PART 3

Burns, Fire, and Radiation

CHAPTER 14

Wildland Fires: Dangers and Survival

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> There can be few natural physical phenomena with the scope and complexity of a forest fire. The fuel that powers it is found in a huge range of sizes, quantities, and arrangements in space. The weather affects the current condition of this fuel array in a bewildering maze of drying and wetting effects, each fuel component responding to a "different drummer." The combustion process itself, once under way, responds to a complex blend of fuel variation, moisture status, topography, wind speed, and other atmospheric factors. Its frontal intensity varies over an immense range, from tiny flickers easily stepped over, to dense sheets of flame whose fierce radiation keeps the observer at a distance. —*van Wagner (1985)*

In describing the 13 wildland firefighter fatalities that occurred on the Mann Gulch Fire near Helena, Montana, on August 5, 1949, Norman Maclean[285] wrote in his award-winning 1992 book *Young Men and Fire,* "They were still so young they hadn't learned to count the odds and to sense they might owe the universe a tragedy." Three years later, Canadian folksinger-songwriter James Keelaghan, inspired by Maclean's book, paid tribute to the fallen firefighters in a haunting ballad entitled "Cold Missouri Waters." The Mann Gulch Fire has been called "the race that couldn't be won."[418] Although the crew increased their pace ahead of the fire, the fire accelerated faster than they did until fire and people converged. Miraculously, three people were able to survive the fire's wrath. Smoke jumper foreman Wagner Dodge ignited an "escape fire" by burning off a patch of cured grass,[26] into which he tried to move all his crew, while two others found a route to safety and escaped injury on a nearby rockslide.

Many improvements in a firefighter's odds of surviving an entrapment or burnover encounter with a wildland fire have occurred since 1949. These advances include improved understanding of fire behavior, increased emphasis on fire safety and fire training, and development of personal protective equipment.[143] However, as incidents such as the 14 firefighter fatalities on the 1994 South Canyon Fire in western Colorado (Figure 14-1) and in 2015 in Washington have shown, tragedies can and continue to occur.[178] Norman Maclean's son, John, would in turn write about this fatal fire 50 years later.[286] Grief over lost loved ones can sometimes lead to further tragedies. For example, one of the smoke jumpers killed on the 1949 Mann Gulch fire, Stan Reba, had been married less than a year. His widow grieved for him and never remarried, then 10 years later took her own life.[247,299]

The latest major multiple-casualty wildland firefighter fatality event to occur, the Yarnell Hill Fire in central Arizona, took place on the last day of June 2013. Nineteen members of the 20-person Granite Mountain Hotshots perished during the fire's major run.[532]

Wildland fires are a threat to human life, property, and natural resources in many regions of the world (Figure 14-2). Although the total number of deaths among the general public caused by wildland fires in modern times pales in comparison with the death toll and destruction from other natural hazards (e.g., hurricane, tornado, flood, earthquake, tsunami, avalanche)[86] and human-made disasters, the fatalities are frequent and nevertheless devastating.[488]

There are very few comprehensive summaries of deaths from wildland fires on a worldwide basis. The compilation of U.S. wildland firefighter fatalities begun in the early 1970s[536] is unique.[353] Statistics on the number of civilian or wildland firefighter fatalities from being trapped or overrun by wildland fires on a global basis are unfortunately not kept in any systematic manner.[245] It is, however, well known that more than 300 deaths caused by bushfire entrapments and burnovers occurred in the state of Victoria in Australia alone during the 20th century.[259] On Saturday, February 7, 2009, Australia experienced a bushfire disaster of unparalleled portions[491]:

> In the wake of a long drought, and on a day of high temperatures, strong winds and low humidity, bushfires swept through residential and farming communities in Victoria. Some 430,000 hectares [one million acres] of forest and farmland, countless homes and other buildings were burnt, and hundreds of millions of dollars damage were done to economic and community assets. Far more tragically, it was Australia's worst civil disaster: 173 lives were lost. February 7th 2009 has become Black Saturday, to be (one imagines) seared into the Australian psyche for generations to come.

On the fatal day, more than 300 fires were reported across the state. Fifteen of these developed into major incidents, with the most extensive damage and loss of life resulting from four fires.[142,203,311] The Kilmore East Fire alone was responsible for 70% of the 173 deaths that occurred.[162] A royal commission was established soon afterward to investigate the causes and responses to these fires (www.royalcommission.vic.gov.au/). The commission's final report, issued at the end of July 2010, sets out 67 recommendations for protecting human life, "designed to reflect the shared responsibility that governments, fire agencies, communities, and individuals have for minimizing the prospect of a tragedy of this scale ever happening again."[477] In their report, the commissioners offered a warning: "It would be a mistake to treat Black Saturday as a 'one-off' event" because "the risks associated with bushfires are likely to increase."

Given the occurrence of other major wildfire disasters involving significant loss of life among civilian populations in recent years—for example, Greece in August 2007 (84 fatalities),[545,546] western Russia during the 2010 summer fire season (63 fatalities),[218] Mount Carmel in northern Israel in December 2010 (44 fatalities),[531] and Valparaiso, Chile, in April 2014 (15 fatalities)[412]—this prediction has global application.

This chapter describes the current look at fire as a historical force and discusses fire management policies, the nature and scope of wildland fire hazards, behavior of fires, typical injuries, fatality fire statistics, several fatal fire incidents, and survival techniques. Although the emphasis is on North America, reference is made to other regions of the globe, most notably Australasia and Europe. Wildland fire, like many other disciplines and subjects, has its own unique terminology, so readers may need to consult glossaries.[198,313,359,456]

WILDLAND FIRE MANAGEMENT AND TECHNOLOGY

Programs for dealing with the overall spectrum of fire are collectively termed *fire management.*[58] They are based on the concept that fire and the complex interrelated factors that influence fire phenomena can and should be managed to the extent

FIGURE 14-1 Flame front spreading upslope through Gambel oak *(Quercus gambelii)* and pinyon *(Pinus edulis)*–juniper *(Juniperus monosperma)* fuel complex during the major run of the South Canyon fire in western Colorado on the afternoon of July 6, 1994. Approximately 2½ minutes after this photograph was taken, the first of 14 firefighters was overtaken by the advancing flames, estimated to have traveled 110 to 165 m/min (360 to 540 ft/min). *(Courtesy USDA Forest Service; photo by S. Archuleta.)*

that they can. The scientifically sound fire management programs that respond to the needs of people and natural environments must also maintain full respect for the power of fire.

Since the early 1900s, federal, state, and local fire protection agencies in the United States, for example, have routinely extinguished wildfires to protect watershed, range, and timber values, as well as human lives and property. The basic methods of fire suppression[219,280] have changed very little, although new technologies have gradually been implemented (Figure 14-3). However, improvements in fire detection, fire danger rating systems, and fire suppression methods have been developed by fire science laboratories and two equipment development centers maintained by the U.S. Department of Agriculture (USDA) Forest Service, as well other organizations (e.g., state agencies and universities). Patrol planes, some with infrared heat scanners, other fixed-wing aircraft (Figure 14-4), and helicopters (Figure 14-5), can deliver firefighters, equipment, and fire-retarding chemicals or water to the most remote fire. These firefighting resources are organized under an Incident Command System that can easily manage simple to complex operational, logistic, planning, and fiscal functions associated with wildfire suppression actions.[117,192,346] Many other countries have followed a somewhat similar path in their evolution with regard to wildland fire suppression and supporting research and development.[396-398,401]

Modern fire suppression technology, however, cannot indefinitely reduce the area burned by wildfires, as demonstrated by numerous large fires and major fire seasons in the past 35 years or so in North America, specifically the United States and Canada. This includes, to name a few: Mack Lake Fire in Michigan in 1980; the "Siege of '87" in California in 1987; Silver Complex in Oregon in 1987; Greater Yellowstone Area fires in 1988; Stanislaus Complex in California in 1989; Foothills Fire near Boise, Idaho, in 1992; Garnet Fire near Penticton, British Columbia, in 1994; Millers Reach Fire in Alaska in 1996; Virginia Hills Fire in Alberta in 1998; Florida fires of 1998; Silver Creek Fire in British Columbia in 1998; Cerro Grande fire in New Mexico in 2000; Valley Complex in Montana in 2000; Chisholm Fire in Alberta in 2001; Biscuit Fire in Oregon in 2002; Hayman Fire in Colorado in 2002; Rodeo/Chedeski Fire in Arizona in 2002; House River Fire in Alberta in 2003; "Firestorm 2003" season in British Columbia; record-setting fire seasons in Alaska and the Yukon Territory in 2004 (Figure 14-6); the Slave Lake Fire in Alberta in 2011; and the 2014 fire season in the Northwest Territories, Canada. Similar incidents have occurred in other regions of the world. The hard lesson learned from these and other incidents is that conflagrations or large wildfires are inevitable unless mitigation measures are taken. Several factors have coincided to produce massive forest mortality, including drought, epidemic levels of insects and diseases,[250,333,337] and unnatural accumulations of fuels at the stand level and at a growing landscape scale in some but not necessarily all vegetation types,[252] as a result of policies and practices of attempted fire exclusion.[16,221] The resulting dry forest type of areas in the western United States was foreshadowed by a forester, Harold Weaver,[517] in the early 1940s. Many agencies are now using prescribed fire more frequently, deliberately burning under predetermined conditions to reduce accumulations of fuels and to protect human life, property, and other values that are at risk by wildfire.[315,334,368]

Research has indicated that fires are not categorically "bad."[432] In fact, many plant communities in North America are highly flammable during certain periods in their life cycle.[84] For example, annual grasses, ponderosa pine, and chaparral plant communities

FIGURE 14-2 Wildland-urban interface fire in the Amarante region of Portugal on August 5, 2005. Drought conditions contributed to an exceptionally severe fire season in southern Europe during 2005. Twelve firefighters and 10 civilians were killed in Portugal. Eleven firefighters were killed in one separate incident in a nature reserve in the Guadalajara area east of Madrid, Spain, on July 17, 2005. *(Courtesy* Publico *newspaper; photo by Paulo Ricca.)*

FIGURE 14-3 A helitorch, or flying drip torch, is a specialized aerial ignition device slung below and activated from a helicopter (**A**). It dispenses and ignites gelled fuel. The use of a helitorch in wildfire suppression operations can take many forms (e.g., to reduce fire intensity; to slow or steer a fire; to remove potentially dangerous fuel concentrations; to widen and strengthen control lines; to expedite mop-up operations). Regardless of its specific purpose, the main objective of this application of "fighting fire with fire" is to speed up or strengthen control actions (**B**). Aerial backfiring and burning out with a helitorch can be one of the safest, most economic, fastest, and least damaging means of widening control lines and constitutes one of the major innovations in wildland fire suppression technology in the past 35 years. The helitorch is also used in prescribed burning operations. *(Courtesy Alberta Sustainable Resource Development and Wildfire Consulting Ltd, Edmonton, Alberta; photos by O. Spencer and W. Bereska.)*

are flammable during almost every dry season. Other communities, such as jack pine or lodgepole pine forests, although fire resistant during much of their life cycle, eventually become fire prone when killed by insects, diseases, and other natural causes. The spread of non-native grasses, such as cheatgrass and red brome, in the arid regions of the western United States has increased the frequency of fires in desert shrublands.[549]

Wildland fires can benefit plant and animal communities. Evolutionary development produces plant species well adapted to recurrent fires. Fire tends to recycle ecosystems and maintain diversity.[279,543] Thus, there is growing consensus that fire should be returned to many wildland ecosystems, where appropriate, to perpetuate desirable fire-adapted plant and animal communities and to reduce fuel accumulations.[251]

A landmark report in 1963 to the U.S. National Park Service by the Advisory Board on Wildlife Management described how the western slope of the Sierra Nevada had been transformed by a policy of forest fire protection over the preceding approximately 100 years[271]:

> When the forty-niners poured over the Sierra Nevada into California, those that kept diaries spoke almost to a man of the wide-spaced columns of mature trees that grew on the lower western slope in gigantic magnificence. Today much of the west slope is a dog-hair thicket of young pines, white fir, incense-cedar, and mature brush—a direct function of overprotection from natural ground fires. Not only is this accumulation of fuel dangerous to the giant sequoias and other mature trees, but the animal life is meager, wildflowers are sparse, and, to some at least, the vegetative tangle is depressing, not uplifting.

It must also be acknowledged that in some cases, past logging practices contributed to the resulting fuel structure. Nevertheless, the board recommended that the Park Service recognize in management programs the importance of the natural role of fire in shaping plant communities.[422]

WILDLAND FIRE MANAGEMENT POLICIES

Significant wildfire tragedies in the western United States have focused attention on the need to reduce hazardous fuel accumulations.[460] The events associated with the 1994 fire season created a renewed awareness and concern among federal land management agencies about wildfire impacts, leading to a combined review of fire policies and programs. The result was enactment of a new interagency federal wildland fire management policy, which provided a common approach to wildland fire among federal agencies and called for close cooperation with tribal, state, and other jurisdictions.[351] The principal points of the 1995 federal wildland fire policies are as follows:

- Firefighter and public safety remains the first priority in wildland fire management. Protection of natural and cultural resources and property is the second priority.
- Wildland fire, as a critical natural process, must be reintroduced into the ecosystem, accomplished across agency boundaries, and based on the best available science.
- Where wildland fire cannot be safely reintroduced because of hazardous fuel accumulations, pretreatment must be considered, particularly in the wildland-urban interface.
- Wildland fire management decisions and resource management decisions are connected and based on approved plans. Agencies must be able to choose from the full spectrum of actions, from prompt suppression to allowing fire to have an ecologic function.

FIGURE 14-4 Specialized fixed-wing aircraft such as the amphibious CL-415 "superscooper" are capable of delivering water and chemical fire retardants on or near a wildfire. Although such planes are used in sustained-action situations on isolated sectors of large fires, they are most effective in initial attack operations during the incipient phase of fire growth. In such cases, their primary purpose is to slow down the progress of the fire until such time as ground suppression resources are able to arrive and effect direct containment. Wing-tip vortices are created in the wake of low-flying aircraft. These vortices gradually dissipate as they descend to the ground level. They can cause a sudden, unexpected increase in fire activity as a result of the momentary wind gust. This can pose a threat to anyone located near the fire perimeter. *(Photo by T. Nebbs.)*

FIGURE 14-5 Several different sizes and models of rotary-wing aircraft or helicopters are used in a wide variety of direct roles as well as support functions in wildland fire suppression, including the dropping of water or fire-retarding chemicals directly on the fire. Helicopters also create wake vortices while in forward motion, just like airplanes, but generally these vortices are much weaker. A more common safety issue with helicopters is the downward induced air flow or rotary downwash. Some downwash effects are unavoidable when helicopters are engaged in direct attack on the fire with water or chemicals. Anyone located near the fire perimeter during such operations could be at risk. Even with a "long line" delivery system operated from a Bell 212 helicopter, as illustrated here on the Anarchist Mountain Fire near Osoyoos in southern British Columbia on July 16, 2003, rotary downwash can still be a significant issue. *(Courtesy Alberta Sustainable Resource Development.)*

- All aspects of wildland fire management will involve all partners and have compatible programs, activities, and processes.
- The role of federal agencies in the wildland-urban interface includes firefighting, hazardous fuel reduction, cooperative prevention and education, and technical assistance. Ultimately, the primary responsibility rests at the state and local levels.
- Structural fire protection in the wildland-urban interface is the responsibility of tribal, state, and local governments.
- Federal agencies must better educate internal and external audiences about how and why we use and manage wildland fire.

The 1995 U.S. federal wildland fire management policy was reviewed and updated in 2001,[356] following a particularly severe fire season in the western United States the previous year; about 2.8 million hectares (7 million acres) were burned over by about 89,000 fires during the 2000 fire season in the United States.[497] Results of the 2001 review and update were defined in the "2003 Interagency Strategy for the Implementation of Federal Fire Management Policy."[266] This strategy broadened the scope of fire management to balance fire suppression with management for ecologic benefits and supports the use of the full range of fire management activities to achieve ecosystem stability, including fire use. The 2003 implementation strategy stresses the need to complete or revise fire management plans that are more effectively and directly integrated with other natural resource goals.[80] One of the other outgrowths of the 2000 fire season was the National Fire Plan (www.forestsandrangelands.gov/resources/overview/), which calls for the following actions:

- Ensuring that necessary firefighting resources and personnel are available to respond to wildland fires that threaten lives and property
- Conducting emergency stabilization and rehabilitation activities on landscapes and communities affected by wildland fire
- Reducing hazardous fuels (dry brush and trees that have accumulated and increase the likelihood of unusually large fires) in U.S. forests and rangelands
- Providing assistance to communities that have been or may be threatened by wildland fire
- Committing to the Wildland Fire Leadership Council, an interagency team created to set and maintain high standards for wildland fire management on public lands

It is clear from these objectives that one of the major foci of the U.S. National Fire Plan is the human dimension of wildfire (i.e., rural homeowners and communities).[246,283]

The 2003 implementation strategy was further revaluated in 2008, leading to another review and update. This resulted in the 2009 Guidance for Implementation of Federal Wildland Fire Management Policy (www.nifc.gov/policies/policies_documents/GIFWFMP.pdf). This update reaffirmed that the 1995 Federal Fire Policy remains sound and presents a single, cohesive federal fire policy for the USDA and Departments of the Interior. It provides the highest degree of flexibility ever afforded to managers and facilitates their ability to respond to changing conditions and complexities of a wildfire event. However, some communications issues were identified involving inconsistent terminology, which this update corrected. One of the most significant changes was removal of the distinction between "wildland fire use" and "wildfire."[266]

The latest development in the evolution of wildland fire management policy in the United States is a comprehensive strategic plan, the National Cohesive Wildland Fire Management Strategy (NCWFMS) (www.forestsandrangelands.gov/strategy/). Its focus is to promote a collaborative working relationship among all stakeholders and across all landscapes, using the best science to make meaningful progress toward the following goals:

1. Restored and maintained landscapes
2. Fire-adapted communities
3. Safe and effective wildfire response

FIGURE 14-6 Swan Lake Fire in northern British Columbia (near border with Yukon Territory) during midafternoon on June 23, 2004. Such high-intensity fire events continue to spread until such time as burning conditions ameliorate, as when a change in weather conditions (e.g., winds die down) or fuel type (e.g., leafed-out hardwood stand) occurs, or a wide, natural barrier to fire spread is encountered (e.g., large lake or river). The natural fire regime in the boreal forest of Canada and neighboring Alaska is characterized by the periodic occurrence of large crown fires. In the Yukon, for example, the average area burned over the past 25 years has been about 120,000 hectares (297,000 acres) per year. During the 2004 fire season, a record-setting 1.7 million hectares (4.2 million acres) and 2.7 million hectares (6.7 million acres) were burned over in the Yukon and Alaska, respectively. *(Courtesy Yukon Government, Department of Energy, Mines, and Resources; photo by M. Clark.)*

The NCWFMS's stated vision is, "To safely and effectively extinguish fire when needed; use fire where allowable; manage our natural resources; and as a nation, to live with wildland fire." The final phase of the NCWFMS was completed in April 2014.[232] Both the Federal Wildland Fire Management Policy and the NCWFMS emphasize the importance of risk and risk management as a sound foundation for wildland fire programs.

In 2005 the Canadian Council of Forest Ministers issued the Canadian Wildland Fire Strategy Declaration (www.ccmf.org/english/coreproducts-cwfs.asp),[111] which is based on principles of risk management and hazard mitigation. This strategy strives to balance public safety, forest protection and health, and fire management expenditures, to maintain a strong and effective fire suppression organization, but it also includes innovative hazard mitigation, preparedness, and recovery programs. In other words, this is a more holistic view of wildland fire envisioned about 45 years ago as land management agencies made the transition from fire control to fire management. This strategy recognizes the need for shared responsibility among the various stakeholders (i.e., property owners, industries, and local, provincial, and federal governments).[241] One of the guiding principles of this new declaration was that "public safety—including the safety of firefighters—is paramount."

Fire management policies similar to those of the United States and Canada exist in other parts of the world.[199] The Food and Agriculture Organization of the United Nations[200] prepared a generic set of fire management guidelines to serve as a basis for developing policies. The Fire Paradox project, a research initiative supported by the European Commission from 2006 to 2010,* examined wildland fire from multiple perspectives as a basis for influencing policies on integrated fire management.[443]

PRESCRIBED FIRE AND WILDLAND FIRE USE

Prescribed fire, the intentional ignition of grass, shrub, or forest fuels for specific purposes according to predetermined conditions, is a recognized land management practice.[36,512,525] The objectives of such burning vary: to reduce fire hazards after logging, expose mineral soil for seedbeds, regulate insects and diseases, perpetuate natural ecosystems, and improve range forage and wildlife habitat.[321,518] In some areas managed by the National Park Service, USDA Forest Service, and Bureau of Land Management, naturally ignited fires may be allowed to burn according to approved prescriptions; fire management areas have been established in national parks and wildernesses from the Florida Everglades to the Sierra Nevada in California (Figure 14-7). Planned-ignition prescribed fires are also carried out. Similar policies exist in Canadian National Parks.[235] Visitors are increasingly aware that wildland fires can be an important part of the natural cycle of an ecosystem, and that the future health of wilderness areas and parks may depend in part on today's managed fires.[314]

FIGURE 14-7 Lightning-ignited fires in some wilderness areas and national parks in the United States that meet certain criteria have been allowed to burn freely under observation since the early 1970s as part of a fire management strategy to allow natural ecosystem processes to operate more freely. *(Courtesy USDA Forest Service.)*

WILDLAND-URBAN INTERFACE: NEW LOOK AT A HISTORICAL PROBLEM

Just as resource agencies are attempting to provide a more natural role for fire in wildland ecosystems, the general public is increasingly living and seeking recreation in many of these same areas. The area where houses and other human-made structures meet or are intermingled with wildland vegetation is regarded as the wildland-urban interface, or intermix (WUI; pronounced "woo-ee"), although other names have been used (Figure 14-8). It is a growing problem from a wildland fire perspective in the United States,[76,405,485] Canada,[220,239] and many other regions of the world,[175,263] As mentioned earlier, past fire exclusion practices in the United States have allowed abnormal fuel accumulations in some forest types and regions, and this fact has combined with the sacrifice of relatively safe perimeter fire suppression strategies in favor of directly protecting people and their possessions.[535] Direct suppression actions within the fire's perimeter place firefighters at a greater disadvantage from a safety standpoint. The new interagency policy that emphasizes firefighter and public safety as the first priority will result in less effort to save structures in dangerous situations. Thus, what is known of fire behavior

FIGURE 14-8 Fire in the wildland–urban interface, or intermix. This particular wildfire occurrence took place on the outskirts of Kamloops, British Columbia, during the afternoon of July 26, 2007. The fire is spreading through ponderosa pine *(Pinus ponderosa)* in the "red attack" stage as a result of being killed by mountain pine beetle *(Dendroctonus ponderosae)* following attack one year earlier. *(Courtesy British Columbia Ministry of Forests and Range; photo by J. Hodge.)*

*www.researchgate.net/publication/253642532_FIRE_PARADOX_A_European_initiative_on_Integrated_Wildland_Fire_Management).

and fire survival principles must be readily available to emergency medical personnel, wildland dwellers, and recreationists. In fact, fire protection agencies and others have been making such information more readily available to the general public for some time now,[118,169,201,519] although much more needs to be done.[17]

NATURE OF THE PROBLEM

Hot, dry, and windy conditions annually produce high-intensity fires that threaten or burn homes where wildland and urban areas converge (Box 14-1). Can the historical levels of destruction, injury, and fatality be repeated today in the face of modern fire suppression technology? The answer to this question requires an analysis of the conditions, for example, that created such high-intensity fire behavior events in the forests of northern Idaho and northwestern Montana during late August 1910, in which 85 people, including 78 firefighters, were killed.[139,187,399,455] (Figures 14-9 and 14-10).

The earliest fire incident of note involving a large loss of human life was the series of conflagrations in the Miramichi region of New Brunswick and adjacent areas in Maine in early October 1825, in which at least 160 people[144,388] perished.[282,489] This was followed by several fatality fires in the U.S. Lake States region, including the Peshtigo and area fires (www.peshtigofire.info/) in eastern Wisconsin in October 1871 (about 1300 fatalities),[238,272,526] the Lower Michigan fires of September 1881 (169 fatalities),[243] the Hinckley Fire in east-central Minnesota in September 1894 (418 fatalities),[264] the Baudette Fire in northern Minnesota in October 1910 (42 fatalities),[388] and the Cloquet Fire in Minnesota in October 1918 (538 fatalities).[112,243] The western United States experienced other fatality fires, such as in western Washington and Oregon in mid-September 1902 (38 fatalities).[83,309] Canada suffered similar tragedies.[24] For example, the province of Ontario experienced several significant settler-related wildfire fatalities in 1911, 1922, and 1938, including the 1916 "Matheson Holocaust" in which as many as 400 people were killed.[56,166,308] In 1908, a forest fire destroyed the city of Fernie, British Columbia; 22 people were reported killed.[289]

Other countries, such as New Zealand[312] and France,[201] are reported to have suffered similar but varying losses in the 20th century. In Australia, for example, possessing some of the world's most fire-prone environments,[119] 71 lives were lost in the state of Victoria on "Black Friday" in January 1939.[201,364] On August 1, 1959, 48 people were reported killed by a forest fire northeast of Massif des Aures, Algeria.[245] In early September 1963, forest fires swept about 2 million hectares (4.9 million acres) in Paraná State in southern Brazil, destroying more than 5000 homes and

BOX 14-1 What Is It Like to Experience a Wildland-Urban Interface Fire? A Town That Nearly Went . . . Up in Smoke by D. Blasor-Bernhardt[71]

Tok, Alaska, July 1, 1990, 15 to 30 minutes after the lightning strike that started the Tok Fire. *(Photo by D. Blasor-Bernhardt.)*

July 1, 1990, started out like any other Sunday, but it quickly turned Tok, Alaska, into a near raging inferno. I was working at the Chamber of Commerce Main Street Visitor Centre when an otherwise beautiful day suddenly turned black and foreboding. Blowing in, a huge thundercell hung just southeast of town.

I stepped outside just in time to see a long, crooked finger of electricity split from an ominous cloud and drill its way into Earth. Minutes later, where the lightning had hit, a mushroom-shaped cloud began to grow. I grabbed my camera and snapped a few shots.

Five days later, and in spite of several thousand firefighters and equipment from all over Alaska, Canada, and the States, Tok was completely under siege and at risk of being cremated. The wind-blown inferno licked greedily at several unoccupied dwellings, then consumed them. East-side residents were evacuated. We, on the west side, were told to pack our things, to be ready to leave, and to await further instructions.

Tok was enveloped on two sides by fire—from the eastern and northern directions. My log home was about a mile from the north front of the fire. I stood on the cabin's sod roof, watching the fire, when the kids and extended family converged there about the same time, looking to me for instructions. All day, I had the sprinklers and hoses running full blast over the cabins, garage, and surrounding area. By now, the area looked like a swamp. Good. I'd leave them on, even if we evacuated, in the hope that it would help save some of our place from destruction.

Smoke stifled each breath. Helicopters screamed back and forth carrying people, equipment, and large buckets of water.

There was no fear, no panic, in anyone—just resignation. And there was no way our town would be destroyed.

I told the kids to first pack up whatever was closest to their hearts—it didn't matter how silly an item seemed if that made them feel good. The first thing I placed in my own car was my late husband's ashes. I couldn't bear to leave him behind. Next, we would take irreplaceable things: photo albums, mementos. Then down to brass tacks: the necessary things for survival and rebuilding in the event we were burned out. Bombers loaded with retardant flew directly overhead. We were in a war zone—man against fire.

The girls loaded their cars with personal items. Mine was loaded with blankets, groceries, and clothing. The boys readied our tandem-axle trailer, loading it with items from the garage—chainsaws, tools, portable generator, water jugs. If the fire drew too near and we had to evacuate, the plan was for the girls and I to load our pets while the boys quickly cut the trees down around the cabins, hopefully providing a bare, wet perimeter between them and the fire.

Fully loaded, we assembled in the driveway, ready for word to come. Besides myself, six young adults, a baby, half a dozen dogs, numerous cats, a snake, six vehicles, and a trailer comprised the Bernhardt entourage. We were ready. We waited in the foul air, our eyes smarting from the smoke. An ember hit me on the shoulder, burning a hole though my shirt. Sadly, I turned to look at our homes one last time. Tomorrow they would be gone.

Imperceptibly at first, a slight shift in the wind began. I held my breath. "Mom?" my son said. "Yes," I answered, "but I'm afraid to hope." The wind, definitely shifting now, was no longer blowing toward us. A sweet, light rain began to fall. While the eight of us stood together, soaking wet in the rain, a trooper came by to tell us the worst was over.

In all, the fire burned 109,501 acres (44,314 hectares) at a cost of over $35 million (U.S.), yet not one person had been injured, not one occupied dwelling destroyed, and Tok had been spared by a miracle wind.

From Blasor-Bernhardt D: A town that nearly went . . . up in smoke, *Guide to the Goldfields and Beyond* (Harper Street Publishing, Dawson City, Yukon Territory) Summer: 52, 1997.

FIGURE 14-9 These burned-over and wind-thrown trees resulted from the intense fire behavior associated with a forest fire near Falcon, Idaho, in August 1910. *(Courtesy USDA Forest Service; photo by J.B. Halm.)*

killing 110 people.[451] More than 100 people were killed by extensive forest and savannah fires in Cote D'Ivoire (Republic of Ivory Coast) on the southern coast of western Africa during the 1982–1983 fire season.[431]

On October 8, 1871, the same day that fire wiped out the town of Peshtigo, Wisconsin, and surrounding communities, the Great Chicago Fire devastated urban Chicago.[526] Comparative statistics for those two fires highlight the destructive potential of wildland fires. In every way, the Peshtigo conflagration was far worse than the Chicago blaze. The Peshtigo Fire covered about 518,000 hectares (1,280,000 acres) and as indicated earlier, killed approximately 1300 people, whereas 906 hectares (2240 acres) burned and some 200 lives were lost as a result of the corresponding urban fire.[227] The Great Chicago Fire is generally acknowledged as the birthplace of modern urban fire prevention. As Lloyd[277] notes, "Mention the name Peshtigo to most people and all you get is a blank stare. Mention Mrs. O'Leary's cow to the same person and they will think right away of the Great Chicago fire," and "Some of the same social misconceptions that allowed Peshtigo to be all but forgotten persist today." So, it is perhaps fitting to consider the following poem entitled "The Peshtigo Calamity"[243]:

As the years roll along and the ages have sped
O'er the charred, blackened bones of the Peshtigo dead,
And the story is told by the pen of the sage,
In letters immortal on history's page—
No fancy can compass the horror and fright
The anguish and woe of that terrible night.

The August 1910 wildfires in northern Idaho and western Montana had several elements in common with the Peshtigo fires of 1871: many uncontrolled fires burning at one time; prolonged drought, high ambient air temperatures, and moderate to strong winds; and mixed conifer and hardwood fuels with slash from logging and land clearing. These large fires occurred primarily in conifer forests north of the 42nd meridian, or roughly across the northern quarter of the contiguous United States.[83] One of these critical elements that is not as likely to occur currently as formerly is the simultaneous presence of several hundred uncontrolled fires. The effectiveness of modern fire suppression organizations is now able to reach even the most remote wildland locations. High-velocity winds and more than 1600 individual fires contributed to the spread of the fires in 1910; it is unlikely that a multifire situation of that magnitude would occur today.[82,119] However, multiple fire starts are still possible because of human-caused ignitions (e.g., arson, power lines). For example, on October 16, 1991, 92 separate fires occurred in the Spokane region of eastern Washington[343] in the space of a few hours under the influence of exceedingly strong winds.[32] Prolonged drought, high winds, and flammable fuel types, however, remain significant to the behavior of high-intensity fires.

