	--	--	--	--

Go Back

TABLE 6.10 Types of Federal Assistance Available to Alicia Victims

1. Temporary housing.

2. Small grants for repair of structures to make them habitable (not for repair of extras, such as porches).

3. Grants up to $5,000 for purchase of essential household items.

4. Food stamps for those who qualified and USDA food commodities.

5. Disaster unemployment benefits if laid off because business place was damaged or if self-employed ($135/week).

6. Tax deduction on 1983 federal income tax return if loss greater than 10 percent of adjusted income (could be filed as amendment to 1982 return for immediate rebate).

7. Low-interest loan to farmers with crop loss of 30 percent or more.

8. Legal counseling.

9. Farm loans for debris removal and fence repair.

10. Small Business Administration loans to individual up to $55,000 for damages at 5-7/8 percent or 11-5/8 percent, depending on ability to borrow elsewhere (vacation homes not eligible).

11. Small Business Administration loans to businesses up to $500,000 or 85 percent of uninsured losses at 8 percent or 11 percent, depending on ability to borrow elsewhere.

Go Back

TABLE 6.2 Probabilities Attached to the 5 p.m. Monday, August 15, NHC Advisory

Coastal Locations	Through 1 p.m. Tuesday	Additional Probabilities: 1 p.m. Tuesday Through 1 a.m. Wednesday	1 a.m. Wednesday Through 1 p.m. Wednesday	1 p.m. Wednesday Through 1 p.m. Thursday	Total Through 1 p.m. Thursday
St. Marks, Flor.	x	x	1	1	2
Apalachicola, Flor.	x	x	1	2	3
Panama City, Flor.	x	x	1	2	3
Pensacola, Flor.	x	1	1	3	5
Mobile, Al.	x	2	2	3	7
Gulfport, Miss.	1	3	2	2	8
Buras, La.	4	3	2	2	11
New Orleans, La.	4	3	2	3	12
New Iberia, La.	7	4	2	1	14
Port Arthur, Tex.	6	5	2	2	15
Galveston, Tex.	9	5	2	2	17
Port O'Connor, Tex.	4	7	2	2	16
Corpus Christi, Tex.	1	7	3	4	15
Brownsville, Tex.	1	7	3	2	14
Sotolamarina, Mex.	x	2	5	3	10
Tampico, Mex.	x	1	3	3	7
Tuxpan, Mex.	x	x	2	3	5
Veracruz, Mex.	x	x	x	2	2

NOTE: x means less than one percent.

Go Back

TABLE 6.3 Probabilities Attached to the 11 a.m. Tuesday, August 16, NHC Advisory

Coastal Locations	Through 7 a.m. Wednesday	Additional Probabilities: 7 a.m. Wednesday Through 7 p.m. Wednesday	7 p.m. Wednesday Through 7 a.m. Thursday	7 a.m. Thursday Through 7 a.m. Friday	Total Through 7 a.m. Friday
Tampa, Flor.	x	x	x	1	1
Cedar Key, Flor.	x	x	x	2	2
St. Marks, Flor.	x	x	1	2	3
Apalachicola, Flor.	x	x	1	2	3
Panama City, Flor.	x	x	1	3	4
Pensacola, Flor.	x	1	2	3	6
Mobile, Al.	x	2	2	4	8
Gulfport, Miss.	1	2	3	3	9
Buras, La.	2	3	3	3	11
New Orleans, La.	3	4	3	2	12
New Iberia, La.	7	5	2	2	16
Port Arthur, Tex.	11	3	2	2	18
Galveston, Tex.	17	2	1	1	21
Port O'Connor, Tex.	12	4	1	2	19
Corpus Christi, Tex.	4	6	3	2	15
Brownsville, Tex.	2	6	3	3	14

NOTE: x means less than one percent.

Go Back

TABLE 6.4 Probabilities Attached to the 5 p.m. Tuesday, August 16, NHC Advisory

Coastal Locations	Through 1 p.m. Wednesday	Additional Probabilities: 1 p.m. Wednesday Through 1 a.m. Thursday	1 a.m. Thursday Through 1 p.m. Thursday	1 p.m. Thursday Through 1 p.m. Friday	Total Through 1 p.m. Friday
Panama City, Flor.	x	x	1	1	2
Pensacola, Flor.	x	1	x	2	3
Mobile, Al.	x	1	1	3	5
Gulfport, Miss.	x	2	2	2	6
Buras, La.	1	2	1	3	7
New Orleans, La.	2	3	2	2	9
New Iberia, La.	10	3	1	2	16
Galveston, Tex.	35	x	1	x	36
Port Arthur, Tex.	23	1	1	x	25
Port O'Connor, Tex.	23	1	1	x	25
Corpus Christi, Tex.	9	5	2	x	17
Brownsville, Tex.	3	4	2	2	11

NOTE: x means less than one percent.