Some of the fires most potentially damaging to human lives and property occur in areas rich in the chaparral shrub fuel complexes in southern California. Wilson[535] and Phillips[386] described the severe 1970 fire season in California, in which official estimates showed that 97% of 1260 fires occurring between September 15 and November 15 were held to less than 121 hectares (300 acres). The other 3% of the fires, fueled by a prolonged drought and fanned by strong Santa Ana winds, produced 14 deaths, destroyed 885 homes, and burned about 243,000 hectares (600,000 acres), as chronicled in the 1971 film *Countdown to Calamity*. Ten years later, the situation recurred over 9550 hectares (23,600 acres) in southern California, the Panorama Fire in November 1980, which resulted in the deaths of four people and loss of more than 325 structures.[108]

On October 20, 1991, a devastating fire "of unprecedented force blew out of control"[4] in the hills above Oakland and Berkeley, California. Burning embers carried by high winds from the perimeter of a small fire resulted in a major WUI conflagration. The impact on people and their possessions was enormous.[4,469] The fire resulted in direct deaths of 25 people, including a police officer and a firefighter, injured 150 others, destroyed 2449 single-family dwellings and 437 apartment and condominium units, burned about 650 hectares (1600 acres), and did an estimated $1.5 billion in damage.[342] The scenario for disaster included a 5-year drought that had dried out overgrown grass, shrubs, and trees, making them readily ignitable. Other factors included untreated wood shingles, unprotected wooden decks that projected out over steep terrain, low relative humidity, high ambient air temperatures, and strong winds that averaged 32 km/hr (20 miles/hr) and gusted up to 56 to 80 km/hr (35 to 50 miles/hr).

FIGURE 14-10 Burned ruins of the foundry in Wallace, Idaho, furnish mute testimony to the destructive force of the 1910 fires. The cottage on the terrace was the only one left standing in that part of town. Of the 85 people reported killed in the "Big Blowup of 1910," 78 were firefighters. *(Courtesy USDA Forest Service; photo by R.H. McKay.)*

The area had not experienced any rain for 67 days before the major fire run, although mean monthly maximum air temperatures in the 6 months preceding the fire were not appreciably high, 18° to 23° C (64° to 73° F).[33] These severe conditions produced a voracious fire that consumed 790 homes in the first hour. Winds lessened to 8 km/hr (5 miles/hr) by the first evening, which assisted with the containment of the fire. Firefighters had the situation under control by the fourth day, but not before they had been given an awful glimpse of the nature of WUI fires in the future. In late October 2003, fires in southern California burned over 300,000 hectares (742,000 acres) in 1 week alone, taking 23 lives and destroying more than 3300 homes.[107,253,336]

In recent times, wildland fire fatalities among the general public have not been restricted to just California, or the United States for that matter. Four civilians were killed as a result of the massive forest conflagration that converged on the outskirts of Canberra, Australia, in January 2003.[3] During summer 2003 in Portugal, 21 people lost their lives in 18 different fire incidents.[506,509] On January 11, 2005, nine people (including four children and two firefighters) perished on the Eyre Peninsula of South Australia as a result of being overrun by an extremely fast-spreading grass fire in what is now referred to as "Black Tuesday" in the state.[129,447,454] Mutch and Keller[338] give a compelling account of the wildfires that occurred in Texas and Oklahoma during late 2005 and early 2006, in which 19 civilians and six firefighters died.

In many parts of the world, but especially in the United States and Canada, the primary response has been to evacuate all people threatened by wildfires.[1,140,404] For example, more than 200,000 people were evacuated in Canada between 1980 and 2007 in more than 500 separate incidents.[70] The pros and cons of evacuation are extensively discussed in Chapter 12 of Webster's seminal work,[519] *The Complete Bushfire Safety Book,* entitled "The Decision—Evacuate or Stay? Safety or Suicide?" In this regard, Phil Cheney,[123] a renowned Australian bushfire research scientist, states, "What it comes down to is a civil right to risk your own life to save your house. I personally am in favor of people taking risks in their lives provided that they also bear the responsibility for the consequences."

Some amazing logistic feats have taken place to date without incident using both ground and air transportation. A good example of the latter occurred in early June 1995 as the residents of Fort Norman and Norman Wells in Canada's Northwest Territories were airlifted to Yellowknife, the territorial capital.[167] However, statements later on from the public (e.g., "I think they took us away just in time") suggest that this approach is not infinitely infallible. Coupled with this reality is the fact that modern fire records indicate that the vast majority of area burned by wildfires is the result of a small percentage of fires.[466] Thus, on some days, adverse fuel and weather conditions, coupled with an ignition source, will conspire to produce conflagrations that occur despite our best fire prevention, detection, and initial attack efforts. Climate change will only exacerbate the situation.[196] Recent research involving simulations of evacuations in response to a threatening wildfire has revealed that strategic planning is essential.[157-159,170] Communities need to ensure that they are fully prepared well in advance of a threatening wildfire occurrence by developing individual and local government emergency action plans.[378] Taylor[473] has emphasized that managing the fire risk at the WUI is a shared responsibility involving both private citizens and numerous government agencies.

Past fire experiences in Australia[374,519] have demonstrated that often "houses protect people and people protect houses." Research had demonstrated that a well-prepared house can provide protection from fire, and that the presence of people prepared to defend against their home burning down is the most significant factor in determining its survival (Table 14-1). Obviously, zones of defendable space around homes must be established in advance of fires; young people, older adults, and infirm persons are generally encouraged to leave well ahead of the fire. Communities at risk from wildfires should be encouraged to be responsible for their own safety, because fire service personnel may not be available when burning conditions are severe. The major issue is whether able-bodied residents should stay and

TABLE 14-1 Approximate Probabilities of a House Surviving a Wildland Fire*

Scenario A: Total disregard for any fire safety precautions
Scenario B: Fire safety precautions taken only in regard to fuels surrounding house
Scenario C: Fire safety precautions taken only in regard to the house itself
Scenario D: All reasonable fire safety precautions to and near the house taken

	Without Persons in Attendance Fire Intensity Class (kW/m)				With Persons in Attendance Fire Intensity Class (kW/m)		
Scenario	**500-1500**	**1500-10,000**	**10,000-60,000**	**Scenario**	**500-1500**	**1500-10,000**	**10,000-60,000**
A	14.4%	1.2%	0.3%	A	29.9%	10.3%	2.3%
B	16.0%	4.9%	1.0%	B	63.6%	32.1%	8.9%
C	26.1%	8.7%	1.9%	C	76.5%	46.8%	15.3%
D	59.1%	28.1%	7.4%	D	93.0%	78.2%	42.6%

kW/m × 0.29 = BTU/sec-ft
The following attributes were considered in the above scenarios:

	Scenario			
House and Surrounding Fuel Conditions	**A**	**B**	**C**	**D**
Flammable objects nearby (e.g., firewood heap)?	Yes	No	Yes	No
Wooden shingle roof?	Yes	Yes	No	No
Nonwooden or nontile roof with pitch >10 degrees?	No	No	Yes	Yes
External walls made of brick, stone, or concrete?	No	No	Yes	Yes
Trees (5+ m high) within 40 m of house?	Yes	No	Yes	No

From Alexander ME: *Proposed revision of fire danger class criteria for forest and rural areas in New Zealand,* ed 2, Christchurch, New Zealand, 2008, Scion Rural Fire Research Group. www.scionresearch.com/fire.
m × 3.3 = feet.
*Based on a logistic regression model as developed from an analysis of 455 houses, which were completely destroyed, threatened, or sustained minor damage by the bushfire that swept through the township of Mount Macedon in Victoria, Australia, on the evening of Ash Wednesday (February 16) in 1983.[537,540]

defend or "fight" for their homes, or "flee" in the hopes of escaping an advancing fire.[539]

In the late 1990s, the Tasmania Fire Service had a policy that provided guidance on bushfire safety and evacuation decision making called "Prepare, Stay, and Survive."[213] When there was a threatening wildfire, people were told to go home and assist in the protection of their property. Because human lives and property values are at risk when threatened by wildfires, exemplary cooperation and teamwork are required to ensure adequate safety margins. Team members identified for reducing the loss of life and property include state agencies, local government, the communities, and individuals.

The "Stay or Go" policy concerning evacuation was advocated by the Australasian Fire Authorities Council (AFAC)[48] as a fundamental component of community bushfire safety in Australia.[233] Variants to this general theme exist (e.g., "prepare, leave early, or stay and defend"). However, the essence of the approach urges people to make the decision to prepare themselves and their properties to "stay" and defend when a wildfire is likely, or to "go" well before a fire is likely to arrive. Although early evacuation may contribute to increased personal safety, bushfire property losses are likely to increase. Conversely, late evacuation may put people at greater risk than had they stayed in the house as the fire passed around them.

An evaluation of this policy was the focus of Project C 6—Evaluation of Stay or Go Policy undertaken by the Australian Bushfire Cooperative Research Centre (www.bushfirecrc.com/), led by co-project leaders John Handmer, RMIT University, and Alan Rhodes, Country Fire Authority of Victoria. Fire management agencies and the public alike will find the final results of this research project of great interest. The preliminary results generally supported the 2005 AFAC position, while recognizing that implementation issues remained.[90,92,231,236,278,482] However, the fires of February 7, 2009, in Victoria, Australia, and in turn the Royal Commission's report[477] have changed the context for this approach quite significantly. There are a number of emerging issues (e.g., limit of validity), so the policy is most likely to evolve in coming years[414] in the aftermath of the Black Saturday fires, as evidenced by AFAC's revised position on bushfire community safety based on emergency risk management principles.[52]

The 2009 Black Saturday fires have placed an urgent emphasis on the continuing debate over what constitutes the safest strategies for survival in the WUI. The Victorian fires led to the creation of a catastrophic, or "Code Red," level of fire danger. When this category of fire danger is forecast for the next day, it is recommended that people in a high-risk bushfire area leave the night before or in the early morning (www.cfa.vic.gov.au/warnings-restrictions/). At the next two lower levels ("Extreme" and "Severe"), it is recommended to stay only if one's home is well prepared, well constructed, and can be actively defended.

Testimony by John Handmer before the 2009 Victorian Bushfires Royal Commission,[477] coupled with analyses produced by his research team,[230] indicate that only a small percentage of homes and property were adequately prepared to be fire resistant. Without preparing a fire-resistant home and property in advance, the only prudent course of action is to evacuate early.

This issue of whether to "prepare, stay, and defend" or evacuate early is a subject considered worthy of more open debate and discussion in North America.[17,307,339,379,459] Two communities in the United States—Painted Rocks in Montana and Rancho Sante Fe in California—have adopted variations of the original Australian model of "Prepare, Go Early or Stay and Defend."[339] Both communities have had the "Stay and Defend" practice successfully tested by wildfires. Both U.S. communities are carefully monitoring the lessons learned from the 2009 Black Saturday fires to determine if any change is needed in their approach. Meanwhile, Ready, Set, Go! (RSG) was rolled out as a full-scale pilot program by the Ventura County Fire Department and the Orange County Fire Authority for the 2009 fire season in Southern California. Other fire departments, such as Los Angeles County,[156] Los Angeles City, San Bernardino County, Riverside County, Santa Barbara County, and Cal Fire, have adopted the basic approach. The RSG approach involves preparing one's house to withstand a wildfire, preparing one's family for evacuation, and finally, leaving earlier. The program is now endorsed by the International Association of Fire Chiefs (www.iafc.org/displaycommon.cfm?an=1&subarticlenbr=1229).

In many regions of the world, people are warned that wildfires are dangerous and that they always need to evacuate. This "scare tactic" approach reinforces the concepts that wildland fires are always dangerous and that people must leave their homes. Perhaps one solution to dealing with fires in the WUI in the future would be to embrace the concept of "A Dream, a Team, and a Theme."[335] The "dream" would be one where houses are able to survive fires even when fire services personnel are not available. The "team" would consist of the effective partnership between the fire services and home dwellers. The "theme" would comprise the dual strategy of adequate defensible space coupled with the home dweller's motivation to remain on site as an important factor in suppressing fires initiated by ember attack. In order for this approach to work, rural homeowners must understand that although wildfires can be dangerous, with proper precautions, people can remain with their homes and be an important part of the solution to the WUI fire problem. Empowering communities at risk from wildfire to play an active part in their own protection is viewed as a viable long-term strategy to enable safe and harmonious coexistence with fire as an element of nature.[121]

During the 2000 fire season in western Montana, some individuals opted to stay with their homes as flame fronts advanced. They created defensible space, installed sprinkler systems, engaged in fire suppression activities, and provided local intelligence to incoming fire service personnel. No home was lost as people demonstrated responsibility for their personal well-being. A similar "prepare, stay, and defend" action was successfully carried out during the 2003 fire season on the Wedge Fire along the North Fork of the Flathead River in western Montana. The property was prepared in advance to be "fire safe," the homeowner remained with volunteer fire department officials, and the home survived the passage of a high-intensity crown fire (Figure 14-11).

Wildland fires that threaten human lives and property are not exclusively located in southern California because the exodus to wildland regions has become a national phenomenon. Fires burned about 81,000 hectares (about 200,000 acres) in Maine in October 1947, killing 16 people;[93,180] another area of about 81,000 hectares (about 200,000 acres) burned in New Jersey in April 1963.[55] Wildland fire disasters have not always been large in size. On September 26, 1936, most of the coastal town of Bandon in western Oregon was destroyed, and 11 people were killed by a wildfire that covered probably no more than about 4000 hectares (10,000 acres).[243] The prevalence of gorse, a non-native plant, was considered a key contributing factor to the resulting devastation (Figure 14-12). On July 16, 1977, the Pattee Canyon Fire that occurred near Missoula, Montana, destroyed six homes and charred about 500 hectares (1200 acres) of forests and grasslands in only a few hours.[195] Similarly, more than 70 homes were damaged or destroyed by fires in the southern Cape Peninsula region of South Africa that burned about 8000 hectares (about 19,800 acres), during January 16 to 20, 2001.[109,504] A host of other cases have occurred in North America[242] and are steadily accumulating.

Fires at the WUI are also increasing internationally. For example, the Ash Wednesday fire disaster in southeastern Australia on February 16, 1983 burned about 340,000 hectares (840,000 acres) of urban, forested, and pastoral lands in the states of Victoria and South Australia, killing 77 people, injuring about 3500, and destroying more than 2500 homes.[59,237,366] Phenomenal fire spread rates in both forests and grasslands occurred,[254,407] and flame heights of almost 200 m (650 feet) were observed.[472] In May 1987, wildfires in northeastern China[425] added a new perspective regarding the devastating impact wildland fires may have on human lives, property, and natural resources. These fires reportedly burned about 1.34 million hectares (3.31 million acres), killed 212 people, seriously injured another 226, and left about 56,000 homeless.[173] Clearly, it was a disaster of major proportions. These fires resulted from a combination of plentiful

FIGURE 14-11 Homeowners and firefighters successfully prepared, stayed, and defended this rural home in western Montana from a high-intensity flame front associated with the Wedge fire in July 2003. *(Courtesy Big Fork Volunteer Fire Department.)*

fuels, sustained drought, low fuel moistures, and strong winds.[465] Rates of spread during the major runs reached 20 km/hr (12 miles/hr). Protecting lives and property from wildfires at the WUI represents one of the greatest challenges faced by wildfire protection agencies.

Large forest fires during the intense El Niño drought conditions of 1997 and 1998 focused public and media attention once again on the need to evaluate public policies and practices in the forestry and nonforestry sectors that directly or indirectly contribute to the impact of wildland fires. The size and damage attributed to these fires were so immense that the *Christian Science Monitor* termed 1998 "The Year the Earth Caught Fire." At times, that seemed to be literally true, as smoke palls blanketed large regional areas, disrupted air and sea navigation, and caused serious public health threats.[214,403,430,542] At least 60 people were killed in Mexico as a result of the fires,[486] and ecosystems that generally are not subjected to fires, such as the Amazon rain forest and the cloud forest of Chiapas, Mexico, sustained considerable damage. A global fire conference sponsored by the Food and Agricultural Organization of the United Nations in October 1998 brought together specialists from 33 countries to review the

FIGURE 14-12 **A,** Old man's gorse *(Ulex europaeus)* is probably the worst fuel type in the world from the standpoint of wildland fire management for two main reasons. **B,** Density of the vegetation and its sharp spines or thorns make it extremely difficult if not nearly impossible to physically engage in any kind of fire suppression activity. Vigorous stands grow outward, crowding out all vegetation and forming a center of fine, dry, dead, elevated fuel. **C,** This fuel structure, coupled with the plant's oil content, readily contribute to the development of high-intensity flame fronts even under relatively mild fire weather conditions. Gorse is native to central and western Europe, where it has long been cultivated for hedgerows. It has been introduced to Australia, New Zealand, the U.S. West Coast (California, Oregon, and Washington), and southwestern British Columbia. It has also been reported in Costa Rica and the Hawaiian Islands. In the northeastern United States, it has established itself along the Atlantic Coast from Virginia to Massachusetts. *(Courtesy Ensis Bushfire Research Group, New Zealand.)*

serious nature of worldwide vegetation fires.[199] Participants at the conference in Rome concluded that governments needed to enact more sustainable land use policies and practices to reduce the impacts of wildfires on people and natural resources.

It is becoming increasingly rare to have a wildland fire situation or incident that does not involve people and their homes. However, people are not fully aware of the fire risks and hazards of living and traveling in or near wildlands.[65,224] "Risk," in the jargon of the wildland fire specialist, is the probability that a fire will occur. "Hazard" is the likelihood that a fire, once started, will cause unwanted results. Risk deals with causative agents or ignition sources; hazard deals with the fuel complex.[205] The results of two surveys carried out in the western United States during the 1970s indicated a general feeling of overconfidence by most residents toward the potential danger or threat of a wildland fire. About 80% of Seeley Lake, Montana, forest residents interviewed thought that the forest fire hazard was low to moderate in their area.[204] About 75% of Colorado residents interviewed thought that the forest fire hazard was low or moderate in mountain subdivisions of their state.[244] Forest fire hazards in these two areas were much higher than these public estimates. A survey of attitudes toward bushfires in the Dandenong Ranges of Victoria, Australia, found that people who had experienced bushfires tended to rank their area with a higher rating than did people without such experience.[183] However, the survey also revealed that 40% of the people with recent severe bushfire experiences still did not rate bushfires as one of the three most important environmental problems in their area. Dr. Sarah McCaffrey,[306] a research social scientist with the USDA Forest Service who has studied the social dynamics of fire management for many years, suggests that the general public is much better informed of the issues dealing with the WUI fire problem than during the 1970s and 1980s.[304,305] She attributes this fundamental change to programs such as *Firewise*, fire safe councils, and media coverage. No doubt the large number of conflagrations in the past 25 years has also contributed to an increased awareness regarding the realities of wildland fire.

In more recent surveys carried out in Florida and Minnesota[362] of homeowners' preferences for vegetation and defensible space near their homes, people recognized the wildfire threat but varied in their perceptions of effective wildfire prevention measures and willingness to take actions to reduce the potential threat to themselves and their homes. Most supported the use of planned fire to reduce fire potential, especially if wildland fire experts who understand the local ecology and fire behavior conducted the prescribed burns. In-depth interviews conducted with homeowners along the northern part of the Colorado Front Range revealed that these people face difficult decisions regarding implementation of wildfire mitigation measures.[79] Perceptions of wildfire mitigation options were found to be possibly as important as perceptions of risk in determining likelihood of implementation. These mitigation options were often viewed as trade-offs between wildfire risk and preferred landscapes. The study participants also reported, however, that one-on-one information sharing with wildland fire experts, as well as increased understanding of the flexibility of mitigation options, encouraged implementation. Personalized contact appears to be a key factor in educating homeowners about the realities of living in a wildland environment.[303]

Participants in a survey conducted in Michigan[541] considered wildland fires as inherently uncontrollable and the resulting damage essentially random. Thus, they only weakly supported investments in fire suppression infrastructure but strongly supported fire prevention programs that reduced the number of fire starts, were unlikely to take all possible steps to safeguard their own properties, and exhibited a negative view of prescribed fire to the extent that it could preclude its use as a risk management tool.

There is a growing need for the general public, emergency medical personnel, and fire suppression organizations to be well prepared to deal with wildland fire encounters (Box 14-2). As Reitz and Geissler[410] noted, "The old model of individual homeowners and neighborhoods depending solely on government provided firefighting resources is gone. Recent wildland fires

BOX 14-2 Recommendations to Reduce Loss of Life and Property in the Wildland-Urban Interface (WUI)

Fire Protection Services

Remember that firefighter and public safety is the first priority in every fire management activity.
Ensure that all personnel receive regular cross-training in fighting wildfires and structural fires.
In urban departments, in particular, recognize the need to extinguish fires in wildland fuels by using thorough mop-up procedures.
Recognize the need for close coordination of response efforts among neighboring departments or agencies.
Develop specific mutual-aid plans for coordinating resources to attack fires in the WUI.
Schedule and conduct regular mutual-aid training exercises.
Regularly schedule and conduct fire prevention and fire preparedness education programs for the general public and homeowners.
Conduct an assessment of fire risks, and prepare a strategic plan to reduce these risks.
Work effectively with lawmakers and other government officials to help prevent unsafe residential and business development.

Legislators

Examine existing laws, regulations, and standards of other jurisdictions that are applicable locally in mitigating hazards associated with wildland fires.
Adopt National Fire Protection Association (NFPA) guidelines in the form of NFPA 1144 (formerly NFPA 299, 1991 edition), *Standard for the Protection of Life and Property from Wildfire*.[344] The purpose of this standard is to provide criteria for fire agencies, land use planners, architects, developers, and local government for fire-safe development in areas that may be threatened by wildfire. NFPA 1144 provides minimum planning, construction, maintenance, education, and management elements for the protection of life, property, and other values that could be threatened by wildland fire. It is designed to assist local, state, and federal fire agencies in dealing with the escalating challenges presented by the proliferation of WUI communities and the monetary losses of structures in WUI areas. These guidelines address the following topics: assessment and planning; access, ingress, egress, and evacuation; fuel modification area; water supply; and residential development design, location, and construction.
Provide strong building regulations that restrict untreated wood shingle roofs and other practices known to decrease the fire safety of a structure in the wildlands.

Planners and Developers

Create a map of potential problem areas based on fuel type and known fire behavior.
Evaluate all existing or planned housing developments to determine relative wildland fire protection ratings, and advise property owners of conditions and responsibilities.
Ensure that all developments have more than one ingress-egress route.
Offer options for fire-safe buildings.
Provide appropriate firebreaks, fuel breaks, or greenbelts in developments.
Ensure that adequate water supplies exist in developments.
Follow specifications in NFPA 1144 *Standard for the Protection of Life and Property from Wildfire*.[344]

Public and Homeowners

Determine the wildfire hazard potential of the immediate area before buying or moving into any home.
Contact federal, state, and local fire services for educational programs and materials regarding fire protection.
Provide a fuel-modified area or defensible space around vulnerable structures to reduce the likelihood of ignition by an advancing wildfire.
Design and build nonflammable homes.
Urge lawmakers to respond with legislative assistance to require appropriate fire safety measures for communities.

have demonstrated that community firefighting resources are easily outpaced when multiple structures are burning simultaneously. The cure is to move most structure protection responsibility to the homeowner and community."

In 2000, 450 residents of Strathcona County, Alberta, Canada, were randomly selected to test which three educational methods would produce the greatest change in homeowner behavior with respect to the WUI.[461] The study showed that residents could be influenced to change their behaviors when provided with the information materials that enabled them to select between fire safety alternatives.

A 2003 study evaluated workshops for the adult public featuring experimental learning about wildland fire.[377] Participants used hands-on activities to investigate fire behavior and ecology and to assess hazards in the WUI. Effectiveness was examined using a pretest, a post-test following the program, and another post-test 30 days later. Participants' knowledge increased after the workshop, and attitudes and beliefs became more supportive of fire management. The study concluded that hands-on activities can help adults become better informed about wildland fire and more positive about fire management.

WILDLAND-URBAN INTERFACE LESSONS LEARNED

Recommendations to reduce the loss of life and property in the WUI will be useless unless they are implemented at the grassroots level by all stakeholders. An excellent example of a community-based program is one implemented at Incline Village and Crystal Bay in the Lake Tahoe basin in Nevada.[448] The objective of this program is to "reduce the potential for natural resource, property, and human life losses due to wildfire by empowering the communities' residents with the knowledge to address the hazard, providing the resources necessary to correct the problem, and encouraging the cooperative efforts of appropriate agencies." The three major components of this defensible-space program include neighborhood leader volunteers, a slash removal project, and agency coordination. The key to protecting life and property in the WUI is property owners' realization that they have a serious problem and that their actions embody a significant part of the solution. In the Incline Village and Crystal Bay community fire plan, neighborhood leader volunteers are trained in defensible-space techniques and are expected to teach these techniques to their neighbors and to coordinate neighborhood efforts. Such concerted community action will greatly minimize threats from the southern California type of "fires of the future," as discussed earlier.

It is also wise to have sensible land development practices, because tragedies arise not only from ignorance of fuels and fire behavior (Figure 14-13), but also from a greater concern for the aesthetics of a home site than for fire safety.[345] The following aspects of development detract from fire safety in the WUI[141,195]:

- Lack of access to adequate water sources
- Firewood stacked next to houses
- Slash (i.e., branches, stumps, logs, and other vegetative residues) piled on home sites or along access roads
- Structures built on slopes with unenclosed stilt foundations
- Trees and shrubs growing next to structures, under eaves, and among stilt foundations
- Roads that are steep, narrow, winding, unmapped, unsigned, unnamed, and bordered by slash or dense vegetation that makes them extremely difficult if not impossible for fire appliances to negotiate
- Subdivisions on sites without two or more access roads for simultaneous ingress and egress
- Roads and bridges without the grade, design, and width to permit simultaneous evacuation by residents and access by firefighters and emergency medical personnel and their equipment
- Excessive slopes, continuous or heavy fuel situations, structures built in box canyons, and other hazardous situations
- Lack of constructed firebreaks and fuel breaks around home sites and in subdivisions

FIGURE 14-13 This permanent residence, located in west-central Alberta, Canada, is unlikely to survive exposure to even a low-intensity wildland fire, and it would be difficult to stay and defend it for a number of reasons. There is dense forest vegetation immediately adjacent to the structure. Cedar shakes have been used for roofing. This has been shown time and time again to be the "kiss of death" in wildland-urban interface fires (at the time this photo was taken in 1997, the shingles were in such bad shape that they had lichens growing on them). The homeowner also liked to store flammable materials under his deck. *(Courtesy Yukon Wildland Fire Management; photo by A.K. Beaver.)*

- Living fuels that have not been modified by pruning, thinning, landscaping, or other methods to reduce cured vegetation, and litter that readily contribute to spot fire development and fire intensity
- Homes constructed with flammable building materials (e.g., wooden shake shingles)
- Propane tanks exposed to the external environment
- Inability to deliver water effectively before and during passage of a fire front around the home property (e.g., lack of proper equipment, such as sprinklers)

In many cases, simply cutting the grass and keeping the yard cleaned up will dramatically increase the chances of the house surviving a wildfire.[130]

WHAT SOME ORGANIZATIONS HAVE TO OFFER THE GENERAL PUBLIC

The National Disaster Education Coalition is a group of U.S. federal agencies and nonprofit organizations that support common goals in disaster and hazards education. This group worked with leading social scientists in this area to produce a state-of-the-art guide for public risk education. The group developed a standardized guide[341] on hazard safety messages, providing information that all organizations agreed on for national use. The guide covers many different hazards, including wildland fires, as well as general preparedness issues.

Firewise Communities is a national mitigation planning program that encourages communities to include land use planning, building codes, landscaping codes, zoning, and fire protection in developing new communities and in retrofitting existing communities.[54,390] *Firewise Communities* is a national initiative designed to reach beyond the fire service and involve homeowners, community leaders, planners, developers, and others in the effort to protect people and property from the dangers of wildland fire. *Firewise Communities* programs include the *Firewise Communities* Workshop series, *Firewise Communities*/USA Recognition Program, and support for fire organizations and community groups. The *Firewise Communities* program is part of the Wildland-Urban Interface Working Team of the National Wildfire Coordination Group (NWCG), a consortium of wildland fire agencies that includes the USDA Forest Service, U.S. Department of Interior, National Association of State Foresters, U.S. Fire Administration, Federal Emergency Management Agency (FEMA), and National Fire Protection Association (NFPA). *Firewise Communities* emphasizes that everyone in every community is responsible for fire protection. *Firewise Communities* workshops help define responsibilities for a network that includes many partners. The intent is to undertake planning and actions to ensure that people live more compatibly in every neighborhood situation in a wildland fire environment. Toward this end, a website has been developed (www.firewise.org), and several publications and books[345,445] have been published to assist homeowners living in the WUI.

A team of scientists from across the United States has been visiting communities to identify the activities they need to undertake to increase their wildfire preparedness and the resources necessary to support these activities. This research was funded by the National Fire Plan and is led by the Social and Economic Dimensions of Ecosystem Management Research Work Unit of the USDA Forest Service's North Central Research Center. Research partners include the USDA Forest Service's Pacific Northwest Research Station, University of Minnesota, Southern Oregon University, and University of Florida. Sixteen community preparedness case studies were completed between 2002 and 2004 in a variety of locations throughout the continental U.S. (jfsp.fortlewis.edu).[527,534]

In 1990, Partners in Protection (PiP) of Alberta, Canada, was established. PiP is a coalition of professionals representing national, provincial, and municipal associations and organizations committed to raising awareness, providing information, and developing forums to encourage proactive, community-based initiatives regarding fires at the WUI. In 2008, PiP was invited by the Canadian Council of Forest Ministers to develop a proposal for a nationally oriented effort. In response, PiP developed the FireSmart Canada program that addresses the goals necessary to protect lives and properties across Canada. PiP has produced a comprehensive manual with respect to the WUI fire problem entitled *FireSmart: Protecting Your Community from Wildfire*.[378] This well-illustrated guide focuses on how individuals and communities can work together to reduce the risk for loss from wildfires in the WUI. It provides practical tools and information for use by residents and by individuals and organizations that operate in the WUI. The primary topics are description of interface issues, evaluation of hazards, mitigation strategies and techniques, emergency response for agencies and individuals, training for interface firefighters, community education programs, and regional planning solutions. The manual, available in both book form and CD-ROM, can be viewed online (www.firesmartcanada.ca/resources-library/protecting-your-community-from-wildfire) and covers almost every facet of fire preparations in the WUI. In the chapter on communications and public education, for example, the following principles are cited for effective communication:

- Begin with clear, explicit objectives.
- Do not make assumptions about what people know, think, or want done. Take time to find out what people are thinking by using surveys, focus groups, or other research.
- Involve all parties that have an interest in the issue. Identify and address the particular interests of different groups.
- Identify with your audience. Put yourself in their place, and recognize their emotions.
- Take time to coordinate with other organizations or groups.
- Choose your spokespeople carefully, and ensure they have the training to communicate your messages effectively.
- Practice and test your messages.
- Do not either minimize or exaggerate the level of risk.
- Promise only what you can do. Do what you promise.
- Plan carefully, and evaluate your efforts.

Kumagai and colleagues[261] also offer some excellent advice with respect to wildland fire education and communication with the general public.

Most local, state, provincial, territorial, and federal fire management agencies now have some type of outreach program related to the WUI. For example, the State of Alaska offers teachers both face-to-face wildland fire workshops and an online training course.[468] In 1993 the Country Fire Authority of Victoria, Australia, developed a program called "Community Fireguard," which assists communities in developing wildfire survival strategies.[74]

FIGURE 14-14 In an attempt to avoid the intense heat of the Battlement Creek Fire in southwestern Colorado on July 17, 1976, four firefighters took refuge in the fire line, in the foreground at point *A*. Affected by intense convective and radiant heat and dense smoke, one individual ran into the fire and died at point *B*. Another individual ran about 300 m (1000 feet) down the ridge, where his body was found at point *C*. The third fatality was a person who remained at point *A*; he died a short time after this position was overrun by fire. The only survivor also remained in a prone position at point *A* with his face pressed to the ground. At one point he reached back and threw dirt on his burning pants legs. The survivor sustained severe burns to the backs of his legs, buttocks, and arms. The deaths of the other three individuals were attributed to asphyxiation. *(Courtesy USDA Forest Service.)*

WILDLAND FIRE BEHAVIOR

URBAN AND WILDLAND FIRE THREATS

Safety precautions for wildland firefighting crews are continually upgraded as new knowledge is gained about fire behavior and human behavior. The sites where people were injured or killed by fire are routinely examined afterward to assess fuel conditions, terrain features, probable wind movements at the time of the fire, and actions of firefighters[294,329,530] (Figure 14-14). In this regard, Maclean[285] has noted:

> It is hard to know what to do with all the detail that rises out of fire. It rises out of a fire as thick as smoke and threatens to blot out everything. Some of it is true but doesn't make any difference. Some of it is just plain wrong. And some doesn't even exist, except in your mind, as you slowly discover long afterwards. Some of it, though, is true—and makes all the difference.

The information gleaned from past wildland firefighter fatalities, as well as data about hazards in the WUI, are now included in training programs and safety briefings.

In reviewing many past wildland fire tragedies, a sobering observation is that crew members are almost always experienced and well-equipped firefighters, trained to anticipate "blowup" fire conditions (i.e., a temporary escalation in fire behavior). However, when visibility is lowered to 6 m (20 feet), noise levels preclude voice communication, eyes fill with tears, and wind blows debris in all directions, a person's judgment is greatly impaired. For many members of the general public, the first wildland fire they may experience will in all likelihood be a high-intensity conflagration. As Cheney[122] notes:

> The approach of a major fire can appear ominously threatening to those directly in its path, but is often viewed with curiosity and with little concern if it appears that the wind will direct the fire past their properties. Thus, when a combination of circumstances, often associated with a frontal wind passage, exposes residents to a high-intensity fire environment, they are very much unprepared. Their senses are assaulted by sudden darkness, thick blinding and choking smoke, buffeting winds and unexpected calm periods, searing heat and flames which illuminate the smoke-obscured scene and a roaring noise of wind and explosive combustion. In all this activity they observe flames which change from a metre or two to engulfing whole trees. In such a dramatic and emotional

situation, many people are apt to invent phenomena (such as, houses exploding, the air burning, fantastic spread rates and the like) to explain the extent of the devastation that confronts them when the smoke clears away.

Even for experienced firefighters, previous training can give way to panic-like attacks and poor decision making, leading to actions that can result in serious injury or death.[370] This scenario is most evident in urban fires; the pattern of hysteria affecting people trapped in burning buildings is all too familiar to urban firefighters.[452] The way fire kills in the urban setting can be compared with wildland fires, as summarized here[373]:

1. Heat rises rapidly to upper stories when a fire starts in the basement or on the ground floor. Toxic gases and smoke rise to the ceiling and work their way down to the victim—a vital lesson for families planning protective measures. Smoke poses the double problem of obscuring exit routes and contributing to pulmonary injury and oxygen deprivation.
2. As the fire consumes oxygen, the ambient oxygen content drops, impairing neuromuscular activity. When the oxygen content drops below 16%, death by asphyxiation will ensue unless the victim is promptly evacuated. Asphyxiation, not fire itself, is the leading cause of fire deaths.
3. Ambient air temperatures may rise extremely rapidly from even small fires. Temperatures of 150° C (300° F) will cause rapid loss of consciousness and, along with toxic gases, will severely damage lung tissues. Warning devices may offer the only possibility for survival because of the rapid onset of debilitating symptoms.

Obvious similarities and differences are seen between wildland fires and urban fires:

1. Smoke, heat, and gases are not as concentrated in wildland situations as in the confined quarters typical of many urban fires.
2. Flames are not a leading killer in either the urban or the wildland situation, although admittedly, autopsies are generally not performed, so this assertion awaits confirmation.
3. Although oxygen levels may be reduced near wildland fires, there is usually sufficient replenishment of oxygen in the outdoor environment to minimize deprivation. Asphyxiation, however, can also be an important cause of death in wildland fires.
4. Inhalation of superheated gases poses as serious a threat to life in wildland fires as in urban fires.
5. Wildland smoke does not contain toxic compounds produced by combustion of plastics and other household materials, but it does impair visibility, contains carbon monoxide, and carries suspended particulates that cause severe physical irritation of the lungs.
6. Sprinkler systems and automatic early-warning devices to detect smoke or heat may protect people from serious injury or death in the urban environment, but in the wildland environment, people must rely on their experience, senses, knowledge, and skills or ingenuity to provide early warning of an impending threat to life.

The general public needs to appreciate that fires occurring under certain fuel, weather, and topographic situations may result in explosive fire growth on an area basis (Figure 14-15). The fire that burned through Faro, Yukon, on June 13, 1969, is a good example of this type of behavior.[255] The Faro Fire, which burned about 15,500 hectares (38,300 acres) resulted from a lightning strike that occurred 8 km (5 miles) west of town at 5:04 PM. The fire started to spread fairly quickly in an easterly direction. Fire crews were dispatched from town by vehicle to take suppression action, but little could be done because of crowning activity. By 8:30 PM, the fire had burned through town and was continuing to spread farther east. In other words, the fire had traveled 8 km (5 miles) in less than 3.5 hours. This equates to a rate of spread of around 2.3 km/hr (1.4 miles/hr) or 40 m/min (131 ft/min). This would not be considered an unusual situation in many regions of the North American boreal forest.[30,160] How wide would the fire have likely been when it hit the edge of town? A rough rule of thumb is to divide the separation distance by a factor of 2 to 4 based on an assumed wind-driven fire shape.[475]

FIGURE 14-15 View of the Crutwell Fire as it burned toward the city of Prince Albert, Saskatchewan, during its initial major run that started during the late afternoon of June 28, 2002. This photo was taken from a building in the downtown area when the fire was about 18 km (11 miles) away. The fire was started by lightning during the morning of a day of extreme fire danger. On escaping initial containment, this wind-driven fire advanced by crowning through jack pine forests at rates of about 2.3 km/hr (1.4 miles/hr) at the height of activity. Spotting up to 1 km (0.6 mile) was observed. Fortunately, changes in fuel types and less severe fire weather conditions during the night contributed to the effectiveness of the fire suppression operations. *(Courtesy Saskatchewan Health; photo by G. Matchett.)*

The fire would have thus been about 2 to 4 km (1.2 to 2.5 miles) wide when it hit the western edge of Faro.

Fire Behavior Knowledge: a Wildland Fire Early-Warning System

Fire behavior is defined as the manner in which fuel ignites, flame develops, and fire spreads and exhibits other related phenomena as determined by the interaction of fuels, weather, and topography. The science of fire behavior describes and predicts the performance of wildland fires in terms of ignition probabilities, rates of spread, intensity levels, spotting distances and densities, and crowning potentials.

To the layperson, a wildland fire can be a perplexing event. As Countryman and Schroeder[155] note:

> A casual observer seeing a forest fire for the first time would probably decide there is little rhyme or reason to the way a fire burns. Its sudden variations in direction of travel, its quick change from a seemingly mild, slow-burning fire to a raging inferno, all seem to add up to erratic behavior without local explanation. Actually a fire behaves in accord with changes in its surroundings—the character and condition of the burnable vegetation, the topography, and the meteorologic factors—that affect fuel flammability, fire intensity, and fire spread. This complex of environmental factors that control the behavior of fire is what we call "fire environment."

Understanding one's fire environment[151] is considered a key factor for safe and effective action in dealing with wildland fires. For example, 4 of the 32 civilians killed in Victoria during the 1983 Ash Wednesday fires in southeastern Australia were caught outside their homes tending to or attempting to herd up livestock,[259] apparently unaware of the change in wind direction and speed that accompanied passage of the cold front through their area.[407] In such situations in southeastern Australia, the strong prefrontal winds are from the northwest. With the passage of the front, the wind direction changes sharply to the southwest, and winds increase markedly in strength. Had these people understood or been aware of the implications of the cold front passage on fire behavior and received some information on the timing of the change, they may have chosen to stay inside their homes.[259] An excellent overview of the fire environment concept has been prepared by the National Wildfire Coordinating Group.[350]

Experienced firefighters routinely monitor the fire and the fire environment and assess the probable behavior of fires using fire behavior guidelines and experienced judgment[35,57] based on current and expected fire weather conditions in relation to local fuel type information, topographic conditions, and moisture levels.[88,273,475] This is also referred to as *situational awareness,* that is, understanding what the fire is doing and what you are doing in relation to the fire and being able to predict where the fire and you will be in the future.[391]

In the conclusions to their detailed case study report on the 1994 South Canyon fire in Colorado, USDA Forest Service fire researchers[98] noted:

> None of the findings and observations discussed in this study represent new breakthroughs in wildland fire behavior understanding. Rather, the findings support the need for increased understanding of the relations between the fire environment and fire behavior. We can also conclude that fire managers must continue to monitor and assess both present fire behavior and potential future fire behavior given the possible range of environmental factors.

The emergency medical person, backcountry recreationist, and wildland homeowner must also understand certain basic fire behavior principles to provide for adequate personal safety. A cardinal rule in wildland fire suppression is to base all actions on current and expected fire behavior.[300,322] Attention to simple principles, indicators, and rules should enable wildland users to anticipate and avoid wildfire threats.

Heat, oxygen, and fuel are required in proper combination before ignition and combustion will occur[57,209] (Figure 14-16). If any one of the three is absent, or if the three elements are out of balance, there will be no fire (Box 14-3). Fire control actions are directed at disrupting one or more elements of this basic fire triangle.[14]

PHYSICAL PRINCIPLES OF HEAT TRANSFER

Heat energy is transferred by conduction, convection, radiation, and spotting, but generally only the last three processes are significant in a wildland setting.[106] Although conduction through solid objects is important in the burning of individual logs,[57] this process does not transfer much heat outward from a flaming front, unless there is a substantial accumulation, such as is found in blowdown fuel complexes.[208]

Convection, or the movement of hot masses of air, accounts for most of the heat transfer upward from the fire. Convective currents usually move vertically unless a wind or slope generates lateral movement (Figure 14-17). Convection preheats fuels upslope and in shrub and tree canopies, which contributes further to a fire's spread and the onset of crowning forest fires.

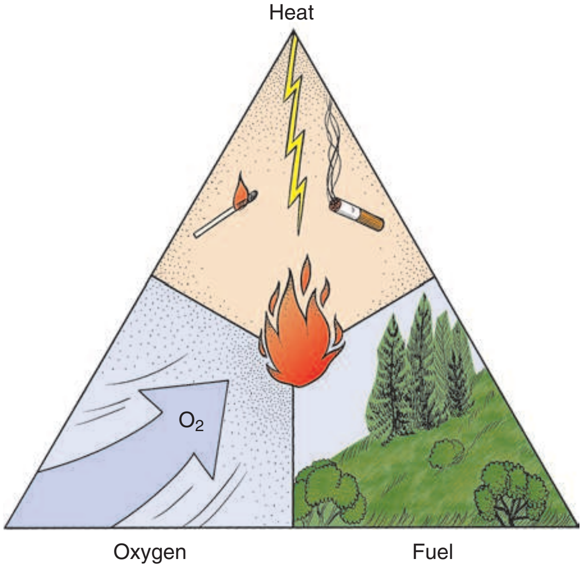

FIGURE 14-16 Combustion is a process involving the combination of heat, oxygen, and fuel. An understanding of the variations of these three factors is fundamental to an understanding of wildland fire behavior. *(Modified from Barrows JS:* Fire behavior in Northern Rocky Mountain forests, *Station Paper No 29, Missoula, Mont, 1951, USDA Forest Service, Northern Rocky Mountain Forest and Range Experiment Station.)*

BOX 14-3 Requirements for Wildland Fire Spread

Certain universal principles apply to all spreading fires in vegetation, living or dead. These really have nothing to do with biology but are based purely on the physics and chemistry of combustion:

1. There must be sufficient fuel of appropriate size and arrangement in space.
2. This fuel must be of sufficient dryness to support a spreading combustion reaction.
3. There must be an agent of ignition.

In practical terms, the primary requirement is a continuous layer of finely divided fuel or minor vegetation on the surface of the ground. This material may be conifer needles, hardwood leaves, grass, lichen, moss, finely divided shrubs, or other minor vegetation. However, it must be present and it must be continuous, or the possibility of spreading fire does not really exist. The second requirement is that the material be dry enough. The maximum moisture content at which fire will spread is hard to specify; for any given fuel or vegetation complex, it will depend on the amount of fuel, its arrangement in space, and the wind speed. Thus, fire spreads poorly or not at all in surface litter of various kinds at moisture contents over 25% or 30% (dry weight basis), whereas fine shrubby fuels or conifer foliage may support fast-spreading fires at moisture contents of 100% or more.

The two limiting criteria common to all spreading fires are as follows:

1. The fire must transfer enough heat forward to dry out the unburned fuel and raise it to ignition temperature by the time the flame front arrives.
2. Enough fuel must pass through the moving flame front to produce a continuous solid flame.

The behavior of any fire is the result of a complex process that results in a dynamic equilibrium among all elements of mass and energy flowing in and out of the flame zone. However difficult this whole process may be to describe and predict, the above two criteria run like threads through the whole range of fires in vegetation, whether the fuel itself is dead or live.

From Van Wagner CE: Fire behaviour in northern conifer forests and shrublands. In Wein RW, MacLean DA, editors: *The role of fire in northern circumpolar ecosystems,* Chichester, England, 1983, John Wiley & Sons.

Through *radiation,* heat energy is emitted in direct lines or rays; about 25% of combustion energy is transmitted in this manner. Radiated heat on exposed skin can cause discomfort and severe pain (Figure 14-18), and even death at elevated levels.[118,147] The amount of radiant heat transferred decreases inversely with the square of the distance from a point source. More radiant heat is emitted from a line of fire than from a point source. Radiant heat travels in straight lines, does not penetrate solid objects, and is easily reflected. It is believed to account for most of the preheating of surface fuel ahead of the fire front and poses a direct threat to people who are too close to the fire (see Figure 14-17).

Most organized fire suppression crews in the United States carry protective fire shelters[42,43,382] as part of their personal protective equipment (PPE) (Figure 14-19).[383] These aluminized "pup tent" type of structures are intended to protect against radiant heat.[104,394] The USDA Forest Service fire shelter was never designed to mitigate against sustained, direct flame contact.[317] Certain materials that fail when in direct contact with flames, such as "emergency space blankets,"[201] are also not appropriate for use in wildland fires[87] and in fact could cause serious burn injuries. Similarly, "emergency evacuation smoke hoods," intended for use in urban situations or other human-made environments (e.g., airplanes), have absolutely no application in a wildland fire environment despite manufacturers' suggestions to the contrary.

Spotting is a fire spread or mass-transport heat transfer mechanism by which wind currents carry flaming firebrands or glowing embers land beyond the main advancing fire front to start new

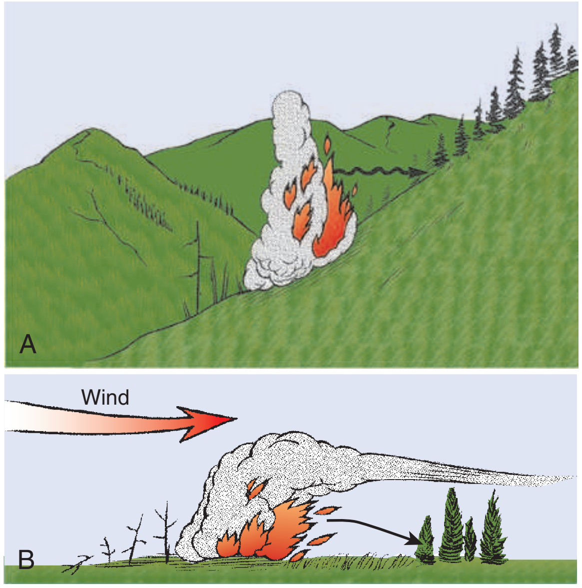

FIGURE 14-17 Fuels and people upslope (**A**) or downwind (**B**) from a fire receive more radiant and convective heat than on the downslope or upwind sides of a spreading fire. *(Modified from Barrows JS:* Fire behavior in Northern Rocky Mountain forests, *Station Paper No 29, Missoula, Mont, 1951, USDA Forest Service, Northern Rocky Mountain Forest and Range Experiment Station.)*

FIGURE 14-18 Most of the heat felt from a fire is radiant heat, which is largely a function of the height, depth, and angle of the flame front. Wildland firefighters work far enough from the radiating flames to avoid pain to exposed skin (e.g., face and ears). This also limits the amount of radiant heat absorbed through clothing. Wildland firefighters working near an active fire edge with hand tools typically adjust their distance from the flames so that the radiant heat they receive from the fire is little more than that of direct sunlight. *(Courtesy British Columbia Forest Service.)*

fires (Figure 14-20). In this manner, fire spread may accelerate very quickly, unexpected new fire starts can occur, and fire intensity and in-draft winds can dramatically increase as spot fires coalesce (Figure 14-21) and directly increase a fire's rate of spread. High-density, short-range spotting up to 100 m (328 feet) is a common feature of many wildfires, especially when fine fuels are very dry.[39] Low-density, intermediate- to medium-range spotting up to about 1 to 2 km (0.6 to 1.2 miles) is a common occurrence with high-intensity crown fires.[30] Longer-range spotting occurs very infrequently in most fuel types. Firebrand material being transported up to 16 km (10 miles) from its source has been reported in North America.[41] The native eucalyptus forests of Australia have a notorious reputation when it comes to spotting behavior because of the bark characteristics of many species, including an authenticated spot fire distance of 30 km (19 miles) or more.[281]

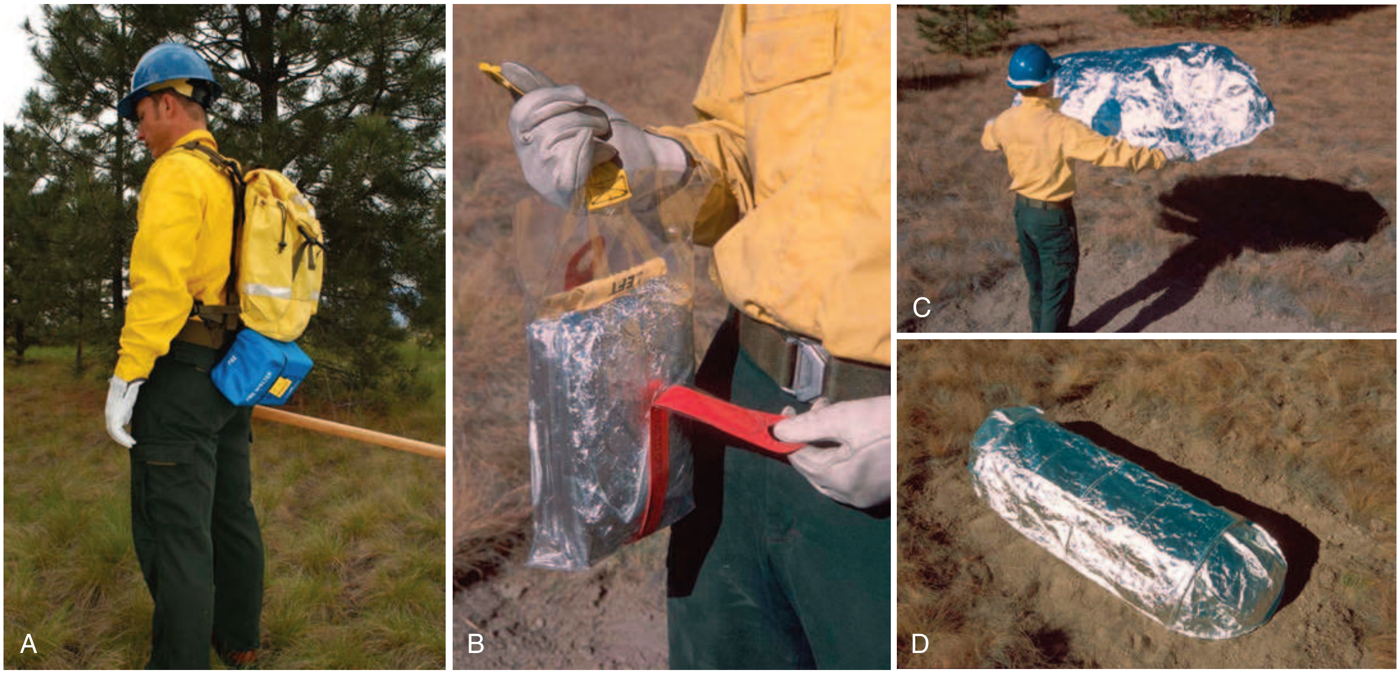

FIGURE 14-19 The personal protective equipment for a firefighter includes hard hat and safety goggles, fire-resistant shirt and trousers, leather boots and gloves, and an aluminized fire shelter carried in a waist pouch (**A**). Firefighters also carry canteens to ensure an adequate water supply in a heat-stressed environment. The fire shelter (**B**) is deployed (**C**) by firefighters as a last resort to provide protection from being exposed directly to radiant heat and superheated air (**D**). *(Courtesy USDA Forest Service.)*

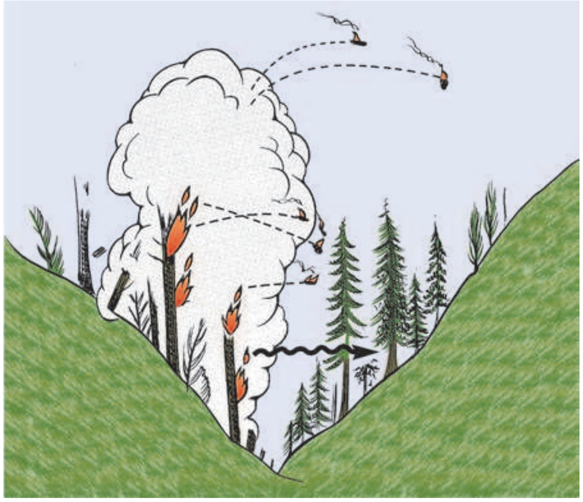

FIGURE 14-20 Fires can easily cross narrow canyons. Fuels and people on the slope opposite a fire in a narrow canyon are subject to intense radiant heat and spot fires from airborne embers. *(Modified from Barrows JS:* Fire behavior in Northern Rocky Mountain forests, *Station Paper No 29, Missoula, Mont, 1951, USDA Forest Service, Northern Rocky Mountain Forest and Range Experiment Station.)*

FUNDAMENTAL WILDLAND FIRE BEHAVIOR CHARACTERISTICS

One important aspect of fire behavior that distinguishes urban or structural fires from wildland fires is the latter's horizontal spread potential or rate of spread.[161] Although urban or structural fires may exhibit some horizontal as well as vertical fire spread potential, for practical purposes, they are considered stationary fire sources. Wildland fires, on the other hand, characteristically involve moving flame fronts, sometimes advancing with astonishing speed (Figure 14-22). Whereas ground or subsurface fires may spread very slowly (about 1 m [3 feet] per hour),[524] surface fires in open grown forests can reach rates of about 15 to 25 m/min (50 to 80 ft/min); conversely, surface fires in closed forest types typically spread at 5 to 6 m/min (16 to 20 ft/min) before the onset of crown combustion. Crowning forest fires generally advance at rates between 30 and 60 m/min (100 to 200 ft/min), occasionally higher.[30,160] Grass fires spread at rates up to about 385 m/min (1263 ft/min) or 23 km/hr (14 miles/hr).[129,365] It is thus quite possible for forest fires to advance up to 80 km (50 miles) in a single day[7,420] and for grass fires to travel correspondingly even farther.[528]

The threat to life and property largely depends on a fire's residence time (Table 14-2). This represents the length of time any object overrun by a fire will be heated by direct flame contact. Coupled with the fire's rate of spread, the residence time determines the depth of the active or continuous flaming front (Figure 14-23). The length of time that a fire will continue to burn by smoldering combustion is much more complicated and depends on the composition, compaction, moisture content, and quantity of fuel present.[202]

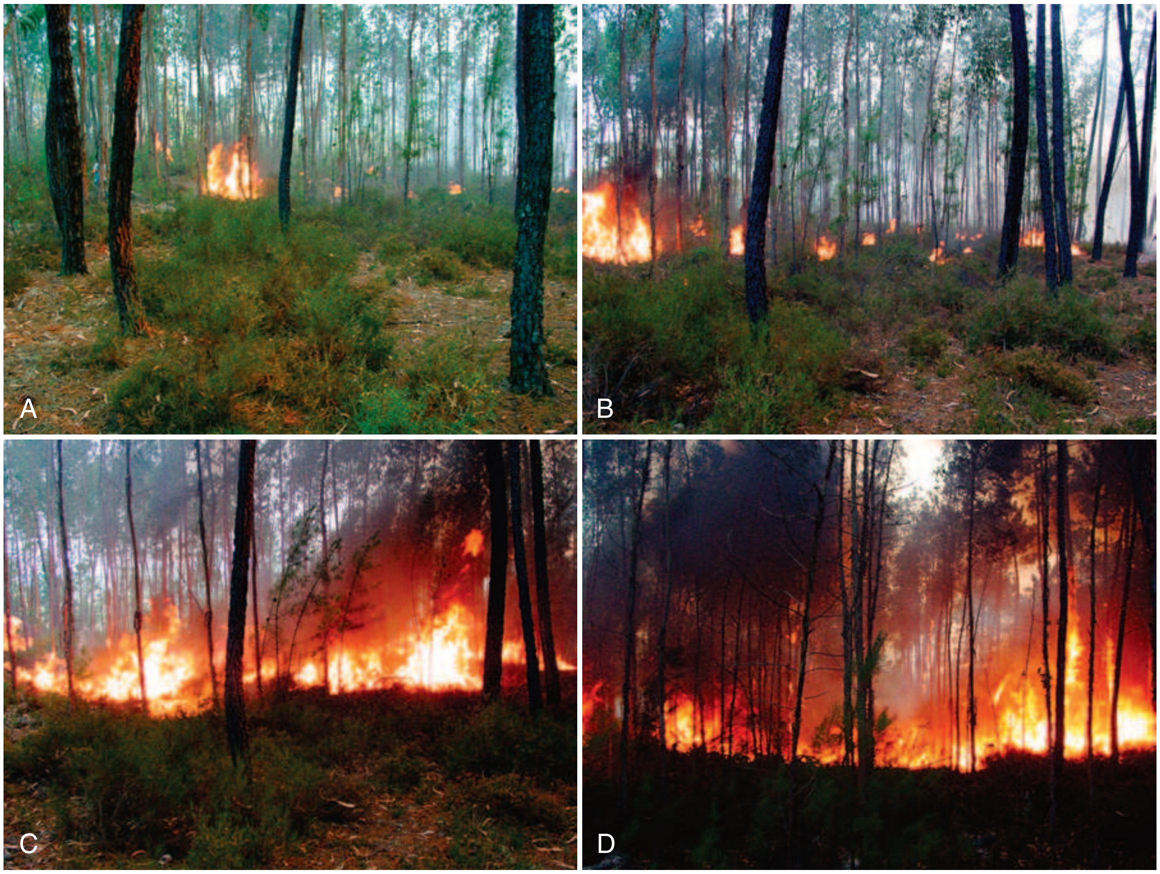

FIGURE 14-21 The occurrence of numerous spot fires is a direct indication that the moisture content of fine fuels has attained a critically dry level and in turn an early-warning signal that the potential for extreme fire behavior exists or is imminent. This sequence of photos (**A** to **D**) spanned a period of just over 100 seconds taken late in the afternoon of July 9, 2005, near Coimbra, Portugal. The fuel type is a blue gum *(Eucalyptus globulus)*–maritime pine *(Pinus pinaster)* stand. *(Courtesy Associação para o Desenvolvimento da Aerodinâmica Industrial; photos by M.G. Cruz.)*

FIGURE 14-22 A novel approach to reminding people of the capricious nature of wildland fire spread. This sign is located at Betty's Bay on the South African coast near Cape Town. The vegetation type is fynbos—a highly flammable Mediterranean shrubland fuel complex.[503] *(Courtesy CSIR Natural Resources and the Environment, Stellenbosch, South Africa; photo by B.W. van Wilgen.)*

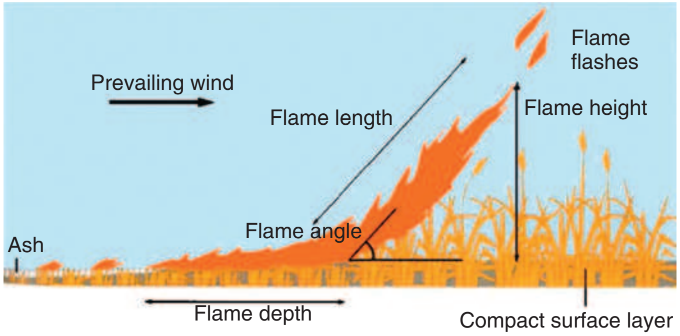

FIGURE 14-23 Cross-sectional view of a stylized free-burning fire in a grass fuel bed. *(From Cheney P, Sullivan A:* Grassfires: Fuel, weather and fire behaviour, *ed 2, Collingwood, Victoria, Australia, 2008, CSIRO Publishing.)*

The most basic features of a wildland fire are that (1) it spreads or moves, (2) it consumes or "eats" fuel, and (3) it produces heat energy and light in a visible, flaming combustion reaction.[6] Byram[105] defined *fire intensity* as the rate of heat energy release per unit time per unit length of fire front, regardless of its depth. Numerically, it is equal to the product of the quantity of fuel consumed in the flaming front, a fire's rate of fire spread, and a fuel heat combustion value. Flame size is its main visual manifestation. The fastest-spreading part of a fire is the head; the back of the fire is the slowest-spreading part, with the flanks being intermediate between the two (Figure 14-24). It is for this reason that the fire intensity, flame length, and flame height (see Figure 14-23) are greatest at the front of the fire and least at the rear[113] (Figure 14-25).