Go Back

TABLE 6.5 Probabilities Attached to 5 a.m. Wednesday, August 17, NHC Advisory

Coastal Locations	Through 1 a.m. Thursday	Additional Probabilities 1 a.m. Thursday Through 1 p.m. Thursday	1 p.m. Thursday Through 1 a.m. Friday	1 a.m. Friday Through 1 a.m. Saturday	Total Through 1 a.m. Saturday
Pensacola, Flor.	x	x	1	1	2
Mobile, Al.	x	x	1	2	3
Gulfport, Miss.	x	1	1	2	4
Buras, La.	x	1	1	2	4
New Orleans, La.	1	1	1	3	6
New Iberia, La.	5	2	2	2	11
Port Arthur, Tex.	24	x	1	x	25
Galveston, Tex.	51	x	x	x	51
Port O'Connor, Tex.	33	1	x	x	34
Corpus Christi, Tex.	16	2	1	1	20
Brownsville, Tex.	3	4	2	1	10

NOTE: x means less than one percent.

Go Back

TABLE 6.6 Local Statements by the Galveston NWS Office

Tuesday, August 16

5:45 p.m. Evacuation recommended of Bolivar Peninsula, west end of Galveston Island, Kemah, Seabrook, low areas near League City, Hitchcock, and coastal areas of Brazoria and Matagorda counties.

9:15 p.m. Galveston city and county officials recommend that evacuation of Bolivar Peninsula and west end of Galveston Island be completed by 3 a.m. Wednesday.

Wednesday, August 17

2:25 a.m. Tides close to Highway 87 on Bolivar Peninsula; west end of Galveston Island could be cut off by flooding before daybreak.

5:30 a.m. Squalls arriving. Four- to five-foot tides at Galveston and Freeport. Roads out at Jamaica Beach and Bolivar Peninsula.

9:00 a.m. Four- to six-foot tides. Tornado watch. Gale-force winds. Galveston city officials recommend voluntary evacuation of island.

1:30 p.m. Winds of 100 mph possible. Tides expected to reach 8 to 10 ft. Landfall expected late tonight between Palacio and Galveston.

4:00 p.m. Baytown Civil Defense recommends evacuation of Brownwood area. Highway 6 at Bayou Vista partially closed. Kemah-Seabrook Bridge closed. Sixty-mph winds on Galveston now. Travel to or from Galveston Island to be completed before nightfall.

5:30 p.m. Winds of 110 mph in Alicia. Matagorda and Brazoria county residents below 10 ft elevation should have made preparations to evacuate. Interstate 45 north of Galveston may be cut by tides. Bolivar ferry stopped running. Ten to fifteen inches of rain predicted.

7:30 p.m. Hurricane-force winds expected tonight. Gusts of 66 mph in Galveston now.

10:15 p.m. Possibility of more northerly track toward Galveston. Potential for landfall on west end of island. Flooding expected in Galveston north of Broadway on bay side. Maximum winds of 115 mph and 12-ft tides predicted.

11:00 p.m. Possible tides of 15 ft along west side of Galveston Bay by morning.

Thursday, August 18

<u>Thursday, August 18</u>

1:25 a.m. Alicia to move over west end of Galveston Island. Gusts of 92 mph in Galveston now.

2:00 a.m. Landfall occurred at 1:40 a.m. over western tip of island. Beware of eye. Gusts of 102 mph in Galveston.

3:30 a.m. Winds diminishing in Galveston. Tornado reports. Flooding possible in Houston.