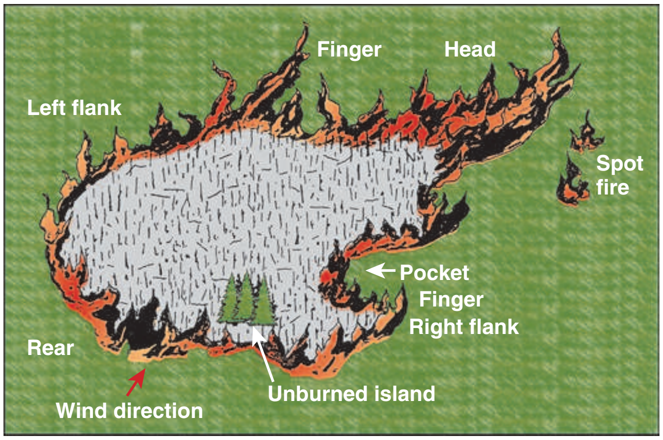

FIGURE 14-24 The parts of a fire are described in terms of its left flank, right flank, head, and back or rear. There may also be unburned islands within the fire and spot fires ahead of the fire. The safest travel routes generally involve lateral movement on contours away from the fire's flank or movement toward the rear of the fire. Moving in front of a head fire should be avoided. The burned area inside the fire's perimeter can offer a safe haven provided smoldering or glowing combustion levels are low and the flaming perimeter can be safely penetrated by an individual; falling trees or snags and rolling rocks could, however, still pose a hazard. *(Modified from Mobley HE, Moore JE, Ashley RC, et al:* Planning for initial attack, *rev ed, Forestry Report SA-FR-2, Atlanta, Ga, 1979, USDA Forest Service, Southeastern Area State and Private Forestry.)*

FIGURE 14-25 Elliptical fires resulting from multiple, wind-driven, point-source ignitions associated with a prescribed burning operation in a southeastern U.S. pine plantation. As indicated by the smoke drift, the winds are blowing roughly from lower right to the upper left. *(Courtesy USDA Forest Service; photo by C.W. Adkins.)*

TABLE 14-2 Nominal Residence Times for Four Broad Fuel Complexes and Computed Maximum Theoretical Flame Depths* Associated with Variable Rates of Fire Spread

	Residence Time		Rate of Fire Spread: 10 m/min (33 ft/min) Flame Depth		20 m/min (66 ft/min) Flame Depth		40 m/min (131 ft/min) Flame Depth	
Broad Fuel Complex	(sec)	(min)	(m)	(ft)	(m)	(ft)	(m)	(ft)
Grassland	10	0.17	1.7	5.6	3.4	11.2	6.8	22.3
Shrubland	20	0.33	3.3	10.9	6.6	21.7	13	42.7
Forest stand	45	0.75	7.5	24.6	15	49.2	30	98.4
Logging slash	90	1.5	15	49.2	30	98.4	60	196.8

*Numerically equal to residence time multiplied by the rate of fire spread (in compatible units).

The amount of radiation received from a flame front is determined by the size and geometry (e.g., height, depth, and tilt angle) of the flame front. Radiation levels coupled with residence times determine the nature of burn injuries.[87,181]

Environmental Factors Influencing Wildland Fire Behavior

A wildland fire behaves according to variations in the fire environment (i.e., fuels, weather, and topography). Box 14-4 lists some of the fire environment factors associated with adverse burning conditions that can signal the potential or onset for severe fire behavior. These factors or indicators are subject to assessment, observation, and measurement.

When a person encounters a wildland fire, the first step should be to review the principles and indicators of fire behavior, sizing up the situation in terms of fuel, weather, topographic factors, and observed fire behavior. After the fire's probable direction and rate of spread are estimated, travel routes that avoid hazards to human life can be planned (see Figure 14-24). The direction of the main body of smoke is often a good indicator of the direction the fire will take.

Fuel. Because wildland fuels vary so widely in their distribution, their physical characteristics or properties (i.e., moisture content, size and shape, compactness or arrangement, load, horizontal and vertical continuity, chemical content), and their effect on fire behavior, some means of classification is needed for their systematic assessment. Fuels are commonly classified into four groups or strata (Figure 14-26). Some fuel types may exhibit only one or two of the strata (e.g., grasslands, shrublands, and logging slash lack the ladder and crown fuel stratum).

An increase in fuel available for combustion affects fire intensity. In other words, the more fuel that is burning, the greater is the heat energy released by the fire. As Brown and Davis[83] noted:

> The ignition, buildup, and behavior of fire depend on fuels more than any other single factor. It is the fuel that burns, that generates the energy with which the fire fighter must cope, and that largely determines the rate and level of intensity of that energy. Other factors that are important to fire behavior (that is, moisture, wind, etc.) must always be considered in relation to fuels. In short, no fuel, no fire!

Certain types of fuel, such as chaparral, pine, and eucalyptus, burn more intensely because their foliage contains flammable oils and resins (see Figure 14-12). The size and arrangement of fuel also influence fire behavior. Small, loosely compacted fuel beds, such as dead grass, long pine needles, and shrubs, burn more rapidly than does tightly compacted fuel. Large fuels burn best when they are arranged so that they are closely spaced, such as logs in a fireplace. Scattered logs with no small or intermediate fuel nearby seldom burn unless they are decomposed. Seasonal changes in the moisture content and live-to-dead ratio (e.g., degree of curing in grasslands) of conifer tree foliage, shrubs, grasses, and other herbaceous plants can result in gradual changes in fuel flammability over the course of a fire season.[153,281]

Wildland fire research has identified a wind speed threshold in fuel types with a discontinuous, combustible surface layer (e.g., caused by the presence of areas of bare, mineral soil).[85,89] In these discontinuous fuel types, fire spread is exceedingly limited until a certain or threshold wind speed level is attained, and then the rate of advance can be quite unexpectedly rapid[207] (Figure 14-27). This type of situation could lead a person into a false sense of security regarding fire potential, until unfortunately it is often too late.

Various weather phenomena (e.g., wind, hail, snow, ice, frost) and insect and disease epidemics can drastically elevate the flammability of a fuel complex, creating decidedly new fire safety concerns.[34] For example, on July 9, 1999, heavy rains and winds in excess of 145 km/hr (90 miles/hr) blew down about 181,000 hectares (447,000 acres) of sub-boreal forest in northeastern Minnesota, resulting in heavy, dead and downed, woody fuel loads.[208]

Weather. The greater the wind, the more rapid is the spread of fire. Thunderstorm downdrafts and winds associated with dry, cold frontal passages can be especially hazardous.[129,427] Low relative humidity and high ambient air temperatures decrease the moisture content of fine, dead fuels and thereby increase ignition ease and rate of spread. Prolonged drought makes more medium and heavy fuels, such as duff and deep organic layers, available for combustion, leading to increased intensity levels. When fuels reach critically dry levels, fires become very responsive to minor changes in wind and slope. Fires tend to burn more vigorously under unstable atmospheric conditions.

The North American continent has been classified into 15 fire climate regions based on geographic and climatic factors[427] (Figure 14-28). Major fire seasons, or periods of peak fire activity, can be used to warn emergency medical personnel and wildland users of the most probable times for life-threatening situations. Exceptions occur. For example, rapidly spreading grass and forest fires can occur during the winter months in the northern latitudes, as occurred in Alberta, Canada, on December 14, 1997, under Chinook conditions and no snow cover.[223] A wildfire near the town of Hinton in the mountainous region of the west-central

BOX 14-4 Early-Warning Signals or Indicators Associated with Extreme Fire Behavior Potential

Fuel
- Continuous fine fuels, especially fully cured (dead) grasses
- Large quantities of medium and heavy fuels (e.g., deep duff layers, dead-down logs)
- Abundance of bridge or ladder fuels in forest stands (e.g., branches, lichens, suspending needles, flaky or shaggy bark, small conifer trees, tall shrubs extending from ground surface upward)
- Tight tree crown spacing in conifer forests
- Presence of numerous snags
- Significant amounts of dead material in elevated, shrubland fuel complexes
- Seasonal changes in vegetation (e.g., frost kill)
- Fire, meteorologic or insect and disease impacts (e.g., preheated canopy or crown scorch; snow-, wind-, or ice-damaged stands; drought-stressed vegetation; or mountain pine beetle–killed stands)

Weather
- Extended dry spell
- Drought conditions
- High air temperatures
- Low relative humidity
- Moderately strong, sustained winds
- Unstable atmosphere (visual indicators include gusty winds, dust devils, good visibility, and smoke rising straight up)
- Towering cumulus clouds
- High, fast-moving clouds
- Battling or shifting winds
- Sudden calm
- Virga (i.e., a veil of rain beneath a cloud that does not reach the ground)

Topography
- Steep slopes
- South- and southwest-facing slopes in the northern hemisphere
- North- and northeast-facing slopes in the southern hemisphere
- Gaps or saddles
- Chutes, chimneys, and narrow or box canyons

Fire Behavior
- Many fires that start simultaneously
- Fire that smolders over a large area
- Rolling and burning pine cones, agaves (a desert plant found in the southwestern U.S.), logs, hot rocks, and other debris igniting fuel downslope
- Frequent spot fires developing and coalescing
- Spot fires occurring out ahead of the main fire early on
- Individual trees readily candling or torching out
- Fire whirls that cause spot fires and contribute to erratic burning
- Vigorous surface burning with flame lengths starting to exceed 1 to 2 m (3 to 6 feet)
- Sizable areas of trees or shrubs that begin to readily burn as a "wall of flame"
- Black or dark, massive smoke columns with rolling, boiling vertical development
- Lateral movement of fire near the base of a steep slope

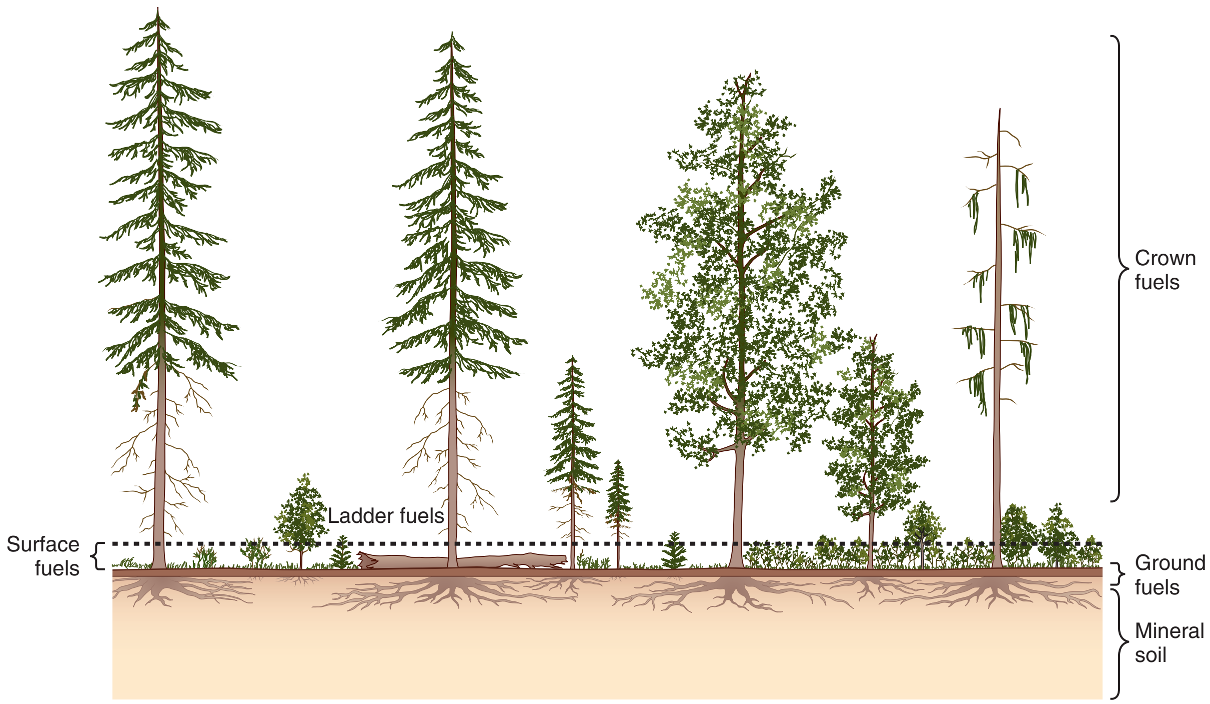

FIGURE 14-26 Profile of a stylized forest stand showing the location and classification of fuel complex strata. Wildland fuels contain energy, stored over extended periods through photosynthetic processes, that is released rapidly, occasionally explosively, in combustion. *(Modified from Brown AA, Davis KP:* Forest fire: Control and use, *ed 2, New York, 1973, McGraw-Hill.)*

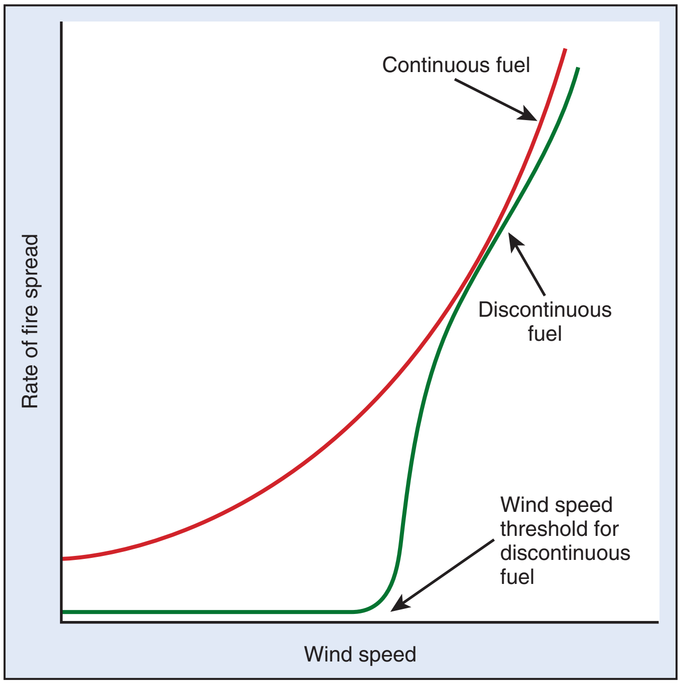

FIGURE 14-27 Discontinuous fuel types will not carry a fire until wind speed exceeds a particular threshold value. For example, a wind of 12 km/hr (7.5 miles/hr) has been identified from conducting experimental fires as a critical threshold for fire spread in spinifex grasslands of central Australia. In contrast, fire spread in continuous fuel types is possible even under calm conditions and, predictably, steadily increases with increasing wind. *(Modified from Gill AM, Burrows ND, Bradstock RA: Fire modeling and fire weather in an Australian desert,* CALMScience Suppl *4:29, 1995.)*

part of the province that spread through conifer forests by intermittent crowning posed a significant threat to the community. A single grass fire in the southwestern plains region advanced 33 km (20.5 miles) in less than 4 hours for a spread rate of around 8 km/hr (about 5 miles/hr), seriously threatening the community of Granum.[73] A similar situation was repeated with grass fires in 2011 and 2012 in southern Alberta.[31]

Although the fire season for the southern Pacific Coast is shown in Figure 14-28 as June through September, critical fire weather can occur year-round in the most southerly portion of the area. Fire seasons are most active during spring and fall in the Great Plains, Great Lakes, and North Atlantic regions. The pattern of seasonal fire occurrence in Australia has also been mapped,[281] as has the frequency of large fires.[119]

Topography. All other environmental factors being the same, the steeper the slope, the more rapid is the spread of fire. Fire usually burns uphill, especially during daylight hours. Changes in topography can cause rapid and violent changes in fire behavior (Figure 14-29). On steep terrain, rolling firebrands may cause a fire initially to spread downhill, followed by upslope runs. Mountainous terrain can modify wind speed and direction and in turn influence fire behavior in exceedingly complex ways.[427] Slope exposure or aspect has a very pronounced diurnal effect on fine-fuel flammability, a fact directly incorporated into the Campbell Prediction System of wildland fire behavior prediction (www.emxsys.com/cps/default.html).[110]

Extreme Fire Behavior

Extreme fire behavior is generally, but not conclusively, considered a level of fire activity that often precludes any fire suppression action by conventional means.[313] It usually involves one or more of the following fire behavior characteristics:

1. High rates of spread and intensity
2. Active crowning
3. Prolific spotting
4. Presence of large fire whirls
5. Well-established convection column

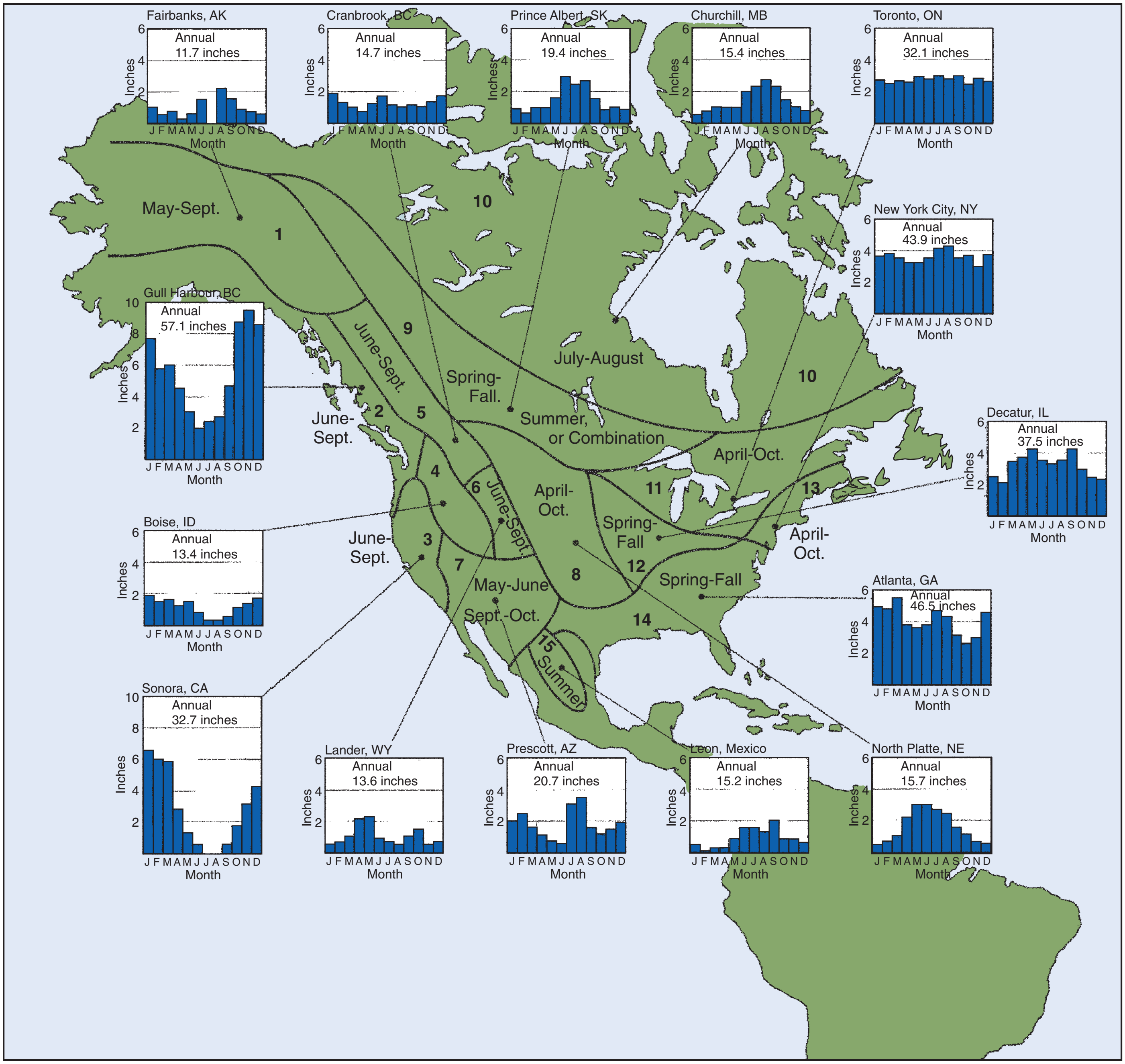

FIGURE 14-28 Fire climate regions of North America, based on geographic and climatic factors: *1,* interior Alaska and the Yukon; *2,* north Pacific Coast; *3,* south Pacific Coast; *4,* Great Basin; *5,* northern Rocky Mountains; *6,* southern Rocky Mountains; *7,* Southwest, including adjacent Mexico; *8,* Great Plains; *9,* central and northwest Canada; *10,* sub-Arctic and tundra; *11,* Great Lakes; *12,* Central States; *13,* North Atlantic; *14,* Southern States; and *15,* Mexican central plateau. The *bar graphs* show the monthly and annual precipitation for a representative station in each of the fire climate regions. Months on the map indicate fire seasons. The graph for Decatur, Illinois, obscures the provinces of Newfoundland and Prince Edward Island on the map. *(Modified from Schroeder MJ, Buck CC:* Fire weather, *Agriculture Handbook 360, Washington, DC, 1970, USDA Forest Service.)*

Fires exhibiting such phenomena often behave in an apparent erratic, sometimes dangerous manner.

Fire whirls appear frequently in and around wildland fires.[150] Most fire whirls are small and short-lived, but occasionally one becomes large and strong enough to do tornado-like damage and cause serious injury, such as occurred at Mt Kuki, Japan, in 1977;[189] death is also a distinct possibility. Their occurrence is usually associated with unstable air, moderate winds, and large heat sources created by plentiful and dry fuel concentrations (Figure 14-30) or terrain configurations that concentrate the heat from the fire (e.g., lee side of a ridge).[215,228] These fire-induced tornado-like whirlwinds can travel up to 2.5 km (1.6 miles) from the main fire[458] and can cause considerable damage and even lead to injuries and fatalities. On March 7, 1964, a fire whirlwind that formed on the Polo Fire near Santa Barbara, California, cut a 1.6-km (1-mile) path, injuring four people and destroying two houses, a barn, four automobiles, and a 100-tree avocado orchard.[387] The fringe of the fire whirl passed over a fire truck and sucked out the rear window. A firefighter standing on the rear platform of the vehicle was pulled up vertically so that his

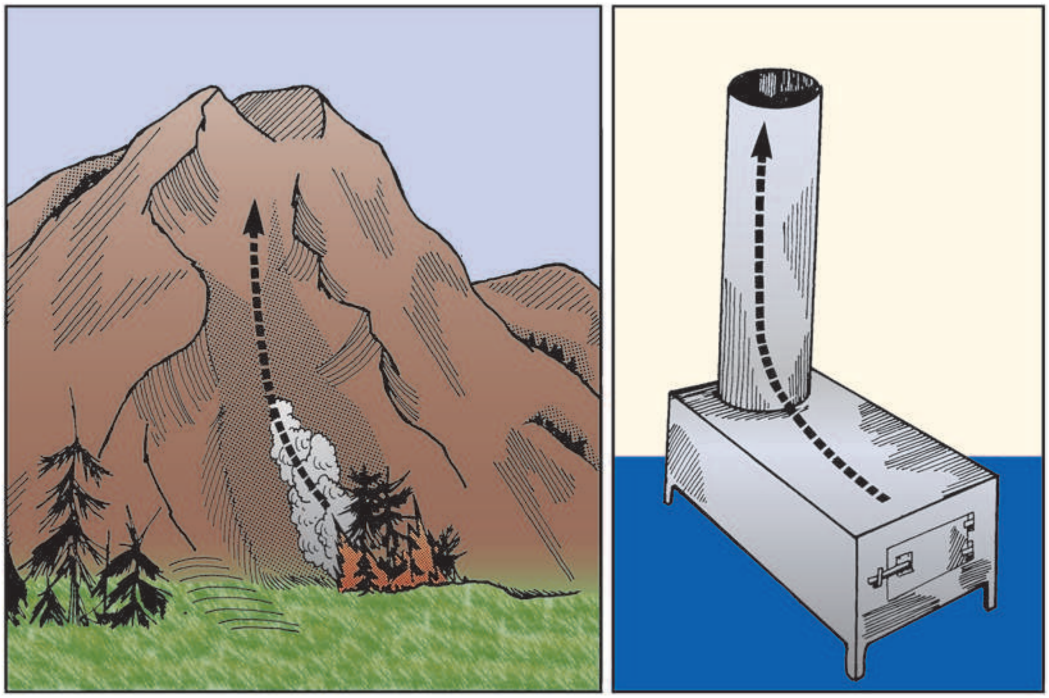

FIGURE 14-29 Chutes, chimneys, and box canyons created by sharp ridges provide avenues for intense updrafts (like a fire in a woodstove) and rapid rates of spread. People should avoid being caught above a fire under these topographic conditions. *(Modified from Barrows JS:* Fire behavior in Northern Rocky Mountain forests, *Station Paper No 29, Missoula, Mont, 1951, USDA Forest Service, Northern Rocky Mountain Forest and Range Experiment Station.)*

FIGURE 14-30 Large fire whirl associated with the burning of logging slash debris near Whitecourt, Alberta. *(Courtesy University of Alberta; photo by M.Y. Ackerman.)*

feet were pointing to the sky while his hands clasped the safety bar. A small piece of plywood was rammed 7.6 cm (3 inches) into an oak tree.

Several years of drought combined with a national forest health issue that has produced many dead and dying forests set the stage for extreme fire behavior conditions that threaten people, property, and natural and cultural resources. Protection from these conditions requires understanding of the crown fire process. *Crowning* involves a fire spreading horizontally as a "wall of flame" from the ground surface up through and above the canopies of trees (Figure 14-31) or tall shrubs. The first views inside a crown fire were documented on videotape during the International Crown Fire Modelling Experiment near Fort Providence in Canada's Northwest Territories in 1997.[476] The onset of

FIGURE 14-31 Experimental crown fire in a northern jack pine *(Pinus banksiana)* and black spruce *(Picea mariana)* forest near Fort Providence, Northwest Territories, Canada. The average height of flames from crowning forest fires is generally one to one and a half times taller than the tree height. Flame flashes will extend considerably higher into the fire's convection column. *(Courtesy Canadian Forest Service.)*

crowning is significant from both a safety and suppression perspective. At a minimum, when a fire crowns, the rate of spread and intensity doubles, and the area burned quadruples.[12]

Maclean[284] gives an indication of how crown fires were handled in the early part of the 20th century by the USDA Forest Service:

> By the time they reached the fire, it had spread all over the map, and had jumped into the crowns of trees, and for a lot of years a prospective ranger taking his exam had said the last word on crown fires . . . When asked on his examination, "What do you do when a fire crowns?" he had answered, "Get out of the way and pray like hell for rain."

This wisdom seems still valid today. Rothermel[417,419] described the conditions that produce a crown fire:

1. Dry fuels
2. Low humidity and high temperatures
3. Heavy accumulations of dead and downed fuels
4. Small trees in the understory, or "ladder fuels"
5. Steep slope
6. Strong winds
7. Unstable atmosphere
8. Continuous crown layer

The two most prominent behavior patterns of crown fires are wind driven and plume (or convection) dominated. Each type of crown fire poses a distinct set of threats to people. Free-burning wildland fires are seldom uniform and well behaved, so these descriptions of wind-driven and plume-dominated crown fire behavior may not be readily apparent. The behavior of these types of fires can be expected to change rapidly as environmental, fuel, and topographic conditions change.[417]

Wind-Driven Crown Fire. A running crown fire can develop when winds increase with increasing elevation above the ground, driving flames from crown to crown (Figure 14-32). Steep slopes can produce the same effect. Spread rates in conifer forests can reach up to 12 km/hr (7.5 miles/hr) for brief periods of time[254,444] and are possibly faster in mountainous terrain,[417] especially in open forest or nonforested or shrubland fuel types.[98,133] A running crown fire is accompanied by showers of firebrands downwind, fire whirls, smoke, and rapid development of a tilted convection column. As long as the wind remains fairly constant from one direction, the flanks of the fire can remain relatively safe. The greatest threat is to people who are immediately at the head, or downwind side, of the fire, although medium- and long-distance spot fires can also pose an unexpected risk.[5,69]

Plume-Dominated or Convection-Dominated Crown Fire. An alternative form of crown fire develops with relatively low wind speeds or when wind speed decreases with elevation above the ground. This type of crown fire is referred to as *plume dominated* or *convection dominated* because it is characterized by a towering convection column that stands vertically over the fire (Figure 14-33). This type of fire poses a unique threat to people because it can produce spot fires in any direction around its perimeter. It can also spread rapidly as the combustion rate accelerates.

One form of a plume-dominated crown fire that can be especially dangerous is when a downburst of wind blows outward near the ground from the bottom of the convective cell. These winds can be extremely strong[226] and can greatly accelerate a fire's spread. This type of wind event occurred during the major run of the Dude Fire near Payson, Arizona, on June 26, 1990, when six firefighters were killed.[216]

Some indicators help signal the onset of a downburst from a plume-dominated crown fire. The surest indicator is the occurrence of precipitation of any amount, even a light sprinkle, or the appearance of virga (evaporating rain) below the base of a cloud formation.[417,427] Another indicator is rapid development of a strong convection column above the fire, or nearby thunder cells. A third and very short warning is the calm that develops when the in-draft winds stop before the turnabout and outflow of wind from the cell. This brief period of calm may be accompanied by a humming sound just before the reversing wind flow arrives. If any of these indicators is present, the area should quickly be evacuated and a safe refuge area sought. The downburst may also break or uproot trees, creating an additional hazard for people.[417]

Value of Fire Danger Ratings

Forest fire control in the early days before organized protection was relatively simple. As Williams[533] explains:

> One tried to keep wild fires out of the settlements and in the woods where they belonged. There was no planning—fire was fought wherever it could not be avoided. Later, as forest fire control became organized,

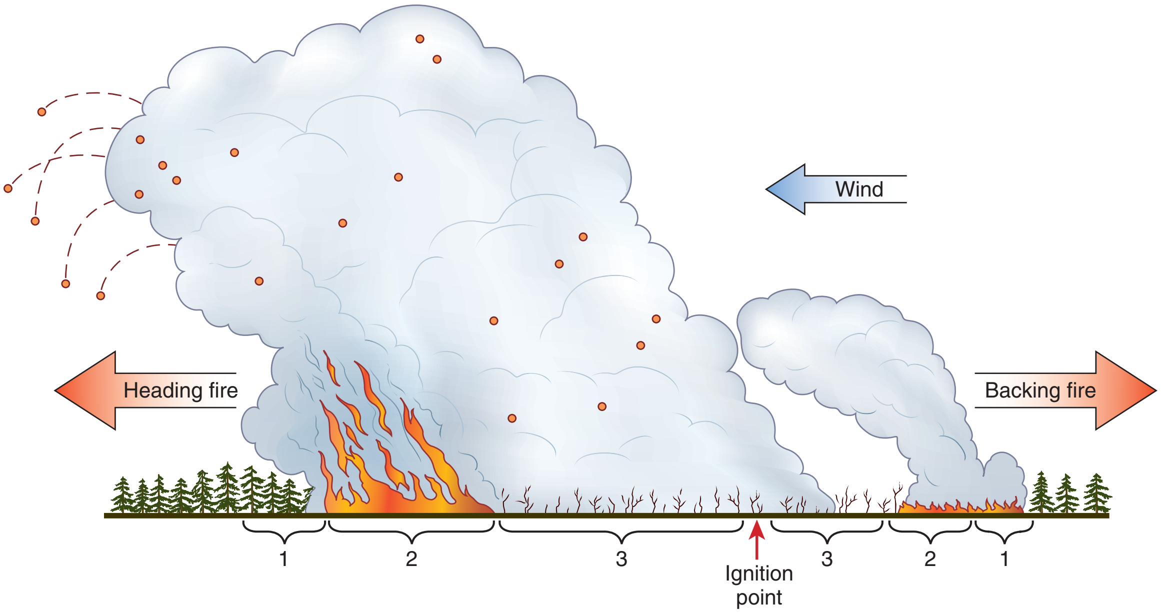

FIGURE 14-32 Cross-sectional view of a wind-driven crown fire, illustrating the various stages of combustion: *1*, preignition; *2*, ignition and flaming combustion; and *3*, glowing or smoldering combustion. People are most at risk on the downwind side and upper flanks of such a free-burning fire. This type of fire is caused by winds that increase in velocity with increasing elevation above the ground. *(Modified from Cottrell WH:* The book of fire, *ed 2, Missoula, Mont, 2004, Mountain Press Publishing Co.)*

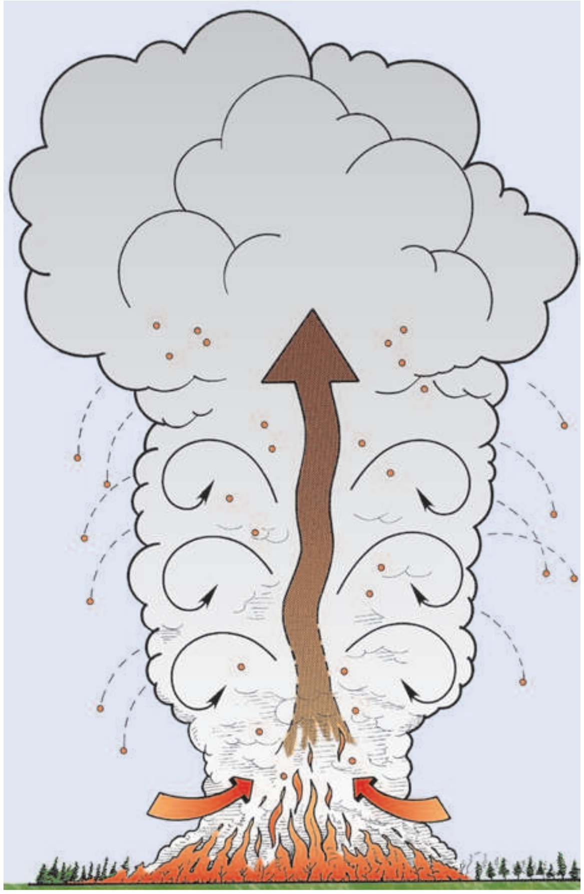

FIGURE 14-33 Cross-sectional view of a plume-dominated or convection-dominated crown fire. People are at risk around the complete perimeter of this type of fire, because it has the potential to spread intensely or spot in any direction around its perimeter with little or no warning. This form of crown fire develops when wind velocities are relatively low or when velocities decrease with elevation above the ground coupled with critically dry and abundant fuel conditions. The convective plume associated with this type of fire may rise to 7600 to 9100 m (25,000 to 30,000 feet) above the ground. *(Modified from Cottrell WH:* The book of fire, *ed 2, Missoula, Mont, 2004, Mountain Press Publishing Co.)*

specific plans for fire control action became an obvious necessity. To form the basis for such plans, a reliable measure of the day-by-day state of forest flammability was needed.

To help fill that need, full-time research into the systematic measurement of forest flammability or "fire danger" began in the United States and Canada in the 1920s and has continued more or less uninterrupted since that time.[22,83]

Fire management agencies employ fire danger rating systems to help them gauge ignition and fire behavior potential based on fuel characteristics, past and current weather conditions, and certain topographic variables that encapsulate fire behavior knowledge garnered from research.[23,281,474] Such systems have been demonstrated to be of value in accurately predicting fire behavior in the WUI.[10] In commenting on the historic fatality fires around the turn of the 20th century, Brown and Davis[83] pointed out that in general terms, these situations reflected the public's indifference to forest fires that had persisted for so many years and still lingers to some degree today:

The Maine fires of 1947 were a sobering reminder in this respect. They occurred at a time when fire danger measurement was well understood and means for mass public dissemination of this information were well developed. Responsible officials were aware of the mounting fire danger. Nonetheless, some fifty fires were reported to have been burning in Maine at the time the major break occurred on October 23. A contributing circumstance was the general feeling that, as it was late October, the fire season was over.

Fire danger rating outputs are being applied directly to the task of community fire safety and protection, including early-warning or alert systems linked to fire weather forecasts that operate during the fire season, such as those developed for the Northwest Territories, Canada.[40] This information is now commonly accessible to the general public on the Internet regarding countries like the United States (www.wfas.net), Canada (http://cwfis.cfs.nrcan.gc.ca), New Zealand (www.ffr.co.nz/), the European Union,* and many other countries (www.fire.uni-freiburg.de). Forecasts of fire weather conditions are by themselves useful; the information can also be used to forecast fire danger indexes and potential fire behavior characteristics.[63,163,427] In Australia, television and radio are relied on extensively to alert the public of "total fire ban" days (i.e., extreme fire danger) based on current fine-fuel moisture levels, drought status, and forecasted fire weather conditions.[127] Fire danger rating and fire behavior predictions can be used to judge whether evacuations are required or to assist people with preparing for the eventuality of a fire arriving.[240] Evacuation routes must be established in advance, and the actual time taken to evacuate to a safe zone needs to be determined in much the same manner as a wildland firefighter uses an escape route to reach a safety zone or an urban dweller evacuates a building fire using preidentified travel routes and exit locations.

FIRE-RELATED INJURIES AND FATALITIES

Few would argue that battling wildland fires is physically arduous work that occurs in austere conditions and includes inherent dangers. As a result, injuries and death occur infrequently but regularly. In the United States, statistics for wildland fire–related serious injuries and deaths have now been maintained for several decades and have provided useful data in developing protocols for safe firefighting practices. The nature of these fatalities can be broadly categorized as deaths directly by fire in burnover or entrapment situations and deaths resulting from fire suppression activities.

Most fatalities in wildland fire burnover situations occur on days of extreme fire danger when people are exposed to abnormally high heat stress caused by weather or proximity to fires. Loss of life is dramatically highlighted under extreme burning conditions; however, many more people are injured than are killed by fires.

One of Australia's worst bushfire disasters occurred on February 7, 1967, when 62 people died in Tasmania.[301,529] Analysis of the locations and ages of 53 individuals at the time of death are instructive (Tables 14-3 and 14-4). Most people whose bodies

*www.researchgate.net/profile/Domingos_Viegas/publication/229042984_Comparative_study_of_various_methods_of_fire_danger_evaluation_in_Southern_Europe/links/0c96051a8bbd686302000000.pdf.

TABLE 14-3 Location of Bodies of 53 Persons Who Died in Tasmanian Fires, February 7, 1967

Location	No. of Deaths
Mustering stock	2
Firefighting	11
Traveling in a vehicle	2
Escaping from and found at some distance from houses	11
Within a few meters of houses	10
In houses	17

From McArthur AG, Cheney NP: *Report on Southern Tasmania Bushfires of 7 February 1967,* Hobart, Australia, 1967, Government Printer.

TABLE 14-4 Age Distribution of 53 Persons Who Died in Tasmanian Fires, February 7, 1967

Age Group (yr)	No. in Group	Average Age (yr)
1-25	1	23
26-50	13	38
51-75	26	64
76-88	13	82

From McArthur AG, Cheney NP: *Report on Southern Tasmania Bushfires of 7 February 1967,* Hobart, Australia, 1967, Government Printer.

were found within or near houses were old, infirm, or physically disabled. More than one-half of the houses vacated by the 11 people who traveled some distance before being killed were not burned. Most of these victims would probably have survived if they had remained in their homes. Most of the 11 firefighters who died were inexperienced. Many might have survived if they had observed fire behavior and safety rules.

Krusel and Petris[259] investigated the circumstances surrounding the 32 civilian deaths that occurred during the 1983 Ash Wednesday bushfires in Victoria. As a result, they identified three categories of victims, suggesting ways to address the deficiencies in the manner in which individuals respond to the wildfire threat:

- Victims who recognized the real threat to their safety with enough time to save their lives, but chose an ineffective survival strategy
- Victims who did not recognize the real threat to their safety in time to implement an effective survival strategy
- Victims who were physically incapable of implementing an effective survival strategy

Similar situations have been reported around the world. For example, during the 1993 fire season in the Tarragona Province of eastern Spain, five people were killed trying to escape from their home, built in the woods and surrounded by a fire; four of the victims were older adults who dared not flee until it was impossible to escape.[505]

In 2007 the National Wildfire Coordinating Group published an analysis of 310 wildland firefighter fatalities that occurred in the United States from 1990 to 2006.[295] During this 17-year period, burnover situations constituted only the fourth most common cause of death, and the number of these incidents declined during the surveyed years. A total of 64 deaths, or 20.6%, were attributed to burnovers during this time period. By comparison, 72 deaths (23.2%) resulted from aircraft accidents, 71 deaths (22.9%) were caused by vehicle accidents, and 64 wildland firefighters (21.9%) died from heart attacks. The remaining percentages were classified as deaths resulting from falling trees, snags, or rocks (3.9%), other medical causes (2.9%), and miscellaneous causes (4.5%). Thus, the three leading causes of deaths related to wildland firefighting activity were not the result of individuals being burned over or entrapped by a wildland fire, although five firefighters were killed at a single location on the 2006 Esperanza fire in southern California.[500] Reports for 2007-2009, in which 49 wildland firefighters died, showed similar trends.[297] Interventions are possible to reduce the number of firefighter fatalities associated with aircraft and vehicle accidents, as well as those linked to heart attacks[292,296] (Box 14-5).

There have been more than 160 wildland fire suppression–related fatalities in Canada during the 70-year period between 1941 and 2010.[25] The names of many of these wildland firefighters are listed, along with their structural brethren, on the Canadian Fallen Firefighters Foundation website (www.cfff.ca/EN/index.html). Although the causes for all these firefighter fatalities are not precisely known, certainly aircraft-related fatalities have been far more common in recent decades compared with earlier years of recordkeeping.

It is much more difficult to gather accurate information regarding the incidence of minor to moderate injuries and episodes of illness among wildland firefighters. These statistics do not exist for several reasons. First, in general, the field draws individuals with a "can-do" attitude who are willing to work through many hardships that would cause workers in a general workforce to take time off for rest. Second, the vast majority of the care happens informally either on the fire lines as work continues or at base camps at temporary, low-level medical facilities where formal records are not maintained. Firefighters will often wait until they leave a fire to seek treatment from a private provider for an ongoing problem, and the injury or illness will not be tracked as a workplace-related incident.

The U.S. Bureau of Land Management has guidelines outlining the nature of burn injuries that require transport to and evaluation at a specialized burn center.[248] This protocol largely corresponds to the guidelines of the American Burn Association (www.ameriburn.org/).

By comparison, other medical protocols are region dependent. Fire suppression crews frequently have one or two medics, usually trained to the Emergency Medical Technician (EMT)–Basic level, among their members. The skill set of these medics depends on whether they are active, professional medical providers when they are not fighting wildland fires, or if they maintain the certification solely for the position on the crew. Larger incidents may employ additional medical personnel to survey personnel on the fire lines or at portable medical tents/trailers in the base camp. Midlevel providers, such as paramedics, nurse practitioners, and physician's assistants, usually staff these facilities. The availability of a medical command physician varies by region in the United States.

When a firefighter requires evaluation and care outside the scope of first responders, the patient must be transported from the incident. The nature of the problem dictates if this transport requires specialized care at a trauma or burn center or if the local hospital closest to the incident can provide care. When large fires require hundreds to thousands of personnel, a small local hospital in a rural area may be overburdened by the temporary additional population. Transport protocols are determined on a regional basis and may use ground ambulances or air medical service (via rotary- or fixed-wing aircraft) depending on the nature of the incident and availability of resources.

COMMON DENOMINATORS OF FIRE BEHAVIOR ON FATALITY FIRES

A review of wildland firefighter fatality records between 1926 and 1976 shows that 145 men died in 41 fires from fire-induced

BOX 14-5 21st-Century Common Denominators for Wildland Fire Fatalities

More than 20% of fatalities during wildland firefighting operations continue to concur in burnovers and entrapments. Carl Wilson's original common denominators[536] are just as important in the 21st as they were in the 20th century. However, as the major causes of firefighter fatalities shift, it has suggested that additional factors need to be considered:

- Firefighters are most likely to die in an aircraft accident. Before every flight, fire managers must ask, "Is this flight essential?" and "Is everyone onboard essential to the mission?"
- Firefighters are nearly as likely to die in a motor vehicle accident as in an aircraft accident. Driving too fast for the conditions, failure to wear seat belts, rushing to a fire, and driving home while exhausted from firefighting kills firefighters.
- Firefighters can reduce their risk for dying from heart attack on the job by staying fit, maintaining their ideal body weight, and having regular medical checkups.
- Unexpected events such as falling snags, rolling rocks, downed power lines, and lightning strikes cause more than 8% of fatalities during wildland firefighting operations. Firefighters and fire managers can reduce fatalities by learning to expect these unexpected events.

Modified from Mangan R: *Wildland firefighter fatalities in the U.S.: 1990-2006,* National Fire Equipment System Publication PMS 841, Boise, Idaho, 2007, National Interagency Fire Center, National Wildfire Coordinating Group, Safety and Health Working Team.

injuries.[353,354,536] Besides the 1949 Mann Gulch and 1990 Dude fires, large losses occurred on the 1933 Griffith Park Fire in California (29 deaths and 150 others injured),[182] the Blackwater Fire in Wyoming in 1937 (15 deaths),[78] the Pepper Hill Fire in Pennsylvania in 1938 (8 deaths),[429] the Hauser Canyon fire in California in 1943 (11 deaths),[114,446] the Rattlesnake Fire in California in 1953 (15 deaths),[287] the 1956 Inaja Fire in California (11 deaths),[428,492] the 1966 Loop Fire in California (12 deaths),[148] and the 1968 Canyon Fire in California (8 deaths).[154] Wilson's review[536] of people killed by wildfires in areas protected by other federal, state, county, and private agencies indicated 77 fire-induced fatalities in 26 fires during this same time period. The United States is not the only country to have had firefighters killed by entrapments and burnovers. For example, 25 soldiers were killed while involved in wildland firefighting operations near Lisbon, Portugal, on September 6, 1966.[245] Australia has experienced a number of firefighter fatality incidents.[119,245] For example, on December 2, 1998, five volunteer firefighters were killed near the town of Linton, Victoria, when the tanker they were traveling in was overrun by fire.[145]

From his analysis of U.S. incidents from 1926 to 1976, Carl Wilson[536] identified several common features associated with fatal fires:

1. Most of the incidents occurred on relatively small fires or isolated sectors of larger fires.
2. Most of the fires were innocent in appearance prior to the "flare-ups" or "blow-ups." In some cases, the fatalities occurred in the "mop-up" stage.
3. Flare-ups occurred in deceptively light fuels.
4. Fires ran uphill in chimneys, gullies, or on steep slopes.
5. Suppression tools, such as helicopters or air tankers, can adversely modify fire behavior (helicopter and air tanker vortices have been known to cause flare-ups).

Many firefighters were surprised to learn that tragedy and near-miss incidents occurred in fairly light fuels, on small fires, or on isolated sectors of large fires, and that the fire behavior was relatively quiet just before the incident, even in the cases involving aircraft.[154,168,225] Many have been led to believe that it is the conflagration or large, high-intensity crown fire in timber and heavy brush that traps and kills firefighters. With some exceptions, however, most fires were innocuous appearing just before the fatal moment. Case studies of wildland firefighter fatality incidents from other regions of the world suggest similar patterns and circumstances, for example, the 25 fatalities at Puerto Madryn, Argentina, on January 21, 1994;[171] 10 fatalities in the Sabie district of the Mpumalanga Province of South Africa in 1994;[172] and five fatalities associated with three different incidents in Portugal during the 1999 and 2000 fire seasons.[508] Wildland firefighter fatalities have been reported in Italy, Spain, Portugal, and Croatia in the last decade.[507,511]

Wilson[536] concluded that the hairline difference between fatal fires and near-fatal fires was determined by the individual's reaction to a suddenly critical situation. Escapes were the result of luck, circumstances, advance planning, a person's ability to avoid panic, or a combination of these factors. Frequently, poor visibility and absence of concise fire information threatened survival opportunities by creating confusion and panic. For many years, Wilson's findings were summarized in a popular booklet, published initially by the USDA Forest Service and in later years by the National Wildfire Coordinating Group.[352] Beginning in 2010, this information has now been incorporated into the *Incident Response Pocket Guide,* published by the U.S. National Wildfire Coordinating Group.[360]

The British Columbia Forest Service found many of the same factors identified by Wilson in their investigation of a number of close calls or near misses that occurred during the 1994 fire season.[53] The few wildland firefighter fatalities in Canada caused by entrapments or burnovers[37,480] are also in alignment with Wilson's findings.[64]

Most fatality fires are the result of a temporary escalation in fire spread, an increase in flame dimensions, crowning and spotting activity, or the development of large fire whirls, often occurring suddenly and with very little warning. A gentle surface fire will rapidly develop into a high-intensity fire. This could result, for example, from thunderstorm downdraft winds,[129,427] a change in fuel types,[53] fire whirl development as the fire reaches a ridgeline with an opposing gradient wind,[150] or a "slope reversal" (e.g., fire slowly backs down a northerly aspect, crosses the drainage, and then rapidly spreads up the south-facing slope),[402] such as documented with time-lapse photography on the 1979 Ship Island fire in central Idaho.[350] As the moisture content of dead and live fuels decreases, fires become increasingly more responsive to slight changes in wind strength and slope steepness. Once "critically" dry levels are reached, fire behavior becomes exceedingly unstable.[29,88,281]

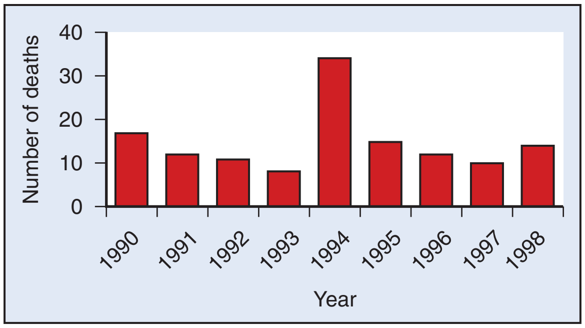

FIGURE 14-34 Annual death toll for persons who died from all causes while involved in fighting wildland fires in the United States from 1990 to 1998 (133 total deaths). *(From Mangan R:* Wildland fire fatalities in the U.S.: 1990-1998, *Technical Report 9751-2817-MTDC, Missoula, Mont, 1999, USDA Forest Service, Missoula Technology and Development Center.)*

NATURE OF INJURIES AND FATALITIES

Fire-related injuries and fatalities are a direct consequence of heat, flames, smoke, critical gas levels, or indirect injuries[293,330] (Figure 14-34). Injuries and fatalities associated with wildland fires fall into one of these five categories:

1. Heat: direct thermal injury, inhalation, and heat stress disorders
2. Flames: direct thermal injury and inhalation
3. Smoke: inhalation and mucous membrane irritation
4. Critical gas levels: oxygen and carbon monoxide (CO)
5. Indirect effects: acute and chronic medical disability and trauma

Intense fires that produce very high temperatures are generally brief. The duration of intense heat increases with fuel load, being greater in a forest fire where heavy fuels[471] are burning than in a grass[129] or shrub fire (see Table 14-2). Temperatures near the ground are lower because radiant heat is offset somewhat by inflow of fresh air, and gases of combustion rise and are carried away by convection.[118] Close to the ground, within a few meters of flames reaching up to 11 m (36 feet), air temperatures may be less than 15° C (59° F) above ambient levels. The breathing of heated air can be tolerated for 30 minutes at 93° C (199° F) and for 3 minutes at 250° C (482° F).[281] Death or severe pulmonary injury occurs when these limits are exceeded. Thermal injuries of the respiratory tract frequently contribute to the clinical picture of smoke inhalation. People trapped in a fire may have no choice but to breathe flame or very hot gases. This usually injures the tissues of the upper airway and respiratory tract, most often the nose, nasopharynx, mouth, oropharynx, hypopharynx, larynx, and upper trachea. These injuries may result in edema that obstructs the airway and produces asphyxia or that causes tracheitis and mediastinitis.

Signs of thermal injury to the airway include thermal injuries to the head, face, and neck; singed facial hair; burns of the nasal, oral, or pharyngeal mucosa; and stridor or dysphonia.[326,467,548] Associated with a history of exposure to flame and hot gases in a closed space, these clinical findings strongly suggest the presence of a thermal injury to the airway. With the potential for acute airway obstruction, there is obvious urgency in establishing this diagnosis. Most experts who treat thermal injuries of the tracheobronchial tree advocate early visualization of the vocal cords by laryngoscopy and bronchoscopy.[327] Bronchoscopy is a useful predictor of the clinical course and urgency of intensive care unit intervention. In addition, one report shows a significantly greater incidence of pneumonia and late mortality in patients with facial burns than in those without them.[544]

Burns of the lower trachea are rarely reported. In fact, injuries to and beyond the carina are difficult to produce when the trachea is cannulated and hot gases are delivered in the anesthetized dog.[324,547] Air has a very low specific heat and is therefore a poor conductor of thermal energy. In addition, the thermal exchange systems of the upper airway are quite efficient. The hot gas or flame is cooled sufficiently in the upper airway so that it does not burn the bronchi or more distal structures. However, although water or steam in the hot gas mixture is probably rare, it is a much more efficient conductor of heat and permits significant thermal injury to the lower trachea and bronchi. A delayed onset (2 to 24 hours after smoke inhalation) of pulmonary edema and adult respiratory distress syndrome is widely reported and should be anticipated.

Heat stress[177,434] occurs when air temperature, humidity, radiant heat, and poor air movement combine with strenuous work and insulative clothing to raise body temperature beyond safe limits. Sweating cools the body as moisture evaporates. When water lost through sweating is not replaced, physiologic heat controls can deregulate, and body temperature may rise, leading to heat exhaustion or heatstroke (see Chapters 12, 13, and 89).

Direct contact with flames causes thermal injury, and death is inevitable with exposure for long periods. Burns may be superficial, partial, or full thickness (see Chapter 15). Immediate death results from hypotension, hyperthermia, respiratory failure, and frank incineration.

As mentioned earlier, the common cause of asphyxia in wildland fire is smoke. Danger increases where smoke accumulates because of poor ventilation, as in caves, box canyons, narrow valleys, and gullies. Dense, acrid smoke is particularly irritating to the respiratory system and eyes. Excessive coughing induces pharyngitis and vomiting. Keratitis, conjunctivitis, and chemosis may make it impossible to keep the eyes open.

The levels of oxygen, CO, and CO_2 associated with wildland fires are a concern. Critical levels readily occur in a closed space and near burning or smoldering of heavy fuels, but the open space associated with wildland fires usually contributes to continual mixing of air. Misconceptions or myths about lack of oxygen or excessive CO and CO_2 in a wildland fire abound in the popular literature.[129]

Flaming combustion can be maintained only at oxygen levels that exceed 12%, a level at which life can also be supported.[118,281] With continued in-drafts of air that feed the flames, a fresh source of oxygen is usually present. Even mass fires, in which large tracts of land are burning, rarely reduce oxygen to hazardous levels. Low oxygen levels may occur, however, where there is little air movement, such as in caves or mine shafts (Figure 14-35) or in burned-over land that continues to smoke from smoldering fuels.

Concentrations of CO exceeding 800 parts per million (ppm) can cause death within hours. Most fires produce small quantities, but atmospheric CO concentrations rarely reach lethal levels because of air movement. High CO concentrations appear to be associated with smoldering combustion of heavy fuels, such as accumulations of fallen tree stems or of slash piles, and CO may also collect in low-lying areas or underground shelters (e.g., root cellars).[120] Outdoors, the danger lies in continual exposure to low concentrations that can increase blood carboxyhemoglobin levels. Prolonged exposure affects the central nervous system, resulting in headache, impaired judgment, progressive lethargy, decreased vision, and other psychomotor deficits.[536]

Carbon monoxide levels of 50 ppm were measured close to a prescribed burn in grass.[149] In another estimate, CO concentrations of 30 ppm were found about 61 m (200 feet) from the fire front. Studies on the 1974 Deadline and Outlaw forest fires in Idaho showed that firefighters were exposed to CO levels above the standards proposed by the National Institute of Occupational Safety and Health (NIOSH): 35 ppm over an 8-hour period.[483] However, more recent measurements of CO levels and particulates made on wildfires between 1992 and 1995[408] indicate that wildland firefighters are seldom exposed to smoke that exceeds U.S. Occupational Safety and Health Administration (OSHA) permissible exposure limits.[409]

Decreased ambient oxygen may contribute to hypoxia and the overall picture of smoke inhalation (Table 14-5). This mechanism is at least variably operant. When standing gasoline was ignited in a closed bunker, the fire self-extinguished, whereas the ambient oxygen level remained at 14%, a survivable level.[324] Injecting burning gasoline or napalm into bunkers produced nearly complete and prolonged exhaustion of ambient oxygen.

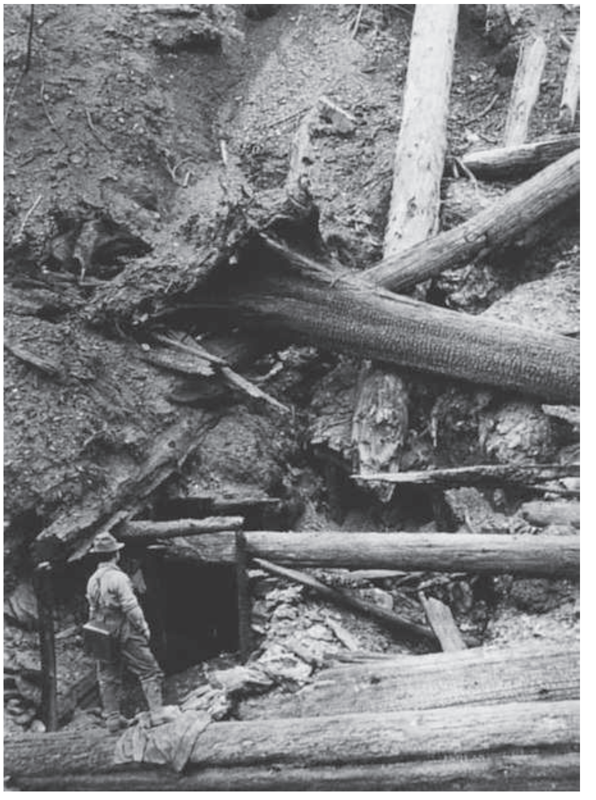

FIGURE 14-35 USDA Forest Service Ranger Ed Pulaski led 42 men and two horses to this mine tunnel near Placer Creek in northern Idaho to seek refuge from the 1910 firestorm. One man failed to reach the tunnel and was burned beyond recognition. All the men in the tunnel were evidently unconscious for a time. Five died inside, apparently from suffocation. The remainder of the crew was evacuated to the hospital in Wallace, where all recovered. *(Courtesy USDA Forest Service; photo by J.B. Halm.)*

TABLE 14-5 Human Response to Decreased Ambient Oxygen at Sea Level

Ambient Oxygen (%)	Human Response
20.9	Normal function
16-18	Decreased stamina and capacity for work
12-15	Dyspnea with walking; impaired coordination; variable impaired judgment
10-12	Dyspnea at rest; consciousness preserved; impaired judgment, coordination, and concentration
6-8	Loss of consciousness; death without prompt reversal
<6	Death in 6 to 10 minutes

Conflicting data make it difficult to classify definitively situations in which decreased ambient oxygen and subsequent hypoxia of exposed individuals contribute to the clinical picture of smoke inhalation. Studies in which ambient oxygen was measured by scientists did not show significant depletion at the scene of the fire.[217]

Few data are available on CO_2 levels around wildland fires. Although it may be produced in large quantities, CO_2 apparently never reaches hazardous concentrations, even in severe fire situations.[118,281]

The quantity of burning fuel and type of topography affect levels of oxygen and toxic gases. Danger is greater in forest fires where heavy fuels burn over long periods than in quick-moving grass and shrub fires. Topography has a major influence: caves, box canyons, narrow canyons, gulches, and other terrain features can trap toxic gases or hinder ventilation, thereby preventing an inflow of fresh air. Although most fatalities result from encounters with smoke, flames, and heat, critical gas levels can induce handicaps sufficient to render the victim more vulnerable to other hazards. Respirators[298] are not routinely used on wildland fires or on WUI fires, but could play a role in the future as a means of protection against airborne toxic materials.

WILDLAND FIRES, AIR TOXINS, AND HUMAN HEALTH

In the United States each year, about 80,000 firefighters are involved with suppression activities on about 70,000 wildland fires that burn an average of more than 0.8 million hectares (2 million acres). In 1988, more than 2 million hectares (5 million acres) of land were burned, with a total combined suppression cost exceeding $600 million. The firefighting effort has another cost that has not been quantified: the effect of smoke on firefighter health and productivity. Over the 4 months of the 1988 Greater Yellowstone Area fires, about 40% of the 30,000 medical visits made by wildland firefighters were for respiratory problems. More than 600 firefighters required subsequent medical care. In the Happy Camp area during the Klamath fire complex in California in 1987, ambient CO concentrations measured as high as 54 ppm on a volume basis.[515] A better understanding of the long-term effects of wildland fire smoke on people is clearly needed, although "firefighters just keep coming back year after year," notes Dr. Brian Sharkey,[439] then a wildland firefighter health and safety specialist with the USDA Forest Service's Missoula Technology and Development Center (MTDC), who coordinated an 8-year study of the health hazards of smoke on wildland firefighters.[435,437]

Combustion of wildland fuels produces many by-products in a variety of concentrations, depending on the type of fuel and the nature of the fire characteristics.[371] The impact of these byproducts is very difficult to assess. Short-term studies have been inconclusive, and long-term studies are enormously complex and essentially absent from the literature. Completion of a prospective epidemiologic study would be highly informative. The combustion products of concern include these classes of materials:

- Particulate matter
- Polynuclear aromatic hydrocarbons
- Carbon monoxide
- Aldehydes
- Organic acids
- Semivolatile and volatile organic compounds
- Free radicals
- Ozone
- Inorganic fraction of particles

Large variances are associated with the development of smoke combustion products and exposure to the materials of concern.[515] Ward and colleagues[516] indicated that the toxicity of the combination of combustion products depends on the relative concentrations of the individual compounds, as well as the overall concentration and length of exposure. Individual toxicities are associated with many of the compounds found in smoke. The combined toxicity of these substances is not known. Detailed studies will perhaps provide answers so that risk management options can be exercised. One of these studies suggested that wildland firefighters experience a small, cross-seasonal decline in pulmonary function and an increase in several respiratory symptoms.[423] Eye irritation, nose irritation, and wheezing were associated with recent firefighting.

The strenuous work of fighting or escaping a fire magnifies chronic illnesses, age disabilities, exhaustion, and cardiovascular instability. Common trauma is induced by falling trees or limbs, rolling logs or rocks, vehicular accidents, poor visibility, panic, falling asleep in unburned fuels that later ignite, and leaving the safety of buildings and vehicles. Cuts, scrapes, scratches, lacerations, fractures, and eye injuries (foreign particles, smoke irritation, sharp objects) are other common afflictions. Poison oak, poison ivy, stinging insects, and poisonous snakes are additional sources of trauma during wildland fires. To avoid fire-related injuries and fatalities, a person must keep attuned to mental and physical stress levels and be aware of cumulative effects.[434] Ignorance of this simple principle is disastrous.

Accurate statistics have not been collected to document the frequency and nature of injuries and illnesses over the course of different fire seasons. The common afflictions previously listed are inherent to completing strenuous work under adverse conditions. Overall, the infrequency of major traumatic injuries speaks to the success of firefighters' adhering to established safety protocols.