Go Back

TABLE 6.7 Evacuation Actions Taken in Selected Locations and Public Response

Location	Action	Response
Cameron Parish, La.	6,000 advised to evacuate on Tuesday.	Very high, 90%(?).
Sabine Pass	Advised to leave at 6 a.m. Wednesday.	50%(?).
Baytown	Advised to leave at 7:45 p.m. Tuesday from areas below 6 ft and in Brownwood area, to be completed by noon Wednesday; told shelter location at 9 p.m.; at 7:15 a.m. Wednesday people below 8 ft told high water will arrive by nightfall, specific areas below 8 ft named; at 2 p.m. Wednesday all mobile home residents told to leave by nightfall, shelter locations announced; at 5 p.m. Wednesday police go through Brownwood, all areas below 10 ft advised to leave; by 7 p.m. all people in Brownwood should be out; by 8:30 p.m. fire department goes through Brownwood with sirens, public address systems; people warned of rising water until 9 a.m. Thursday.	100 evacuated from Brownwood after surge; otherwise good.
Deer Park	Evacuation advised on Wednesday.	Percent leaving not known; building at one shelter loses part of roof and windows during storm.
Shoreacres	Police go door to door in highest risk areas at noon on Wednesday.	50%(?).
Seabrook	Advised to leave late Tuesday; at 7 a.m. Wednesday police go through lowest area (Toddville) with public address systems; go through other areas with public address systems Wednesday afternoon.	
Kemah	No evacuation advised by city; informal shelter set up at local school.	700 leave low-lying areas; many leave Wednesday, some not until Thursday morning.
Galveston County	County judge advises Wednesday morning evacuation of low-lying areas of unincorporated areas of west end of Galveston Island, Hitchcock, and Bolivar Peninsula; County Emergency Management Coordinator plays down risk ("we've had	Deputies report most who were leaving had gone by noon Wednesday, rate very high from west end of Galveston Island.

	Galveston Island, Hitchcock, and Bolivar Peninsula; County Emergency Management Coordinator plays down risk ("we've had worse weekend storms").	day; rate very high from west end of Galveston Island, 90%(?).
Webster	City-wide evacuation advised Wednesday morning.	

TABLE 6.7 (Cont.)

Location	Action	Response
League City	City-wide evacuation advised on Tuesday; five local shelters also house Kemah evacuees.	35%(?); officials believe Galveston's actions affected response in their area; 800 sheltered.
Texas City	People outside protective levee advised to evacuate.	
La Marque	People outside levee, below 6 ft, and with houses that might not withstand wind advised to leave early Wednesday morning; changed to 10 ft at 2 p.m.; shelter opening announced at 10 p.m. (didn't want to encourage people to wait and see); public address systems go out at 10 p.m.	Good.
Hitchcock	Low-lying areas advised to evacuate Tuesday at 6 p.m.; evacuation of areas below 6 ft recommended.	90+%(?) leave from high-risk areas; 150 sheltered locally; group from Bayou Vista goes to Freddiesville Recreation Center, where they have to be rescued by Highland Bayou firemen.
Bolivar Peninsula	People in Crystal Bayou, Port Bolivar, and Gilchrist advised to evacuate Tuesday noon; evacuees on peninsula moved to High Island Wednesday afternoon.	75% to 90%(?).
Galveston City	West Beach residents told via media to evacuate Tuesday afternoon or Wednesday morning; at 11 p.m. Wednesday people in wood-frame houses advised to go to public shelters; areas behind seawall told evacuation is voluntary (i.e., no advice); shelters open one at a time as needed; mayor plays down threat, doesn't want to "cry wolf."	1,000 sheltered on island; 90+% leave West Beach; maybe 10% leave island altogether; damage to Galvez Hotel where many are staying.
Jamaica Beach	Police go door to door urging evacuation Tuesday afternoon.	95+% leave; most gone by Wednesday morning.

	Tuesday afternoon.	gone by Wednesday morning.
Angleton	People advised to leave Tuesday afternoon.	Most leave; one shelter full by 3 p.m. Wednesday, another by 5 p.m.; 1,500 people sheltered (diaper shortage); people move from gymnasium to hallway due to damage.

TABLE 6.7 (Cont.)

Location	Action	Response
Freeport	Told on Wednesday to leave area; no local shelters announced at first; open later.	Most leave Wednesday (50%?); shelters not crowded; many take boats up Brazos River.
Surfside, Clute, Lake Jackson	Advised to evacuate Tuesday afternoon and Wednesday morning.	90%(?) leave in Surfside; 60%(?) in Clute; 50%(?) in Lake Jackson.
Bay City	Advised to leave Tuesday afternoon.	500 in shelters by Wednesday night.
Sargent, Matagorda, Matagorda Peninsula, Palacios	Advised to leave Tuesday afternoon; public address systems go through some areas on Wednesday.	Most leave; 830 in shelters.
Port Lavaca, Comfort Point	Avised to leave at noon Wednesday; public address systems in Comfort Point.	Most leave; traffic bumper to bumper Wednesday afternoon.
Port O'Connor	Advised to leave Wednesday; ambulances with public address systems used.	Most leave dwellings; some stay on boats.
Washington County (WNW of Houston)		3,500 people in shelters.