A range of occupational and overuse injuries consistently emerges over the course of the fire season. Blisters and foot problems occur frequently early in the season, especially if off-season fitness has fallen by the wayside. As with other soft tissue injuries, these can be complicated if not promptly addressed with standard first aid. Muscle strains, back problems, and tendinitis often follow particularly intense work periods. These maladies are best prevented by firefighters' maintaining off-season fitness regimens to endure the physical rigors of firefighting.[276] Research and development carried out by the MTDC of the USDA Forest Service have led to invaluable contributions regarding the health and safety of wildland firefighters, including the following:

- Optimal work-rest patterns
- Firefighter nutrition and hydration requirements and regimens
- Heat stress and uniform/personal protective equipment design
- Tool testing to optimize firefighter efficiency
- The relationship between firefighter nutrition and immune function

These studies have informed U.S. firefighting protocols to improve productivity and firefighter safety.[176,436,438,440,441]

The informal surveys conducted of wildland firefighter health demonstrate a pattern of increasing respiratory symptoms over the course of the fire season. This pattern has become common enough that firefighters have coined a term—"camp crud"—to describe the range of symptoms shared throughout the camps. The severity and frequency of symptoms can have legitimate safety and productivity consequences. Smoke exposure has been considered as one factor contributing to the frequency of respiratory illness[47] and decreased respiratory function over the course of the fire season,[206] but there is no consensus on how interventions could be feasibly instituted to reduce smoke exposure in wildland fire suppression. Regular occurrences of the flulike "camp crud," especially late in the fire season, suggest a classic infectious outbreak pattern. Other infectious outbreaks that have spread through the wildland fire community include a series of methicillin-resistant *Staphylococcus aureus* (MRSA) outbreaks in fire camps during the 2008 and 2009 seasons in the United States.[276,501,502]

Infectious illness shared among firefighters is likely promoted by a variety of factors, including close working and living proximity, challenged immune conditions resulting from strenuous work and nutritional demands, hygiene conditions dictated to some degree by the environment, and potentially firefighters' access to seasonal vaccinations. Identifying possible interventions to decrease the burden from infectious illness would be beneficial to improving firefighter wellness and productivity. The epidemiologic data collected for wildland firefighting are very sparse, either for analysis of short-term outbreak situations or long-term health and wellness.

WILDLAND-URBAN INTERFACE FIRE SURVIVAL: PRINCIPLES AND TECHNIQUES

History has demonstrated repeatedly that individuals simply were not prepared to make correct choices of survival alternatives under stressful situations. At least 437 wildland firefighters were killed in the United States between 1910 and 2009 as a direct result of a burnover or entrapment by a free-burning wildfire.[353,295,297] Overconfidence, complacency, ignorance, bad habits, lack of preparation, poor decision making, and a host of other human factors quickly lead to improper and unsafe actions during wildfire emergency situations.[370,522,536] "Learning from mistakes" in these settings is not a reasonable education strategy because second chances are frequently unavailable in the wildland firefighting profession.

The USDA Forest Service organized a task force in 1957 to "study how we might strengthen our ways and means of preventing firefighting fatalities."[323] A major recommendation was to adopt service-wide standard firefighting orders. Ten standard firefighting orders[300,322] summarize the fundamental principles of safety on the fire line (Box 14-6). Although these were written for wildland firefighters, they apply to all people working, living, or traveling near wildland fires and are adapted here to remind emergency medical personnel, wildland homeowners, and recreationists of safety precautions to be taken around wildland fires. Much of this material is summarized in the handy *Incident Response Pocket Guide*.[360]

LCES: THE KEY TO SAFE PROCEDURES IN WILDLAND FIRE ENVIRONMENTS

LCES stands for lookout(s), communication(s), escape routes, and safety zone(s).[211] These variables are key components in evaluating the threat posed by fire-line hazards and determining the best course of action to follow (Figure 14-36).

Some fire management agencies have added an "A" to LCES, thus LACES, for a variety of meanings—attitude, awareness, and anchor points.[262,479] The Australasian Fire Authorities Council, for

BOX 14-6 Ten Standard Firefighting Orders Adapted for the General Public

1. Keep informed of fire weather conditions, changes, and forecasts and how they may affect the area where you are located.
2. Know what the fire is doing at all times through personal observations, communication systems, or scouts.
3. Base all actions on current and expected behavior of the fire.
4. Determine escape routes and plans for everyone at risk, and make certain that everyone understands routes and plans.
5. Post lookouts to watch the fire if you think there is any danger of being trapped, of increased fire activity, or of erratic fire behavior.
6. Be alert, keep calm, think clearly, and act decisively to avoid panic reactions.
7. Maintain prompt and clear communication with your group, firefighting forces, and command and communication centers.
8. Give clear, concise instructions, and be sure that they are understood.
9. Maintain control of the people in your group at all times.
10. Fight fire aggressively, but provide for safety first. (Nonqualified or untrained and improperly dressed or equipped persons should engage in firefighting operations only when it is absolutely necessary to assist injured persons. Wildland firefighting is a physically demanding task and should not be attempted by persons who are not in good physical condition.)

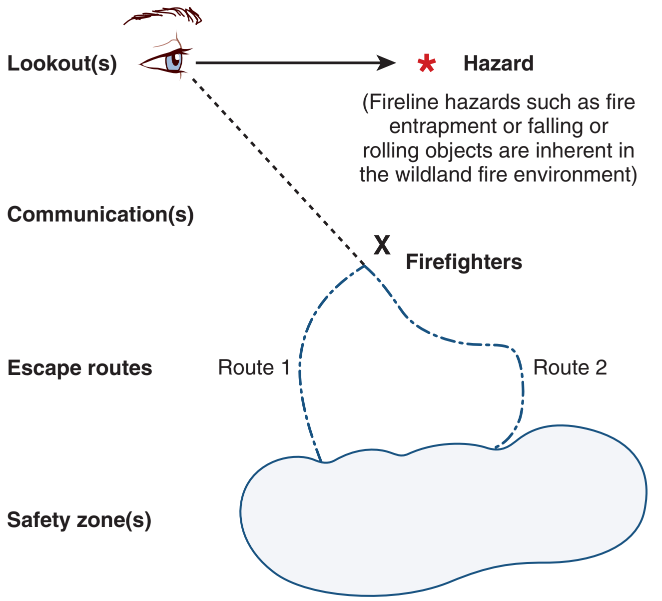

FIGURE 14-36 Concept of the LCES wildland fire safety system. *(From Gleason P: LCES: The key to safety in the wildland fire environment,* Fire Manage Notes *52:9, 1991.)*

example, adopted the LACES wildland fire safety acronym with the proviso that the "A" stands for *awareness*.[49] Most Canadian fire management agencies have taken the "A" in LACES to connote *anchor point*.[38,478] The importance of an anchor point is quite vividly highlighted in the video *A Firefighter's Return From a Burnover: The Kelly York Story,* which details the severe burn injuries received by a volunteer firefighter while attempting to suppress a grass fire in central California during the 1995 fire season.[185] As Australian fire management and research pioneers Harry Luke and Alan McArthur[281] state in their seminal reference book *Bushfires in Australia*, fire suppression "must at all times start from an anchor point."

The wildland fire environment's basic hazards are lightning, volcanoes, falling of fire-weakened trees and snags, rolling rocks and logs, entrapment by free-burning fires, respirable particulates, air toxins, and heat stress. When these hazards exist, there are two options: (1) do not enter the environment, or (2) adhere to safe procedures according to LCES.

LCES should be viewed from a "systems" point of view, stressing their interdependence. For example, the best safety zone is worthless if the escape route does not offer access at the point of need. People must be familiar with the LCES plan well before it is needed. In addition, the nature of wildland fires dictates that LCES be redefined in pace with changing conditions. The LCES wildland fire safety system is implemented as follows:

Lookout(s): Fixed lookouts or roving lookouts must be where both the hazard and the people can be seen. A lookout is trained to observe the wildland fire environment and to recognize and anticipate changes in fire behavior. When the hazard becomes a potential threat or danger, the lookout relays this information so people can depart for the safety zone.

Communication(s): Communication refers to alerting people to the approaching or pending hazard. Promptness and clarity are essential.

Escape routes: These paths lead from a currently threatened position to an area free from danger. More than one escape route must be available. Escape routes are probably the most elusive component of LCES because they change continuously. Timely access to safety zones is the most important component.[66] Research on wildland firefighter travel rates[28,60,102,424] suggests that, although civilians could momentarily advance at a rate in excess of what most wildland fires are capable of achieving, even the most fit individuals would not be able to sustain such a pace for more than a few minutes before being burned over by an advancing fire, especially on steep slopes—escaping uphill is thus a very questionable concept, unless a safety zone is known to be very nearby. Furthermore, some fire researchers believe there is a common tendency to overestimate the distance to a fire when observing through the forest, which may lull firefighters into thinking there is more time available for an orderly exit than is actually the case.[128]

Safety zone(s): In a safety zone, threatened persons find adequate refuge from danger. The size of the safety zone must be sufficient to provide protection from flames, radiant heat, convective heat, falling trees and snags, and rolling rocks and logs. The necessary size varies with changes in fuels, topography, wind conditions, and fire intensity. The question of whether a previously burned area will serve as a safety zone depends not only on the size of the area, but also on the degree of completeness in fuel consumption, both vertically and horizontally.[98,380]

What constitutes a safety zone varies widely among individuals.[457] Based on theoretical considerations for radiation emitted from a "wall of flame" under idealized conditions (e.g., level terrain, steady-state fire conditions),[99] it has been suggested, from the standpoint of flame radiation, that a safety zone should be large enough that the distance between the human occupants and flame front be at least four times the maximum expected flame height at the edge of the safety zone[101] (Table 14-6). It should be emphasized that in deriving this rule of thumb, several assumptions had to be made that could ultimately limit the usefulness of this simple guide,[470] although some field verification has been accomplished.[100] Furthermore, both the modeling and resultant radiation-based guide do not consider flame impingement or horizontal reach into a clearing, fire whirls, or any allowance for convective heat transfer, which will be significant under windy conditions in sloping terrain.[129,416] Obviously, further study, including field measurements, and development are warranted (e.g., allowance for convective heating on a slope), which is indeed the case.[94,96] Nevertheless, while acknowledging these limitations, this rule of thumb has been incorporated into existing operational guidelines,[360] training course material,[480] and computer programs.[44] According to Butler and Forthofer,[103] additional modeling (e.g., radiation on a sloping surface), subsequent observations, and other field measurements support "four times flame height" for minimum safety zone size, although research continues.[95]

While serving as the ignition boss during the International Crown Fire Modeling Experiment (ICFME) in the Northwest Territories,[18,463] one of the authors (MEA) was able to informally evaluate the Butler and Cohen[99,101] safety zone guideline. Based on observations and the experience of being on the backside or upwind edge of all the ICFME experimental crown fires,[464,476] the four-times-flame-height rule of thumb seems to be reasonably valid. As Butler and Forthofer[103] note, "It's important to realize that this should be considered a minimum—meaning that in all cases larger is better."

In using Butler and Cohen's rule of thumb[99,101] for safety zones or in turn, Table 14-6, the logical question is, "How does one go about estimating flame height in advance of a fire's occurrence?" On the basis of various fire behavior observations and various analyses, we can say with some degree of certainty that the maximum flame heights in grasslands, shrublands, and hardwood stands would vary, depending on the burning conditions, from about 2 to 10 m (7 to 33 feet). Thus, a separation of at least 40 m (130 feet) should be adequate in most fuel types that do not contain conifer trees. The average flame height of crown fires in conifer forests is generally 2 to 2.5 times the stand height.[464]

Any area smaller than a safety zone should be regarded as a possible "survival zone" or site. Unfortunately, no quantitative description of what constitutes a survival zone presently exists. The FPInnovations Wildland Fire Operations Research Group (http://wildfire.fpinnovations.ca/index.aspx) and the University of Alberta are currently engaged in a project to better define the criteria for survival zones in wildland fires.[26,27] Nevertheless, specific case study examples (e.g., 1937 Blackwater fire in Wyoming, 1958 Wandilo fire in South Australia, 1976 Battlement Creek Fire in Colorado, 1990 Dude fire in Arizona) suggest that survival is possible in relatively small areas even when exposed to a highly hostile thermal environment, provided a person maintains a prone position and uses every possible protection against radiation, convection, and direct flame contact. Movement within the survival zone may also be possible and necessary as the flame front surrounds the survival zone site.

TABLE 14-6 Minimum Safety Zone Separation Distances and Sizes (Circular Shape) in Relation to Flame Height*

Flame Height		Separation Distance		Area†	
Meters	Feet	Meters	Feet	Hectares	Acres
2	6.5	8	26	0.02	0.05
5	16	20	64	0.13	0.31
10	33	40	132	0.5	1.2
20	66	80	264	2.0	5.0
40	128	160	512	8	20
60	262	240	1048	18	45

*For a single person on flat topography based on the "four-times-flame-height" rule of thumb for radiant heat only (i.e., no convection) and no allowance for flame impingement or other fire line hazards.[99,101] It is assumed that the person is standing upright and is properly clothed, including headgear and gloves.
†Assuming the area of a circle is equal to approximately 3.14159 times the square of the separation distance, where the separation distance is deemed to be the radius of a circle. For perspective, a typical North American ice hockey rink is 0.16 hectare (0.39 acre) in size, whereas Canadian and American football fields are about 0.6 hectare (1.5 acre) and 0.4 hectare (1.1 acres) in size, respectively. In turn, the maximum sizes of outdoor soccer and rugby fields would be approximately 0.8 hectare (2.0 acres) and 1.0 hectare (2.5 acres), respectively. A full-size basketball court is about 0.04 hectare (0.1 acre) in size.

EIGHTEEN "WATCH OUT!" SITUATIONS IN THE WILDLAND FIRE ENVIRONMENT

The following 18 "Watch Out!" situations, adapted from the wildland fire community's safety guidelines,[320,325,449] are of particular relevance to emergency medical personnel and wildland users:

1. You are moving downhill toward a fire, but must be aware that fire can move swiftly and suddenly uphill. Constantly observe fire behavior, fuels, and escape routes, assessing the fire's potential to run uphill.
2. You are on a hillside where rolling, burning material can ignite fuel from below. When below a fire, watch for burning materials, especially cones and logs, that can roll downhill and ignite a fire beneath you, trapping you between two coalescing fires.
3. Wind begins to blow, increase, or change direction. Wind strongly influences fire behavior, so be prepared to respond to sudden changes.
4. The weather becomes hotter and drier. Fire activity increases, and its behavior changes more rapidly as ambient temperature rises and relative humidity decreases.
5. Dense vegetation with unburned fuel is between you and the fire. The danger in this situation is that unburned fuels can ignite. If the fire is moving away from you, be alert for wind changes or spot fires that may ignite fuels near you. Do not be overconfident if the area has burned once, because it can reignite if sufficient fuel remains.
6. You are in an unburned area near the fire where terrain and cover make travel difficult. The combination of fuel and difficult escape makes this situation dangerous.
7. Travel or work is in an area you have not seen in daylight. Darkness and unfamiliarity are a dangerous combination.
8. You are unfamiliar with local factors influencing fire behavior. When possible, seek information on what to expect from knowledgeable people, especially those from the area.
9. By necessity, you have to make a frontal assault on a fire with tankers. Any encounter with an active line of fire is

dangerous because of proximity to intense heat, smoke, and flames, along with limited escape opportunities.
10. Spot fires occur frequently across the fire line. Generally, increased spotting indicates increased fire activity and intensity. The danger is that of entrapment between coalescing fires.
11. The main fire cannot be seen, and you are not in communication with anyone who can see it. If you do not know the location, size, and behavior of the main fire, planning becomes guesswork, which is an unfavorable response.
12. An unclear assignment or confusing instructions have been received. Make sure that all assignments and instructions are fully understood.
13. You are drowsy and feel like resting or sleeping near the fire line in unburned fuel. This may lead to fire entrapment. No one should sleep near a wildland fire. If resting is absolutely necessary, choose a burned area that is safe from rolling material, smoke, reburn, and other dangers, or seek a wide area of bare ground or rock.
14. Fire has not been scouted and sized up.
15. Safety zones and escape routes have not been identified.
16. You are uninformed on strategy, tactics, and hazards.
17. No communication link with crew members or supervisors has been established.
18. A line has been constructed without a safe anchor point.

Each of these situations has come about as a result of one or more wildland firefighter fatalities (http://wlfalwaysremember.org). Artwork has been developed to help illustrate or visualize the 10 standard fire orders and 18 "Watch Out!" situations.[331]

FIFTEEN STRUCTURAL "WATCH OUT!" SITUATIONS FOR THE WILDLAND-URBAN INTERFACE

Continuing development creates ever more WUI area; therefore, fires are tending to occur more often in that interface. These 15 structural "Watch Out!" situations have been defined to increase awareness of structural fire dangers[484]:

1. Access is poor (e.g., narrow roads, twisting, single lane with inadequate turning).
2. Load limits of local bridges are light or unknown; the bridges are narrow.
3. Winds are strong, and erratic fire behavior is occurring.
4. The area contains garages with closed, locked doors.
5. You have an inadequate water supply to attack the fire.
6. Structure windows are black or smoked over.
7. There are septic tanks and leach lines. These are found in most rural situations.
8. A house or structure is burning with puffing rather than steady smoke.
9. Inside and outside construction of structures is wood with shake-shingle roofs.
10. Natural fuels occur within 9 m (30 feet) of the structures.
11. Known or suspected panicked individuals are in the vicinity.
12. Structure windows are bulging, and the roof has not been vented.
13. Additional fuels can be found in open crawl spaces beneath the structures.
14. Firefighting is taking place in or near chimney or canyon situations.
15. Elevated fuel or propane tanks are present.

These are also known as the "Wildland-Urban Watch Outs!"[360]

TAKING REFUGE IN VEHICLES, BUILDINGS, AND PROTECTIVE FIRE SHELTERS USED BY WILDLAND FIREFIGHTERS

The radiant energy of a fire, although highly intense at a given location, typically lasts for only a short time. Because radiant heat travels in straight lines, does not penetrate solid substances, and is easily reflected, seeking refuge in vehicles, buildings, or protective fire shelters should be viewed as a lifesaving solution.

Vehicles

Wildland firefighters have survived severe fire storms or the passage of fire fronts by taking refuge in vehicles.[291,302,375,376] Unfortunately, there are reported cases where civilians would have survived or avoided serious injury had they remained in their vehicles.[245,372] Bereska[68] has indicated that he and two others were forced to drive a ¾-ton Dodge 4 × 4 truck at a moderate speed (25 to 30 km/hr [16 to 19 miles/hr]) through the flame front of a grass fire during a prescribed burning operation in north-central Alberta in early April 1980. Winds at the time of the incident were light (<12 km/hr [7 miles/hr]), and the flames, although high (3 to 4 m [10 to 13 feet]), were not deep (1 to 2 m [3 to 7 feet]). "It got very hot instantly and as we came out of the flames we opened the windows and appreciated the cool fresh air."[68]

The following three U.S. case histories serve as examples of intense burning situations where lives were saved because people stayed inside vehicles while the fire front passed by their location.[449]

- In 1958, a veteran field section fire warden and two young men were fighting forest fires that burned in heavy fuels near the Bass River State Forest in southern New Jersey. A 90-degree wind shift transformed the flank fire into a broad head fire, with the advancing flames reaching up to 12 m (40 feet) in height. The men entered their vehicle, a Dodge W300 Power Wagon, which stood in the middle of a 4-m (13-foot)–wide sand road. Simultaneously, the engine and radio failed. The fire warden repeatedly admonished the crewmen, who wanted to flee, to stay in the truck. Subsequently, the truck was rocked violently by convection currents and microclimatic changes generated by the flames. The men could neither see nor breathe because of smoke, and the cab began to fill with sparks that ignited the seat. The men stayed with the truck for only 3 or 4 minutes during passage of the head fire, but they indicated later that the interval involved seemed more like 3 or 4 hours. At the first opportunity, all of them left the vehicle on the upwind side and crouched beside it to escape the searing heat and burning seats. The warden proceeded to burn his hand severely while disposing of a flaming gas can located in the truck bed. Although the young men escaped virtually unscathed, the older man suffered lung damage and remained on limited duty for 5 years. He eventually recovered completely and subsequently retired.
- In a 1962 California Division of Forestry fire in Fresno County, three men, followed by a flank fire that had turned into a head fire, raced back to their truck only a few feet ahead of the flames. The truck would not restart. After the main body of flames passed over the vehicle, the men jumped out to breathe because the truck was burning. Almost completely blinded by smoke and heat, they stumbled headlong into matted fuels, and two received first- and second-degree burns. One man was not burned but had to be treated for smoke inhalation. The truck was a loss.
- In 1976 a firefighter died while fighting a grass fire near the town of Buhler in Reno County, Kansas. A flashover occurred from buildup of gases on the lee side of a windbreak. A fire truck was caught in the flashover, and the firefighter working from the back of the vehicle ran and was killed. Although the truck burned, the driver was not seriously hurt.

Sitting in a vehicle during a passing fire front is often perilous, but when a person is trapped, it is almost certain doom to attempt escape by running from the fire. The preceding case histories illustrate the following facts about vehicles and fire, which, if remembered, may prevent panic-like reactions:

1. The engine may stall and not restart.
2. The vehicle may be rocked by convection currents.
3. Smoke and sparks may enter the cab.
4. The interior, engine, or tires may ignite. (Tires exploded during the Crank Fire burnover in California in August 1987 involving several wildland fire engines.[348] This is obviously unsettling in an already stressful situation that could lead to panic-like reactions.)
5. Temperatures increase inside the cab because heat is radiated through the windows.

6. Metal gas tanks and containers rarely explode.
7. If it is necessary to leave the cab after the fire has passed, keep the vehicle between you and the fire.

The type of vehicle determines the amount of protection afforded. Two travelers died in a fire in 1967 in Tasmania, Australia, when they were caught in a canvas-topped vehicle.[281] A later fire in Australia led to further research on various vehicles' protection and the explosiveness of gasoline tanks. In 1969 near Lara, Victoria, Australia, a fast-moving grass fire crossed a four-lane expressway.[201,281] Several cars stopped in the confusion of smoke and flames. Seventeen people left the safety of their cars and perished. Six people stayed inside their vehicles and survived, even though one car ignited.

Investigations were carried out by the Forest Research Institute (now the Commonwealth Scientific and Industrial Research Organization [CSIRO], Division of Forestry and Forest Products) in Canberra, Australia, to collect accurate data and dispel the misconceptions that make people flee a safe refuge if trapped by fire.[118] Cars were placed between two burning piles of logging slash to study a car's ability to shield against radiation.[281] The test was a hotter, longer-duration fire than would normally be encountered in a wildland setting.

Car bodies halved the external radiation transmitted at the peak of the fire, but a person inside would have suffered severe burns to bare skin. Although air temperatures inside the car did not reach hazardous levels until well after the peak radiation had passed, smoke from smoldering plastic and rubber materials would have caused discomfort and made the car uninhabitable. In this study, metal gasoline tanks did not explode, whether intact on cars or separated and placed on a burning pile of slash. Apparently, when tanks are sealed, the space above the liquid contains a mixture too deficient in oxygen vapor to support an explosion.

Several years ago, Cheney[118,120] offered the following general advice for survival when in a car and trapped by fire:

- If smoke obstructs visibility, turn on the headlights and drive to the side of the road away from the leading edge of the fire. Try to select an area of sparse vegetation offering the least combustible material.
- Attempt to shield your body from radiant heat energy by rolling up the windows and covering up with floor mats or hiding beneath the dashboard. Cover as much skin as possible.
- Stay in the vehicle as long as possible. Unruptured gas tanks rarely explode, and vehicles usually take several minutes to ignite.
- Grass fires create about 30 seconds (maximum) of flame exposure, and chances for survival in a vehicle are good. Forest fires create higher-intensity flames lasting 3 to 4 minutes (maximum) and lowering chances for survival. Staying in a vehicle improves chances for surviving a forest fire. Remain calm.
- A strong, acrid smell usually results from burning paint and plastic materials, caused by small quantities of hydrogen chloride released from breakdown of polyvinyl chloride. Hydrogen chloride is water soluble, and discomfort can be relieved by breathing through a damp cloth. Urine is mostly water and can be used in emergencies.

Subsequent experiences,[91] coupled with new research carried out by the Australian Bushfire Cooperative Research Centre,[268] have led to more definitive guidelines (Box 14-7).[51]

BOX 14-7 Guidance for People in a Vehicle During a Wildland Fire

Advance Preparation

Always carry woolen blankets, leather gloves, and a supply of water in the vehicle.

Dress in suitable *nonsynthetic* clothing and shoes, including a hat.

Encountering Smoke or Flames

If you see a wildland fire in the distance, carefully pull over to the side of the road to assess the situation. If it is safe to do so, turn around and drive to safety.

If you have been trapped by a wildland fire, find a suitable place to park the car and shelter from the fire.

Positioning Your Car

Find a clearing away from dense bush and high ground fuel loads.

Where possible, minimize exposure to radiant heat by parking behind a natural barrier, such as a rocky outcrop.

Position the car facing toward the oncoming fire front.

Park the car off the roadway to avoid collisions in poor visibility.

Do not park too close to other vehicles.

Inside Your Car

Stay inside your car—it offers the best level of protection from radiant heat as the fire front passes.

Turn headlights and hazard warning lights on to make the car as visible as possible.

Tightly close all windows and doors.

Shut all the air vents, and turn the air conditioning off.

Turn the engine off.

Get down below the window level into the foot wells, and shelter under woolen blankets.

Drink water to minimize the risks of dehydration.

As the Fire Front Passes

Stay in the car until the fire front passes and the temperature has dropped outside.

Fuel tanks are unlikely to explode.

As the fire front approaches, the intensity of the heat will increase, along with the amount of smoke and embers.

Smoke gradually gets inside the car, and fumes will be released from the interior of the car. Stay as close to the floor as possible to minimize inhalation, and cover your mouth with a moist cloth.

Tires and external plastic body parts may catch on fire. In more extreme cases, the car interior may catch on fire.

Once the fire front has passed and the temperature has dropped, cautiously exit the car. (Be careful—internal parts will be extremely hot.)

Move to a safe area such as a strip of land that has already burned.

Stay covered in woolen blankets, continue to drink water, and await assistance.

Modified from Australasian Fire Authorities Council: *Guidelines for people in cars during bushfires,* East Melbourne, Victoria, Australia, 2008, AFAC.

Buildings

The decision to evacuate a house or remain and defend it is not an easy one. Fire services generally prefer that residents evacuate the threatened area so that agencies can concentrate on protecting structures. Authorities also agree that evacuation of older adults and very young, infirm, and fearful people is usually a good idea.[259] People should evacuate only if it can be accomplished safely, well in advance of any danger. If not, it is safer to shelter in place. Several principles should guide the evacuation decision[519]:

1. A fire within sight or smell is a fire that endangers you.
2. Occupants are often quite effective in preventing their house from burning down. The more they understand the dynamics of fire behavior and have prepared for a fire occurrence, the easier and safer this task will be.
3. Evacuation when fire is close is too late; evacuation must only be done when it is certain that it is safe to do so.
4. More people are injured and killed in the open than in houses.
5. Learn beforehand about community refuges.
6. Evacuate only to a known safe refuge and only when it is safe to do so.

Whether people can find refuge in buildings depends on construction materials, house design detail, and proximity of fuels around the structure. If a home is constructed amid flammable vegetation, plans and procedures to safeguard the home and its occupants are essential. A building usually offers protection while the fire passes, even if it ignites during or after the fire's passage, because it shields against radiant heat and smoke. After the fire passes, it may be necessary to exit if the building is burning. Attempt to suppress the fire or to move onto burned ground.

Numerous wildfire case histories from Australia, starting with the 1939 Black Friday fires in Victoria,[270] demonstrate that homes provide safe havens.[259,281,372,540] In 1967 in Tasmania, 21 people left their houses as fire approached. All died, and some were within a few meters of the buildings. Many houses did not burn and would have served as safe refuges.

When taking refuge in a building, give people useful jobs, such as filling vessels with water, blocking cracks with wet blankets, and tightly closing windows and doors. If possible, assign lookouts to keep watch for spot fires on and within the building throughout the fire event.

Before fire approaches the house, plan to have taken the following precautions[269,449]:

- If you plan to stay, evacuate your pets and livestock and all family members not essential to protecting the home well in advance of the fire's arrival.
- Be properly dressed to survive the fire. Wear long pants and leather boots, and carry for protection a long-sleeved shirt or jacket made of cotton fabrics or wool. *Synthetics should not be worn because they can ignite and melt*. Wear a hat that can offer protection against radiation to the face, ears, and neck areas. Wear leather or natural-fiber gloves, and have a handkerchief handy to shield the face, water to wet it, and safety goggles, if possible.
- Remove combustible items from around the house, including lawn and poolside furniture, umbrellas, and tarp coverings. If they catch fire, the added heat could ignite the house.
- Ensure that anything that might be tossed around by strong fire-induced winds is secured (e.g., sheet metal, lumber, plywood).
- Ensure that the areas around any external propane tanks are fuel free for a considerable distance. Ensure that the tanks are properly restrained and the pressure relief value is directed away from buildings and access ways.
- Close outside attic, eave, and basement vents to eliminate the possibility of sparks blowing into hidden areas within the house. Close window shutters.
- Place large plastic trash cans or buckets around the outside of the house and fill them with water. Soak burlap sacks, small rugs, and large rags to use in beating out burning embers or small fires. Inside the house, fill bathtubs, sinks, and other containers with water. Toilet tanks and water heaters are an important water reservoir.
- Place garden hoses so that they will reach any place on the house. Use the spray gun type of nozzle, adjusted to spray. Avoid laying the hose over or adjacent to combustible objects.
- If you have portable gasoline-powered pumps to take water from a swimming pool or tank, make sure they are operating in place and well protected from nearby combustible elements.
- Place a ladder against the roof of the house opposite the side of the approaching fire. If you have a combustible roof, wet it down or turn on any roof sprinklers. Turn on any special fire sprinklers installed to add protection. Do not waste water. Waste can drain the entire water system quickly. Where possible, divert water from gutters back into the firefighting supply.
- Back your car into the garage, and roll up the car windows. Disconnect the automatic garage door opener (otherwise, in case of power failure, you cannot remove the car). Close all garage doors, and seal them with wet rags where possible. Avoid storing combustible elements in a garage that cannot adequately be sealed from ember attack.
- Place valuable papers and mementos inside the car in the garage for later departure following passage of the fire, when it is safe and may become necessary to do so. In addition, place all pets in the car.
- Close windows and doors to the house to prevent sparks from blowing inside. Close the damper on the fireplace to prevent smoke and embers from entering the house. Leave the doors inside the house open. This will enable occupants to remain vigilant throughout the exposure. If a room or area in the house ignites and develops beyond the occupants' ability to contain it, doors can be closed in the house to manage smoke spread. Begin to plan an exit to the outside, bearing in mind the state of the fire outside the house. The approach should be to retreat to a room with an exit door that opens onto a region with little fuel. Turn on a light in each room to make the house more visible in heavy smoke. Have a backup plan for when the electricity supply fails by having flashlights handy.
- Turn off the main gas supply to stoves and furnaces.
- If you have time, take down drapes and curtains. Close all Venetian blinds or noncombustible window coverings to reduce the amount of heat radiating into the house. This provides added safety in case the windows give way because of heat or wind.
- As the fire front approaches, go inside the house. Stay calm; you are in control of the situation. Continually move around inside the house, monitoring its state and the progress of the fire outside. Avoid spending time in the areas that have only one way of exiting the space. If practical, include monitoring of the roof cavity. Goggles will prove handy in dealing with any smoke that enters the house.
- After the fire passes, check the roof immediately. Extinguish any sparks or embers. Then check the attic for hidden burning sparks. If you have a fire, enlist your neighbors to help fight it. For several hours after the fire, recheck for smoke and sparks throughout the house.

It is worth noting the research in this area by the Australian Bushfire Cooperative Research Centre is continuing under Project D1—Building and Occupant Protection under the leadership of Justin Leonard, CSIRO Land and Water.

If a person expects to take refuge in his or her home and in turn survive to ensure its defense, it is critical that steps are taken to reduce the ignition potential of the structure as much as possible. Recent research on home ignition involving field experiments, coupled with modeling and observations of recent WUI fire incidents, has provided valuable new insights into the means of ensuring home survival.[134,135,137] The research has shown that the characteristics of the home (e.g., exterior building materials) and in an area referred to as the "home ignition zone" located within 30 to 60 m (100 to 200 feet) of the home (e.g., surface fuel accumulations immediately adjacent to the structure that would be receptive to ignition by airborne firebrands) principally determines its ignition potential and thus its survivability during exposure to a wildland fire (Figure 14-37); videos that summarize this research are available from *Firewise Communities*.[136,193,194] For example, a home could have little or no natural surface fuel within the immediate vicinity of the dwelling, but because cedar shake shingles were used in the roof construction, it is vulnerable to ignition from airborne embers or firebrands from an approaching wildfire. If such a burning structure is not handled soon after ignition, it can contribute to the demise of neighboring houses if left unattended,[328] or push the limits of fire protection to keep up effectively if too many structures become involved.[138]

The use of external sprinkler systems on a home[146,363,453] should not be viewed as a panacea for a lack of fuel treatment in the home ignition zone and beyond or the use of flammable building materials. There is a perception that sprinklers should be capable of providing thermal protection from a high-intensity wildfire assault when in fact their real value is in preventing ignitions from airborne firebrands,[318] direct flame contact, and radiation. The FPInnovations–Feric Wildland Fire Operations Research Group has been engaged in a number of research studies related to the use of sprinkler systems for home and cabin protection since 2002, including outdoor field trials, using simulated structures, involving both prescribed and experimental fires.[513,514] The group's leader, Ray Ault,[46] maintains that the greatest use of commercially available Rain Bird types of sprinklers and small portable pumps for individual home structure protection is in applying water in sufficient quantities and locations to inhibit external ignitions from airborne firebrands by an approaching or passing wildfire well in advance. If the presoaking or application of water for wetting down fuels is applied for too long, it can lead to other problems (e.g., flooded basements).

Irrigation systems have also been occasionally applied to the task of WUI protection. Other, more elaborate systems have been devised. For example, the Saskatchewan Fire Management and Forest Protection Branch has successfully adapted and applied

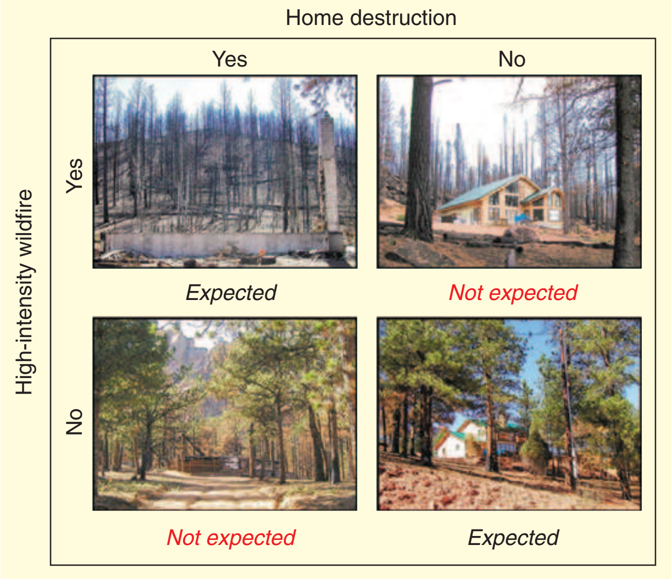

FIGURE 14-37 Expectations of home destruction as a result of exposure to a wildfire. Home survival is expected if low fire intensities occur *(lower right)* and unexpected if the home is destroyed *(lower left).* Conversely, home survival is not expected if high fire intensities occur *(upper left)* and unexpected if the home survives *(upper right). (From Cohen JD: Home destruction. In Graham RT, technical editor:* Hayman fire case study: Summary, *General Technical Report RMRS-GTR-115, Fort Collins, Colo, 2003, USDA Rocky Mountain Research Station.)*

operationally a manure drag hose transportation system to the task of creating wet "breaks or belts" in values protection or to facilitate backfiring or burnout operations.[260]

PROTECTIVE FIRE SHELTERS USED BY WILDLAND FIREFIGHTERS

The concept of a protective fire shelter for wildland firefighters described earlier (see Figure 14-19) was originally conceived by Australian bushfire researchers in the late 1950s.[256,281] The USDA Forest Service equipment development center in Missoula, Montana (now the MTDC) initiated research and development of protective fire shelters about the same time as the Australians,[493] and this work has continued to this day,[104,394] with a view to reducing the number of serious burn injuries and fatalities among firefighters who become entrapped while fighting wildland fires.[42] Shelters designed in the shape of a pup tent protect the firefighter by reflecting radiant heat. Constructed of an aluminum-foil and fiberglass cloth laminate, the shelter reflects about 95% of the radiant heat emanating from a fire. These shelters were never designed for direct flame contact. Fire shelters were first introduced operationally on the wildland fire scene in the United States in the mid- to late 1960s and became a required PPE item for federal wildland firefighters in 1977. More than 1200 U.S. wildland firefighters have deployed their fire shelters to date (up to and including the 2010 fire season).[384] The fire shelter is credited with having saved the lives of more than 320 firefighters and preventing at least 315 serious burn injuries,[384] although it is not known with any degree of certainty how many would have actually survived and suffered no burn injuries without the fire shelter. Some personal accounts of fire shelter deployments have been published[116,411] (Box 14-8).

Why protective fire shelters work well was demonstrated dramatically on August 29, 1985, when 73 firefighters were forced to take refuge in their shelters for about 1.5 hours following passage of a high-intensity, active crown fire that swept over and around their location.[8,340,421] The incident took place during the Butte Fire in the Salmon National Forest in central Idaho. Observers described the crown fire that overran the firefighters as a standing wall of flame that reached about 60 m (about 200 feet) above the treetops. Within the shelters, firefighters experienced extreme heat for as long as 10 minutes. Shelters were so hot that they could be handled only with gloves. After leaving the shelters, some firefighters showed symptoms of possible carbon monoxide poisoning, including vomiting, disorientation, and difficulty breathing. Emergency medical technicians administered oxygen to several individuals before evacuation from the site after the incident. Five firefighters were hospitalized overnight for heat exhaustion, smoke inhalation, and dehydration. The consensus of those interviewed was that without the shelters, none would have survived.[347]

It should be emphasized that the fire shelter was intended to be used as a last resort when it became impossible to escape to a safety zone before being overrun by a fire. However, despite the emphasis placed on this basic tenet and extensive training in entrapment avoidance over the years,[320,322,349,355,480] the results from a study of possible risk taking as a consequence of being provided with fire shelters[77] suggest a possible link to what has been suspected for many years—that some firefighters are likely to engage in behavior that neutralizes the gain in safety afforded by fire shelters. In other words, fire shelters can lead to additional risk taking[426] or what's called "risk homeostasis."[210]

Putnam[392] maintains that "you are always better with a fire shelter in an entrapment situation than not." This seems fair advice. Fire shelters are, after all, relatively light to carry—the current model weighs 1.9 to 2.2 kg (4.2 to 4.8 lb), depending on the size[43,381]—and a minor inconvenience. Even when fire shelters become compromised, they still provide some protection. One of the entrapment survivors of the 1990 Dude Fire, Dave LaTour, deployed his fire shelter before the arrival of the fire front and stayed under his shelter even after a hole was kicked in it by one of the firefighters who got out of his shelter and attempted to evade the flames.[357] This allowed hot gases to enter his shelter. Despite this development, LaTour stayed down on the ground as flat as possible. He did sustain some burn injuries but fully recovered. LaTour was able to concentrate his attention on his family to help him through the ordeal of being burned over by the passage of a high-intensity flame front.

Alexander[11] believes that the main issue regarding use of shelters, beside not knowing what constitutes an adequate clearing size for a shelter deployment in a particular situation,[258] is the time taken for their efficient deployment.[67] In trying to avoid a wildland fire entrapment or burnover, seconds can mean the difference between life and death.[391] Without a regular,

BOX 14-8 What Is It Like to Experience a Wildfire Entrapment in a Protective Fire Shelter?

Shelter deployment on the Shelley fire, Gila National Forest, June 24, 1989. *(Photo by Mark Erickson, copyright 2006.)*

Mark Erickson, a freelance photographer from Silver City, New Mexico, was unexpectedly involved along with 40 wildland firefighters in a fire shelter deployment associated with the major run of the Shelley fire that took place in the Gila National Forest on June 24, 1989. He recently recounted the experience[190]:

Dr Bruce Hayward, a biologist from Silver City, and I had been putting together a joint effort about the Gila Wilderness, he doing text and I covering the photography. It was decided that during the fire season that I should get out and get some images of fire because of its importance as ecological process in the area.

The Shelley fire was started by lightning on June 16, 1989 but I didn't visit the fire site until June 23. I initially went out to the Sheep Corral area toward Goose Lake to photograph the slurry bombers dropping fire retardant but decided to return the next day and get on the line. Jim Turner from the Shasta Ranger District in California was assigned to go with me and we headed up to the Snow Creek spike camp being manned by the local National Guard. The troops had a water tender and some miscellaneous stores with which to resupply the firefighters. We left our vehicle at the spike camp and headed down the fireline in a northeasterly direction. The fire had been turned over to a Class I Incident Command Team and an infrared imaging aircraft had been brought in to determine the location of hotspots. There was major concern down the valley near Lake Roberts about the many structures that could conceivably be in the path of the fire if the current fire suppression efforts were to fail. I photographed many of the hotshot crew members as they built fireline and felled snags near the line. It is hot, dirty work, especially when air temperatures are already high and there is little or no humidity.

Working our way along Panther Canyon, we noticed that there was a large column of smoke in the direction from which we had just come. Apparently the fire was heading right for the Snow Creek spike camp where the National Guardsmen were being hurriedly schooled on the use of fire shelters. A slurry bomber went over just as the Sacramento Interagency Hotshot Crew came up the fireline from the south. I took a few photographs of the hotshots with the "blowout" in the background and we turned and headed back toward a deployment zone or area on the fireline. The guardsmen were spared having to deploy as the fire made another turn and started toward us instead.

Entering the deployment zone, the crew began to take care of the business of stowing gear such as chainsaws and fuel bottles on the perimeter of the area. Cubitainers of water were brought to the center of the deployment zone and personal gear was laid out. Last minute clearing was taking place as the fire began chugging its way closer to us.

Even though there was some "good" black between us and the advancing fire front, the noise created by the crowning was incredible as it got closer to our location. Someone gave the order to deploy the fire shelters and all of us retreated underneath. Located in the center of the deployment zone, I continued to photograph the fire as it crowned around us. Comments from the firefighters about the reverberating sounds created by the fire were prevalent.

The winds created by the fire were truly amazing and I was glad that the folks at the Technology and Development Center in Fort Missoula had seen fit to add straps to the fire shelters so that they wouldn't fly away. Cinders from the fire were making small pin holes in the shelter, resulting in a planetarium effect as the flames surrounded the deployment area. The worst of all was the smoke. Everyone was chattering back and forth checking on their buddies. The duff was really burning when the fire decided to come back on us. We were ordered to move in the opposite direction and ended up laying in the smoldering pine needles. Thank heavens for Nomex as we all ended up with lots of holes in our clothing, but nothing burst into flame. I wish we would have had more time to rake the area before the fire hit our deployment zone. One could really feel the radiant heat from the shelters and I was really glad that we had them. There were many comments about being done on one side and "could we turn over to the other?"

The fire finally moved on down the canyon, but we stayed in the shelters for an hour it seems. Finally we stuck our heads out to a smoke-filled environment where it was difficult to see more than 10 feet. I continued to take photographs as I thought folks wouldn't really believe it if I just told them about this. A few of the crew were having some respiratory problems, but everyone was mobile. The cubitainers had been stripped of their cardboard casings and cases of MREs (meals ready to eat) were burnt to the ground. The handles on the fire tools were history, but the chainsaws and fuel bottles were intact.

The deployment zone was still smoldering. I'm amazed how small it felt during the peak period of fire activity. Our shelters were fairly well spent and we tossed them into a pile—an unwise decision if we had had to deploy later again that day—and we headed down to the spike camp.

General observation: cool heads keep a situation from escalation.

formalized training program, carried out under realistic environmental conditions, the precious time taken to deploy a shelter might be better spent attempting to evade the fire's encroachment on one's position to reach a safer location.[11]

The British Columbia Forest Service is the only Canadian fire management agency to have ever formally included protective fire shelters as part of a firefighter's PPE. In 2005, it undertook an associated risk analysis[62] and as a result decided to have its firefighters no longer carry fire shelters,[234] relying instead on situational awareness and entrapment avoidance. The Australasian Fire Authorities Council has adopted a similar position on the grounds that fire shelters cannot guarantee firefighter survival and may result in firefighters placing themselves at greater risk in the belief that a fire shelter will protect them.[50]

EMERGENCY PROCEDURES DURING A WILDLAND FIRE ENTRAPMENT OR BURNOVER

The danger of being entrapped or burned over and possibly killed or seriously injured by a wildfire is a very real threat for people living, working, or visiting[498] in rural areas subject to wildfires. Arnold "Smoke" Elser,[188] an accomplished Montana outfitter, described how he helped guests avoid entrapment by a forest fire in the mid-1960s:

The fire began at the bottom of the canyon and proceeded up canyon as fires do. However, the wind currents carried the smoke to the east and not up the drainage to the north; therefore, we received no warning of the fire. The Monture Creek trail goes through some very old mature timber which was not burning as we approached. As my stock, the guests, and I arrived at the fire site and realized that we were in danger, we felt we should fall back and try to flank the fire to the east. Starting back toward this trail, we found a ground fire that made it very hazardous to travel in this direction. Because of my knowledge of the trail and terrain, I knew that our best bet would be to wet down the stock, guests, saddles and outer clothing and try to break through the head of the fire. We successfully did this, receiving only a few minor burns on the horses and the loss of some apparel tied to the backs of the saddles. Some lessons that I learned in this experience were that in handling livestock in a fire situation you must have a very close, firm hand on them. It is also very important that no one panics or shows any excitement, as this alarms the livestock and begins the panic run that is so well known. I found that by talking in very low monotone, keeping the pack stock and saddle stock very close together (head to tail), and moving on a good trail, we were able to come through this fire with virtually no harm.

Elser[188] had these additional suggestions for wildland recreationists:

Campers, whether they be livestock-oriented, hikers, or boaters, should know where to camp to provide adequate fire barriers around campsites. All campers should consider at least one, and preferably two, safe escape routes and havens (such as rock piles, rivers, and large green meadows) away from heavy fuel areas. Campers should be alert to canyon air current conditions in critical fire seasons. The safety of many recreationists is threatened by nylon and other synthetic fabrics used in the manufacture of most backpacking equipment. These materials melt upon contact with heat. The very nature of good horse packing equipment is a deterrent to fire; canvas mantles that cover the gear and the canvas pack saddles are easily wet down. Leather items such as chaps, good saddle bags, and western hats [that] can shield against heat blasts all provide important protection for the horse user.

Sometimes there may be no chance to easily escape an approaching wildfire. Injuries can be minimized or avoided and possible death averted by adhering to certain fundamental principles and procedures (Box 14-9). There are, however, four simple concepts that one must try to adhere to at all times[45,118,125,519]:

1. Select an area that will not burn—the bigger the better—or, failing that, with the least amount of combustible material, and one that offers the best microclimate (e.g., depression in the ground).
2. Use every means possible (e.g., boulders, rock outcrops, large downed logs, trees, snags) to protect yourself from radiant and convective heat emitted by the flames.
3. Protect your airways from heat at all costs, and try to minimize smoke exposure.
4. Try to remain as calm as possible.

The first requirement will limit the flame dimensions and in turn the potential heat energy from flame radiation. It will also limit the time of exposure, an important factor in thermal injuries. Radiant heat can kill you long before direct flame contact.[147,519] The more exposed skin, the greater is the likelihood of death.

Obviously, the last requirement—to remain as calm as possible—may seem difficult to establish and maintain. The expectation that people will panic (i.e., a sudden uncontrollable fear or alarm leading to unthinking behavior) during an emergency situation such as wildfire entrapment or burnover is very strong. Admittedly, with the benefit of 20/20 hindsight, it is easy to point to some decisions that were not optimal and played a negative role in the outcome of the fire.[370] Structural fire researchers believe that most people faced with a fire situation react in a rational manner, considering the ambiguity of the initial cues about the fire, their limited knowledge about fire development and fire dynamics, and the restricted time to make a decision and to take action.[452]

Panic is viewed as being synonymous with a frightened, scared, nervous, or anxious response.[452] In actual fact, panic in the form of irrational or crazed behavior (e.g., aimlessly trying to flee) is rare during fires. Social scientists long ago rejected this concept to explain human behavior in urban fires.[131,389,452] Instead of panic, what is commonly observed is an increased level of stress. Stress is not panic. As Dr. Guylene Proulx,[389] a human factors specialist with the National Research Council Canada's structural fire research program, suggests, "This stress is not an abnormal reaction or a negative response; on the contrary, stress is regarded as a necessary state to motivate reaction and action," and that "Decision-making under stress is often characterized by a narrowing of attention and focusing on a reduced number of options. This explains why training is so important because the person is unlikely to develop new solutions under heightened stress; a well-run decision plan learned and practiced beforehand is easier to apply under stress."

There are four fundamental or basic survival techniques, or options (see Box 14-9), available to an individual who is caught out in the "open" and is likely to be entrapped or burned over by a wildfire and is not able to take refuge in a vehicle or building[201,281,519] or have a protective fire shelter. These four survival options are as follows[19,21,433]:

1. Retreat from the fire and reach a safe haven.
2. Burn out a safety area.

BOX 14-9 Surviving a Wildland Fire Entrapment or Burnover

When entrapment or burnover by a wildland fire appears imminent, injuries or death may be avoided by following these basic emergency survival principles and procedures.

- **Acknowledge the stress you are feeling.** Most people are afraid when trapped by fire. Accept this fear as natural, so that clear thinking and intelligent decisions are possible. If fear overwhelms you, judgment is seriously impaired, and survival becomes more a matter of chance than good decision making.
- **Protect yourself against radiation at all costs.** Many victims of forest fires actually die before the flames reach them. Radiated heat quickly causes heatstroke, a state of complete exhaustion. Find shielding to reduce heat rays quickly in an area that will not burn, such as a shallow trench, crevice, large rock, running stream, large pond, vehicle, building, or the shore water of a lake. Do not seek refuge in an elevated water tank. Avoid wells and caves because oxygen may be used up quickly in these restricted places; consider them a last resort. To protect against radiation, cover the head and other exposed skin with clothing or dirt.
- **Regulate your breathing.** Avoid inhaling dense smoke (which can impair both your judgment and eyesight). Keep your face near the ground, where there is usually less smoke. Hold a dampened handkerchief over the nose. Match your breathing with the availability of relatively fresh air. If there is a possibility of breathing superheated air, place a dry, not moist, cloth over the mouth. The lungs can withstand dry heat better than moist heat.
- **Do not run blindly or needlessly.** Unless a clear path of escape is indicated, do not run. Move downhill and away from the flank of the fire at a 45-degree angle where possible. Conserve your strength. If you become exhausted, you are much more prone to heatstroke and may easily overlook a place of safe refuge.
- **Burn out fuels to create a safety zone if possible.** If you are in dead grass or low shrub fuels and the approaching flames are too high to run through, burn out as large an area as possible between you and the fire edge. Step into the burned area and cover as much of your exposed skin as possible. This requires time for fuels to be consumed and may not be effective as a last-ditch effort, and does this work well in an intense forest fire.
- **Lie prone on the ground.** In a critical situation, lie face-down in an area that will not burn. Your chance of survival if the fire overtakes you is greater in this position than standing upright or kneeling.
- **Enter the burned area whenever and wherever possible.** Particularly in grass, low shrubs, or other low fuels, do not delay if escape means passing through the flame front into the burned area. Move aggressively and parallel to the advancing fire front. Choose a place on the fire's edge where flames are less than 1 m (3.3 feet) deep and can be seen through clearly, and where the fuel supply behind the fire has been mostly consumed. Cover exposed skin and take several breaths, then move through the flame front as quickly as possible. If necessary, drop to the ground under the smoke for improved visibility and to obtain fresh air.

3. Hunker in place.
4. Pass through the fire edge into the burned-out area.

These four survival options are presented in no particular order of priority. Such factors as the size of the fire, fire environment, size and location of safety areas or zones, prevailing fire behavior, and location of the person with respect to the head of fire will ultimately dictate which option or options (should the first one of these options selected become compromised) should be selected. Each of these options has its own unique advantages and disadvantages.

Survival Option 1: Retreat From the Fire and Reach a Safe Haven

When people are under pressure, they fall back on habitual, first-learned, and overlearned responses.[522] The natural tendency when a person is threatened by a hazard such as a wildfire is to try and move away from the danger as quickly as possible to a place of safe refuge. If the distance between the fire and safe area is short, the fire's advance slow, the path to the safe area easily traversed, and the person able bodied, then selection of this survival option is appropriate. Bear in mind that a safe refuge may be nearby, so one should not avoid the most obvious place, even though it may temporarily be uncomfortable to reach because of, for example, smoke or low to moderate radiation levels. In some cases, this might mean just taking a few steps into the "black" or recently burned-over ground. The question of whether a previously burned area will serve as a safety zone will depend not only on the size of the area but also on the degree of completeness of fuel consumption, both vertically and horizontally.[98,380] Furthermore, a recently burned-over area may not immediately serve as a safe refuge because of the burnout time of woody fuels and duff,[471] in contrast to grassland fuels, where a person can enter the recently burned area in a few seconds.[129]

Firefighters have escaped injury and death in many cases by being able to outpace or outmaneuver a spreading fire.[380,480] There have also been many well-publicized cases or incidents during which attempting initially to outpace and then ultimately outrun an advancing flame front have ended in tragedy, including several mentioned earlier (e.g., 1938 Pepper Hill Fire, 1949 Mann Gulch Fire, 1953 Rattlesnake Fire, 1956 Inaja Fire, 1966 Loop Fire, 1968 Canyon Fire, 1994 South Canyon Fire). Sadly, there are many other examples,[413] including the 2003 Cramer Fire in central Idaho involving two firefighter fatalities.[133] For information on many of these incidents, consult www.fireleadership.gov/toolbox/staffride/.

Dr. Ted Putnam,[393] a retired wildland fire safety specialist with the USDA Forest Service, considers that many of these fatality fires were in fact escapable had better decision making been employed (e.g., dropped tools and packs earlier to maximize rate of advance, put the fastest pacesetters at the lead, and used fire shelters as shields against radiant and convective heat).

Incidents similar to those experienced by firefighters involving civilians have also taken place. For example, on November 30, 1957, four members of a group of nine young hikers perished while trying to outrun a bushfire in the Blue Mountains of New South Wales, Australia, as it advanced upslope.[201,281] Another incident occurred on August 26, 1995, near the community of São Domingos in the district of Sandtarém, Portugal.[510] Three civilians who had been assisting local firefighters in suppression operations eventually ended up being killed while trying to run ahead of the fire when it blew up. A fourth individual received severe burns to his feet, which eventually led to them being amputated, and he died some months later.

Simulations carried out by the FPInnovations Wildland Fire Operations Research Group based on their research on firefighter travel rates,[164] coupled with case study information gleaned from the 1949 Mann Gulch and 1994 South Canyon fires,[102] clearly indicate that a person is not able to sustain a maximum pace for even a relatively short time without being overrun by a rapidly advancing flame front, even on a moderately steep slope.[28,60] For example, a fire spreading at 60 m/min (197 ft/min) up a 26% slope would, depending on the fuel type, overrun someone in about 6 to 7.5 minutes or after about 360 to 460 m (1200 to 1500 feet) once the "race" had started. Chandler and colleagues[116] state, "In most firefighter fatalities . . . the unsuccessful strategy has been to try and run away from the fire and continue running until exhaustion or the radiant heat load from the fire front fells the victim and allows the flame front to pass over him or her." Thus, trying to outpace a fire for any significant distance, but especially uphill, is "courting disaster."[281] For this reason, escape routes involving travel upslope should generally not be selected.

Survival Option 2: Burn Out a Safety Area

Burning out fuels to create an area of safety or to enlarge an existing burned area is a viable survival technique or option in some situations (e.g., light fuels and having sufficient time to implement). As Luke and McArthur[281] have noted, "Carrying a box of matches is part of survival planning" (in this regard, a windproof type of matches would be ideal, although a fuse would be infinitely more reliable and effective than a match).

Undoubtedly the most publicized example of this survival strategy being used in modern times occurred on the 1949 Mann Gulch Fire, discussed earlier.[285,418] However, the technique was known to have been used by American Indians in the early 1800s[395,494] and undoubtedly by aboriginal peoples in other parts of the world, as depicted, for example, in the 1989 movie *The Gods Must Be Crazy II*. Wag Dodge described his escape fire during his testimony at the board of review investigation into the 1949 Mann Gulch fire as follows:

> After setting a clump of bunch grass on fire, I made an attempt to start another one, but the match had gone out and upon looking up, I had an area of 100 feet square that was ablaze. I told the man nearest to me that we would wait a few seconds to give it a chance to burn out inside, and then we would cross through the flames into the burned area, where we could make a good stand and our chances of survival were more than even.

Interestingly, Dodge's statement was printed in the letters to the editors section of the September 1949 issue of *Life* magazine after publication of an article on the Mann Gulch Fire entitled "Smokejumpers Suffer Ordeal by Fire" from the previous issue. In that letter, the reader stated, "I am sure that there are many people throughout the country who would appreciate and perhaps benefit sometime by a more detailed account of how Foreman Wagner Dodge, who kept calm and did not become panic-stricken, saved himself." It has been estimated that Dodge's escape fire was about 37 m (121 feet) long and 26 m (85 feet) wide at the time that his "island" of survival was engulfed by 3-m (10-foot)–tall flames associated with the main fire front.[26]

Survival Option 3: Hunker in Place

As mentioned previously, when caught in the open, survival may depend on taking advantage of every possible source of cover or protection from radiant and convective heat (e.g., depressions in the ground, large rocks or logs).[201] If a cave (see Figure 14-35) or root cellar[538] is used as a refuge, it is important to vacate into the open at the earliest opportunity because of potential problems associated with accumulations of smoke and carbon monoxide.

In selecting this option, the importance of staying as flat as possible with one's nose and mouth pressed down into the ground cannot be overemphasized, because the reduction in radiation received is considerable.[27] Lying prone not only minimizes one's radiation profile, but cooler, denser air will always be present at ground level. In selecting this option, also bear in mind the following advice[125]:

> When a fire passes over a point, the air temperature near the ground is higher than the air above it and remains higher for longer. So if someone is sheltering from radiation at ground level, they need to stand up as soon as possible after the fire passes to breathe cool, fresh air. This is most apparent in grass fires where air at ground level is hot and smoky for several minutes whereas at 2 m [6.6 feet] it is cool and breathable within 10 to 15 seconds of the flames passing.

Although there have been reported cases of firefighters surviving on large rockslides during a wildfire entrapment or burnover, most notably two smoke jumpers on the 1949 Mann Gulch

Fire,[285,418] there have also been instances in which these apparently safe, fuel-free areas contained enough combustible materials to cause injury or death (e.g., Shephard Mountain Fire in western Montana on September 4, 1996). Four firefighters died on a rockslide during the 2001 Thirtymile Fire in north-central Washington, due in part to the accumulation of duff and rotting wood lodged in the rock crevices that ignited from airborne firebrands.[81,288,496]

In selecting this option, maximum use should be made of any clothing or other readily nonburnable material to protect exposed skin. You may have to improvise.[495] *Synthetics should not be used because they readily melt when exposed to flame radiation*. During the 1983 Ash Wednesday fires in Victoria, Australia, two individuals wearing only summer clothing who covered themselves with a synthetic blanket perished, while two other individuals right next to the two victims covered themselves with a wet woolen blanket and survived the burnover.[259]

A good example of selecting this option was the Wandilo Fire that occurred in an exotic pine plantation near Mount Gambier, South Australia, on April 5, 1958. Eleven firefighters found themselves trapped on a narrow firebreak during a "blowup."[281,302] Eight in the group attempted to run back along the firebreak, but perished after exposure to extreme radiant heat levels and direct flame contact. Of the three who survived, two remained in the cab of their firefighting truck to shelter from the worst of the firestorm and only left this cover when the vehicle was well alight and the fire's peak intensity had abated. The remaining survivor sheltered in a deep wheel rut in the soft sand of the firebreak with his coat over his face during the peak period of extreme fire behavior.

Taking refuge in a natural water body such as a pond, lake, or river must be done with caution, but for other reasons (e.g., swimming ability). For example, in 1986, three firefighters in the province of Quebec, Canada, drowned as a result of being forced to enter a lake with a steep drop-off when their camp location was overrun by fire.[13] The risk for hypothermia must also be considered.[103] Dion[174] described an incident that occurred in west-central Saskatchewan, Canada, in May 1919 in which 11 Cree Indians perished because they were not able to reach a nearby lake or find sufficiently deep water to avoid radiation burns. Of the 12 who survived the ordeal, 11 "bore the marks of their burns for life." One adult member of the group "escaped severe burns by staying under the water" as much as was possible. It has been suggested that the minimum depth of water should be 0.45 to 0.6 m (1.5 to 2 feet) deep.[358,450]

Survival Option 4: Pass Through the Fire Edge Into the Burned-Out Area

Luke and McArthur[281] have suggested that "running through flames cannot be generally recommended and should certainly not be attempted when flames are more than 1.5 m [5 feet] in height or depth." Nevertheless, a number of firefighters have done this very thing and survived (e.g., 1991 Tikokino grass fire in New Zealand[406]). In fact, the five members of the group of young hikers that survived the 1957 bushfire in the Blue Mountains of New South Wales mentioned earlier did so successfully but suffered considerable discomfort. A similar incident occurred on the Warm Springs Indian Reservation in central Oregon in June 1985. Wildland fire behavior analyst Jim Roessler[415] has indicated that those individuals who tried to outrun a grass fire on a moderately steep slope were killed, whereas at least one person who passed through the flame front survived. In contrast, during the blowup of the 1937 Blackwater Fire, the "five horsemen" made the decision to move downhill through the advancing flames.[78] Three did not make it, partly because of the heavy fuel conditions. Of the two who did survive, one died later of burn injuries. A group of 41 on another section of the fire rode out the blowup in a ridgeline clearing as the fire progressed upslope; three were badly burned and eventually died of their injuries.

It has been suggested that a person could theoretically survive passing through flames 3 m (9.8 feet) high and 37 m (121 feet) in depth and still survive.[116] It is presumed that the person would be immersed in flames for less than 7.5 seconds and would require ideal running conditions (e.g., good footing, no obstructions) and would be properly clothed to withstand the direct flame contact. Although it is reasonable to expect a person to be able to hold his or her breath for this long, the very notion of attempting such a drastic or draconian[116] feat seems unimaginable. Nevertheless, it is worth noting that firefighters have lived, although while sustaining severe burns as a result, by running through high-intensity flame fronts. One of the most notable examples of this involved a prescribed fire (PB-3/79) in heavy logging slash near Geraldton, Ontario, Canada, on August 22, 1979.[36,310,332] As a result of a complex set of unforeseen circumstances, eight members of the firing crew found themselves encircled by fire. One member of the party, a local fire technician, realizing that there was no other option except to run through the advancing flame front or face what appeared to be certain death, tried to get seven seasonal employees to follow him. They failed to heed his urgings and were eventually engulfed by the fire, whereas he survived but did sustain serious burn injuries. This outcome is hauntingly reminiscent of the 1949 Mann Gulch Fire and Wag Dodge's escape fire in which 15 firefighters failed to follow his lead and 13 ended up perishing. In this regard, Dr. Karl Weick,[523] a renowned professor of organizational behavior and psychology, points out that there is good evidence to support the notion that when people are threatened, their thinking becomes much more rigid and difficult to change. Furthermore, they tend to seek out and talk to only those who are most familiar to them.[442]

The survival technique or option of moving through the flame front to previously burned ground would logically be most suitable in light, discontinuous fuel types that fail to produce deep, uniform flame fronts, and significant postfrontal smoldering or isolated flaming, such as that afforded by certain grasslands (e.g., heavily grazed areas). Furthermore, if one has the good fortune to take advantage of a lull in the wind, this would lessen the momentary rate of spread and in turn the flame depth (see Table 14-2). An area along the flanks of the fire (see Figure 14-24) would be preferable to the head. One may only have to travel a relatively short distance before reaching previously burned ground that has "cooled" down sufficiently to serve as a safe area.

Having reached the burned area, a person would still have to be cognizant of the danger posed by fire-weakened trees and falling snags, hot ash pits and burned-out stump holes, and rolling rocks or logs.[275] This would apply to the other survival options as well.

It is worth emphasizing that wildland firefighters as well as members of the general public have been killed and seriously burned while engaged in using fire as a land management tool.[36,316,458,506,509] Thus, the survival principles and options discussed earlier are equally applicable to prescribed fires or controlled burns.

Although radiant heat emanating from a wall of flame is generally viewed as the principal killer in wildland fire entrapments and burnovers,[147] under certain conditions, convective gases or superheated air can have lethal consequences with little or no warning, most notably upslope of a fire source. Under strong winds, a fire's convection column will not lift away from the surface of a steep slope.[129] As slope steepness increases, flames gradually "attach" themselves (Figure 14-38), thereby enhancing fire spread by both direct flame contact and convective heat transfer.[416] This is the very reason that fires spread faster upslope than on level ground given the same fuel and weather conditions.

WILDLAND FIRES AND HUMAN BEHAVIOR

As discussed earlier, the reality of human behavior in fires is somewhat different from the panic scenario "nourished by the media and movie industry who like to play on strong emotional images."[389] What is regularly observed in urban fire situations is a lethargic response to fire alarms or even the initial cues of a fire (e.g., smoke and visible flame).

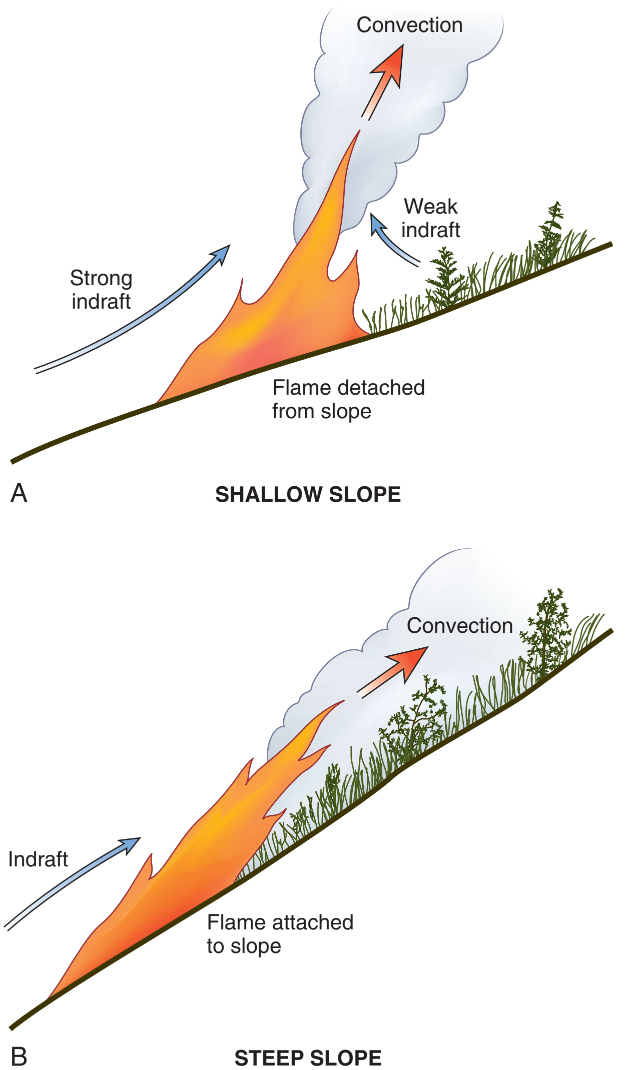

FIGURE 14-38 Effect of slope steepness on degree of flame attachment and convective heat transfer for shallow-sloping (**A**) and steep-sloping (**B**) terrains. *(Redrawn from Rothermel RC: Fire behavior considerations of aerial ignition. In Mutch RW, technical coordinator:* Prescribed fire by aerial ignition: Proceedings of a workshop, *Missoula, Mont, 1985, Intermountain Fire Council.)*

What has been most troubling to the wildland fire community in recent years is that the same mistakes seem to be made time and time again,[178] rather than using "the lessons of the past so we don't have to keep relearning them the hard way."[354] Since the mid-1990s, there has been a growing recognition among the wildland fire community of the role that human factors play in firefighter fatalities.[97,179,391]

Morse[325] considered the development of a mental "scotoma" among firefighters to be a major contributing factor in many wildland fire fatality incidents, noting, "Scotoma is, literally, a blind spot. In a psychological sense, it is that condition which occurs when a person tends to block out from his or her consciousness anything considered not important—or critical—to survival." In other words, blindness to danger perceived as routine takes hold and blocks out sensitivity to hazardous events or conditions present in the wildland fire environment.

The smoke jumpers involved in the 1949 Mann Gulch Fire would appear to have suffered from a psychological scotoma or overconfidence.[521] By the time they had landed and gathered their gear together, it was nearly 5:00 PM. At the time, "They did not feel the fire threatened them then."[418] Less than an hour later, 12 smoke jumpers and a local firefighter were overrun and killed by the fire. Air temperatures reached a maximum of 36° C (97° F) on the day in question, and in turn, the fully cured grasses were in a critically dry state.[418] It was a day of extreme fire danger.[15] One of the survivors, Bob Sallee, commented afterward[418]:

> I took a look at the fire and decided it wasn't bad. It was burning on top of the ridge and I thought it would continue on up the ridge. I thought it probably wouldn't burn much more that night because it was the end of the burning period (for that day) and it looked like it would have to burn down across a little saddle before it went uphill any more.

One crew member was reported to have been taking photographs of the fire less than 10 minutes before the first fatalities occurred.[285,418] Similarly, photographs were being taken by firefighters on the line just moments before the 1994 South Canyon fire blowup,[98] in which 14 of their fellow firefighters were overrun and killed (see Figure 14-1).

Even on the major run of the Thirtymile Fire in north-central Washington on July 10, 2001,[81,288] the firefighters behaved more as spectators than as potential victims until it was too late for some. A total of 16 people (14 firefighters and 2 civilians) were entrapped and required to deploy protective fire shelters. Four firefighters were killed, and two were injured, one with severe burns. Earlier during the day in question, the feeling was that the fire was "basically a mop-up show."[81] Some of the firefighters who were overrun by the fire "spent time taking photos or making journal entries" just a half hour before the incident.[81]

Although wildland firefighters may be subject to a host of human failings or other psychological phenomena,[133,369,522] openly acknowledging and constantly being aware of the potential for entrapment or a burnover, regardless of the situation, is the initial key step in reducing the risk for injury or death from wildland fires. Complacency may be the most difficult factor to overcome.[330] The late Paul Gleason,[212] a veteran wildland firefighter and accomplished rock climber, noted that three major causes of climbing accidents are ignorance, casualness, and distractions.

Although firefighters are expected to engage a wildfire, civilians are not. Nevertheless, the general public could also become complacent about wildfires and fail to fear the worst, until, unfortunately, it is too late. This may result in part from a fascination with fire in general (Figure 14-39), denial, indifference, or a complete ignorance about free-burning fire behavior. In any case, there is a perception that there is no real sense of urgency until the threat is imminent. As Proulx[389] points out, "People are often too cool during fires, ignoring or delaying their response to the initial cues of an actual emergency. Once occupants decide that the situation requires moving to an area of safety, the time left could be minimal." This is probably best exemplified by an urban fire case study. On May 11, 1985, 56 people burned to death and more than 200 were injured when a rapidly growing fire, caused by a cigarette, engulfed the wooden main grandstand at Valley Parade Stadium in Bradford, England, during a soccer match. Filmed documentation of the fire indicates that the blaze spread the entire 88-m (289-foot) length of the stand in less than 5 minutes—a rate of 18 m/min (59 ft/min). Although people in the immediate vicinity of the developing fire moved toward exits, "Persons in remote sections of the grandstand continued to watch the match, apparently unconcerned about (or perhaps unaware of) the developing fire."[257] One of the seven factors that contributed to the loss of life was "the failure of patrons to perceive the danger of the developing fire in the early stages and begin evacuation."[257]

It is sometimes difficult to believe that a wildland fire could become life threatening, especially if it is far away from the observer or small in size and is not burning very vigorously at the time. However, danger is inherent in every wildland fire occurrence, whether a wildfire or a prescribed fire. Some wildland fire situations are simply more hazardous than others and can catch a person or persons off guard (Figure 14-40), possibly leading to severe injuries or even death.[57,88]

Tom Leuschen[274] is an experienced fire manager and wildland fire behavior analyst who worked for many years in north-central Washington, within sight of the area struck in 2001 by the Thirtymile Fire. He was involved in the accident investigation and had the following to say about the incident:

FIGURE 14-39 Rural homeowners (**A**) observing the Haeckel Hill Fire (**B**) near the city of Whitehorse, Yukon Territory, Canada, on June 22, 1991. *(Courtesy Yukon Wildland Fire Management.)*

FIGURE 14-40 Fires in fully cured grasslands are very responsive and can attain exceedingly rapid rates of spread. The flank of a grass fire, with a change in wind direction, can quite quickly become the head and catch unwary persons off guard. This scene from the multifire situation that occurred in the Spokane, Washington, area on October 16, 1991 (**A**), reinforces the importance of having well-established escape routes that can be easily navigated (**B**) to a designated safety zone. *(Courtesy Spokane Statesman Review/WorldPictureNews; photos by K. King.)*

BOX 14-10 Envisioning the Worst

Karen Cerulo argues that people have a clear preference, culturally shaped, for paying attention to best-case scenarios and casual attention to worst-case scenarios. Whether people render the worst-case invisible or vague or recast the worst case as positivity in disguise, the result is that they are unable to envision the worst case and unprepared to avoid it or deal with it. Thus, the plaintive phrase provides the title of this work, "we never saw it coming."

The reader comes away from this book with a new appreciation of the need for mindful attention, resilient action, and skills of improvisation. With these three resources as part of an action repertoire, we will go a long way toward acknowledging and preparing for worst-case scenarios.

Excerpt from Weick KE: Book reviews: Never saw it coming: Cultural changes to envisioning the worst, *Am J Sociol* 113:1762, 2008.

When I stand at the deployment site and look at their pictures, knowing what I know about the fuels, barriers, and interactions between fires, I honestly do not expect that they will have to shelter either. I am as wrong as they were. Things got very complex as the fires joined at their location. The obvious lesson is that we must prepare for the worst when trapped, regardless of what we may anticipate. They were entrapped at 1634 and deployed at 1724. They had time to get organized.

Anyone involved in a wildland fire can become a victim of an entrapment or burnover at any time given the precarious nature of wildland fires and their environmental influences. People need to be constantly mindful or conscious of this fact because, as Weick[520,522] says, "Safety is not bankable," and it is "an ongoing struggle for alertness." Plan for and expect the worst every time out. This may be difficult, because a blatant disregard for worst-case scenarios is one of the common, yet least studied, human traits[115] (Box 14-10).

PROPER CLOTHING

There are documented cases in which homeowners, who were seemingly prepared to stay and defend their property, have died because they were not properly dressed to do so (e.g., clad only in shorts or a bathing suit and slippers).[519] Clothing protects against radiant heat, embers, and sparks, so it is sensible to dress appropriately.[146,372] The cover of a recent book on the WUI fire situation in southern California[229] depicts a lightly clad homeowner on the roof of his house presumably attempting to extinguish sparks or embers with a garden hose as a high-intensity flame front approaches (Figure 14-41). This is a potential recipe for disaster in many respects. This person is not properly attired to stay and defend his property, nor is this the correct approach.

Closely woven material is more resistant to radiation and less likely to ignite than is open-weave material. Natural fibers are best. Wool is more flame resistant than cotton, although cotton can be improved by chemical treatment to retard flammability. As mentioned earlier, synthetic materials are a poor choice because they readily absorb heat or, worse, can ignite and melt onto the skin.[385]

Closely woven materials that provide protection also restrict airflow, so clothes should fit loosely so that they do not interfere with dissipation of body heat. Cotton long johns or undergarments absorb sweat, aid evaporation, and do not melt; however, *underwear made of synthetic materials does melt*. Wearing excessive layers of clothing generally contributes to heat stress.

As little skin as possible should be exposed to fire. Long trousers and a long-sleeved shirt should be worn. For maximum protection, the shirt should be kept buttoned with the sleeves rolled down.

Brightly colored (yellow or orange) coveralls or shirts are worn by organized firefighting crews. These colors improve safety and communications because they are visible in smoke, vegetation, and blackened landscapes.

FIGURE 14-41 An inappropriately clad and positioned homeowner attempting to defend his property from ember attack during a wildfire in Rancho Penasquitos, San Diego, California, on August 25, 1995. The fire at the moment appears largely dominated or supported by a plentiful fuel source. However, given the capricious nature of fire and winds, this fire could have easily turned into a more wind-dominated event at any time. Thus, this individual could have been incapacitated by a momentary blast of superheated air from the convection or radiant heat produced by the spreading fire. In the absence of any outside assistance, this would then have left him vulnerable to burning by direct flame contact along with his home. Fortunately for this individual, shortly after the photo was taken, an air tanker dropped a load of fire retardant near the advancing flames and effectively nullified the fire's spread and intensity. *(Courtesy California Chaparral Field Institute; photo by R.W. Halsey.)*

Other essential apparel includes a safety helmet (hard hat), gloves (leather or natural fiber), leather work boots, woolen or cotton socks, a warm jacket for night wear, goggles, and a handkerchief. *Clothing, backpacks, tents, and other camping equipment made of synthetic materials should be discarded when a person is close to a fire.*

WATER INTAKE

Sweating is the primary method for body cooling, although exhaling warm air and inhaling cooler air also decreases body temperature (see Chapter 89). Because the cooling effect of sweat evaporation is essential for thermoregulation, fluids lost during strenuous work must be replaced. In firefighting, water losses of 0.5 L/hr (1 pt/hr) are common, with losses of up to 2 L/hr (2 qt/hr) under extreme conditions.[281] Unless water is restored regularly, dehydration may contribute to heat stress disorders, reluctance to work, irritability, poor judgment, and impatience.

Thirst is not a good indicator of water requirements during strenuous work, so additional drinking of small quantities of water at regular intervals is recommended. A useful signal of dehydration is dark, scanty urine.

An excessive amount of electrolytes may be lost through sweating, leading to nausea, vomiting, and muscle cramps. When meals are missed or unseasoned foods are eaten, electrolyte supplements may be needed to replace lost salts. Sweetened drinks should be used as a source of energy if solid food is not available.

PERSONAL GEAR

Some rescue and medical missions take a few days. Therefore, it is necessary to be prepared for extended periods and changing conditions in the backcountry (Box 14-11).

HOW TO REPORT A WILDLAND FIRE TO LOCAL FIRE PROTECTION AUTHORITIES

A caller should be prepared to provide the following information when reporting a fire:

- Name of person giving the report
- Where the person can be reached immediately
- Where the person was at the time the fire was discovered
- Location of the fire; orient the fire to prominent landmarks, such as roads, creeks, and mileposts on highways
- Description of the fire: color and volume of the smoke, estimated size, and flame characteristics, if visible
- Whether anyone is fighting the fire at the time of the call

The phone number to call varies locally. For example, in Alberta, Canada, the number for reporting wildland fires is 310-FIRE or 310-3473 in both the northern and southern halves of the province, even though they have different area codes. In other locations, it may simply be 9-1-1. Rural homeowners should make a point of finding out the number to call before the beginning of fire season.

PORTABLE FIRE EXTINGUISHERS

People should know which extinguisher to select for a specific hazard in the home or recreational vehicle and be trained in its use. When a fire is discovered, first evacuate occupants to safety and promptly report the fire to the appropriate authorities. If the fire is small and poses no direct threat, an extinguisher should be used to fight it.

The three major classes of fires are as follows:

Class A fires: Fueled by ordinary combustible materials, such as wood, paper, cloth, upholstery, and many plastics

Class B fires: Fueled by flammable liquids and gases, such as kitchen greases, paints, oil, and gasoline

Class C fires: Fueled by live electrical wires or equipment, such as motors, power tools, and appliances

The right type of extinguisher must be used for each class of fire. Water extinguishers control class A fires by cooling and soaking burning materials. Carbon dioxide or dry chemical extinguishers are used to control class B fires by smothering flames. Multipurpose dry chemical or liquefied gas extinguishers control class A, B, and C fires by a smothering action. Liquefied gas extinguishers also produce a cooling effect. A dry chemical or liquefied gas extinguisher is recommended for recreational vehicles.

BOX 14-11 Personal Gear for a Rescue Mission on a Wildland Fire Incident

- Boots (leather, high-top, lace-up, nonslip soles, extra leather laces)
- Socks (cotton or wool, at least two pairs)
- Pants (natural fiber, flameproof, loose fitting, hems lower than boot tops)
- Belt or suspenders
- Shirt (natural fiber, flameproof, loose fitting, long sleeves)
- Gloves (natural fiber or leather, extra pair)
- Hat (hard hat and possibly a bandanna, stocking cap, or felt hat)
- Jacket
- Handkerchiefs or scarves
- Goggles
- Sleeping bag and ground cover
- Map
- Protective fire shelter
- Food
- Canteen
- Radio (AM radio will receive better in rough terrain; FM is more line-of-sight; emergency personnel should have a two-way radio)
- Bolt cutters (carried in vehicles to get through locked gates during escape from flare-ups or in the rescue of trapped people)
- Miscellaneous items (mess kit, compass, flashlight, extra batteries, toilet paper, pencil, notepaper, flagging tape, flares, matches (windproof), can opener, washcloth, toiletries, insect repellent, plastic bags, knife, first-aid kit, and lip balm)

BASIC WILDLAND FIRE MATERIALS, TRAINING COURSES, AND OTHER INFORMATION RESOURCES

A large number of reference or textbooks on wildland fire suppression currently exist, many of which have been cited or referenced in this chapter. *Wildland Fire Fighting for Structural Firefighters* is a comprehensive text written specifically for firefighters whose primary focus is fighting structure fires, but who also have wildland and WUI responsibilities.[219] The book provides an excellent overview on wildland fire behavior, fire apparatus and communications equipment for wildland fires, wildland firefighting tools and PPE, extinguishing agents, wildland incident management, fire suppression methods, wildland and interface fire suppression, firefighter safety and survival, fire prevention and investigation, and fire protection planning. The booklet *Planning for Initial Attack* published by the USDA Forest Service is a handy reference on basic fire behavior and fire suppression principles.[319] Other reference books exist on the basics of wildland fire suppression.[280] For a good general reference on forest fires, see the recent contribution by Omi.[367] *Managing Fire in the Urban-Wildland Interface* is the most comprehensive professional guide on the WUI fire problem.[72]

Wildfire magazine, the official publication of the International Association of Wildland Fire, is an excellent source of information on current fire management topics (www.iawfonline.org), as is *International Forest Fire News* (www.fire.uni-freiburg.de/iffn/iffn.htm) and *Fire Management Today* (www.fs.fed.us/fire/fmt).

Other information that would be valuable to emergency response personnel includes reference materials and materials associated with the Publications Management System (PMS) and "S," or suppression skills, training courses available through the U.S. National Wildfire Coordinating Group's National Fire Equipment System (NFES) based at the National Interagency Fire Center in Boise, Idaho.[361] These include "Firefighter Training" (S-130, 2003), "Look Up, Look Down, Look Around" (PMS 427, 1992),[349,350] "Lookouts, Communications, Escape Routes and Safety Zones (LCES)" (S-134, 2003), "Fire Operations in the Wildland-Urban Interface" (S-215, 2003), and "Lessons Learned: Fatality Fire Case Studies" (PMS 490, 1998).[354,355] The latter course uses nine past fatality fires as a learning tool to help fire line tactical decision makers avoid similar mistakes. It is worth noting that some NFES publications are available online (www.nwcg.gov). The WFSTAR (Wildland Fire Safety Training Annual Refresher) website (www.nifc.gov/wfstar) is an excellent resource for the latest information on wildland firefighter safety. The Wildland Fire Staff Ride Library (www.fireleadership.gov/toolbox/staffride/), developed by the National Wildfire Coordinating Group, is also a highly useful source of information on past firefighter fatality incidents.

There are also several CD-ROM–based training courses available on fire line safety,[37,480] fire behavior,[481] and fire danger rating.[462] For additional information on introductory to advanced wildland fire training courses available at the local area, geographic area, and national levels in the U.S., visit the Wildland Fire Training website (www.nationalfiretraining.net). For national wildland fire training courses in Canada, visit the website of the Canadian Interagency Forest Fire Centre (www.ciffc.ca).

One of the initiatives of the U.S. National Wildland-Urban Interface Fire Program was a firefighter safety program in the WUI series. This training package, which includes three videos, was developed for small community fire departments to address the problems faced by structural and wildland firefighters when fighting fires, especially those threatening structures in the WUI.[267] Copies can be ordered from *Firewise Communities* online catalog.

The Wildland Fire Lessons Learned Center (www.wildfirelessons.net) is a good source for information on almost all aspects of wildland fire management, including an annotated reading list and bibliography on wildland firefighter safety management.[265] The Fire Research Institute library (www.fireresearchinstitute.org/), which provides online search capability, is a good source of scientific and technical wildland fire literature.[222]

Wildfire Today (www.wildfiretoday.com) and the Global Fire Monitoring Center (www.fire.uni-freiburg.de) are popular websites for the latest news in wildland fire management. *Wildland Fire: Home of the Wildland Firefighter* (www.wildlandfire.com) is another unique website serving the global wildland fire community.

CONCLUDING REMARKS

Fire suppression efforts in the late 1800s and early 1900s were largely ineffective because of limited access, absence of trained firefighting organizations, and lack of a fire detection network. During these times, many residents and numerous firefighters died in wildland fires in the United States and Canada. In the recent past, firefighters were more vulnerable to injuries and fatalities from wildfires than was the general public. At present, with many people living and seeking recreation in wildlands, the odds for serious fire encounters are shifting toward an inexperienced populace. Large property losses and direct injuries are being reported in increasing numbers in the WUI. It has now become not a question of "if" a wildfire will come or it "can't happen here," but rather "when and where" the next major WUI conflagration will take place (Figure 14-42). Emergency medical personnel will probably have increasing exposure to wildland fires in the future and will need to know more about fire-related injuries, fire safety, and fire survival.

Many wildland firefighters are in turn feeling compelled to save homes,[197] in part as a result of the expectations placed on them by the general public and homeowners in particular, coupled with a culture derived from more than a century of wildland fire suppression.[61] Not surprisingly, many wildland firefighter fatalities in recent years have been associated with WUI incidents (e.g., the 2003 Cedar Fire in southern California).[107] Given even the best practices,[290] there is an overwhelming need to impress on rural homeowners that no home is worth a firefighter's life.

Although wildland fires have not yet posed a serious threat to backcountry recreationists in the United States to any appreciable degree, the prospect for such confrontations is growing. For example, two recreationists were involved in entrapment and burnover associated with the major run of the 2001 Thirtymile Fire.[186] Fire investigators concluded they would probably not

FIGURE 14-42 The Strawberry Hill Fire near Kamloops, British Columbia, about 10 minutes after ignition on August 1, 2003. The white plume in the background is the convection column associated with the McLure Fire. Although it does seem theoretically possible to completely eliminate the threat of conflagrations, this is unlikely to happen. Even with the most highly effective fire prevention, fuel management, and fire suppression programs, the likelihood that members of the general public will encounter a high-intensity wildfire event at some point in their lives is gradually increasing as long as they continue to live, recreate, and work in fire-prone environments. Coexistence or living with fire involves taking a proactive stance, including being prepared for when wildfire arrives in a community. *(Photo by D. Christie.)*

have survived, although they did sustain minor injuries, had they not joined up with the firefighters just before (~14 minutes) their location was overrun.[498]

Many years of practical experience with wildland fires allow us to conclude the following:

- Many indicators show that financial support and programs that address only emergency responses to wildfires will result in more damaging and expensive wildfire emergencies in the future. Public policies and public education that link sustainable land use practices with emergency preparedness are likely to be most successful in the long run.
- Residential shifts to the WUI will increase exposures to life-threatening situations.
- Expanded use of fire in managing national parks and wilderness areas will increase the likelihood that backcountry recreationists will encounter free-burning fires.
- By and large, the general public tends to underestimate existing fire hazards and for the most part is usually not experienced in avoiding wildfire threats.
- In some cases, attempted fire exclusion practices have contributed to development of hazardous wildland fuel situations in terms of quantity and continuity, setting the stage for extreme fire behavior in some plant communities. The national ecosystem health issue has compounded this problem by producing vast expanses of dead and dying forests, increasing the threat to people from fast-moving, high-intensity fires.
- Knowledge of fire behavior principles and survival guidelines will prepare people to take appropriate preventive measures in threatening situations.

The general public must share responsibility with suppression organizations to minimize fire hazards created by humans. Care with fire, proper cleanup of debris, fuel reduction efforts on wildland property, fire-safe construction guidelines, and application of survival skills will minimize fire threats. Such precautions should become as commonplace in the wildland environment as smoke alarms and fire extinguishers have become in urban settings. Every community should undertake, as part of the risk management process associated with the wildfire threat, an assessment of their fire environment in terms of potential fire behavior. A good example of this type of analysis has been completed for over a hundred communities in northern Saskatchewan, Canada.[165]

Unfortunately, major disasters are often required for fundamental changes to occur. Disasters do not simply happen.[488] They usually involve an "incubation period" that involves "the accumulation of an unnoticed set of events that are at odds with the accepted beliefs about hazards and the norms for their avoidance."[487]

Wildland fire suppression agencies will continue to provide fast, safe, and energetic initial attack responses to protect human life, property, and natural resources.[14] Many fires will start and burn under environmental conditions that permit their control at a very small size. However, in certain situations (e.g., critically dry fuels or strong winds), some fires[9,32,33] will defy control until burning conditions ameliorate. The major runs of the 1985 Palm Coast Fire in south Florida[2] and the Millers Reach Fire that occurred near Anchorage, Alaska, on June 2, 1996,[132] are good examples of this type of fire behavior and associated suppression problems. No radically new concept of fire suppression for stopping the head of a hot, fast-running wildland fire should be anticipated in the future.[152] In *An Introduction to Fire Dynamics*, Drysdale[181] states, "Further major advances in combating wildfire are unlikely to be achieved simply by continued application of the traditional methods. What is required is a more fundamental approach which can be applied at the design stage. . . . Such an approach requires a detailed understanding of fire behavior."

Strategic fuel management and land use planning could reduce the total number and size of wildfire occurrences, as well as influence their geographic distribution, and thereby mitigate the impacts of too much of the "wrong kind of fire."[400] Science-based-only solutions[221] are considered insufficient; effective wildland fire policy must integrate ethics, economics, aesthetics, and values.[400] Furthermore, as Cheney[122] points out, if we are to encourage people to live safely in the wildland environments, they need to be fully aware of the full potential for fire behavior and what can be done to protect themselves and their assets. "They must be individually persuaded to recognize what constitutes the fuel for a forest fire and be convinced that, since they own the fuel, they also own the fire it produces and are responsible for the damage they or others nearby incur."[122] The public and fire management agencies themselves must fully appreciate that fuel management is not a panacea for conflagration mitigation, but rather a prerequisite to aid in successful fire suppression.[20,75,126,490] An excellent source of information on fuel management is the USDA Forest Service Fuels Synthesis Project (www.fs.fed.us/rm/pubs/rmrs_rn019.pdf).[499]

After the 1983 Ash Wednesday fires in southeastern Australia, the editor of *Australian Forestry* commented on what could be learned from studying such wildland fire disasters[184]:

> Advances in technical areas will be of great value. It would be valuable too to make comparable advances in the areas of public policy. People forget, community attitudes change and policies erode. Perhaps one of the greatest challenges, given the realities of southeastern Australia, is to learn how to ensure the permanence of public interest policies where permanence is required.

Twenty years later and following the bushfires that engulfed Canberra, Australia, in 2003 (https://en.wikipedia.org/wiki/2003_Canberra_bushfires), Cheney[124] offered some advice on this matter:

> . . . I believe that there is strong evidence that the policies and institutional arrangements of organizations, both those directly related to fire management and those completely unrelated, will have the result of perpetuating major fire disasters. I also believe that the legal framework in which we're working is one that [militates against] individuals taking responsibility for their own actions and lifestyle choices. In this country wildfire is inevitable but the impact of disastrous fires can be reduced. But this will only be achieved if policies focus on the physics of fire spread and foster a climate of awareness where fuel reduction, from the backyard to beyond, is encouraged and supported by legislation.

At the end of the day, though, what can an individual do to improve matters when it comes to living with fire? Kaufmann and colleagues[249] offer some very practical advice:

- Get involved in a community-based conservation group working on local landscape restoration projects.
- Educate yourself about the role of fire in your local ecosystems.
- Provide feedback on agency land management plans.
- Consult with regional experts on how to safely reintroduce fire on to your land holding.
- Participate in local workshops (e.g., *Firewise Communities*) to learn how to treat fuels around your home and create defensible space.

Their final suggestion: "Start simply. But start." Local forestry and fire management agencies are more than willing to offer technical advice and information. Just give them a call to get started today, before wildfire comes knocking![191]

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CHAPTER 15

Emergency Care of the Burned Patient

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EPIDEMIOLOGY

In 2013, approximately 486,000 individuals in the United States were burned seriously enough to seek medical care, and approximately 40,000 of such burned patients annually require hospitalization.[73,74] These numbers represent a continued downward trend in burn injuries. Number of deaths attributable to burns decreased from 12,000 in 1979 to 3240 in 2013. More than 60% of U.S. acute hospitalizations for burn injury were patients admitted to 128 burn centers.[6] Burn centers average more than 200 annual admissions for burn injury and skin disorders requiring similar treatment. The other 4500 U.S. acute care hospitals average less than three burn admissions per year. In the mid-1970s, patients with more than 20% total body surface area (TBSA) burns often died.[75] Currently, patients with 80% TBSA burns can survive, although often with permanent impairments. Although treatment facilities have greatly reduced death rates from similar-sized burns, the marked decrease in burn incidence results from better prevention (e.g., burn education, engineering improvements, widespread use of smoke detectors in public and private dwellings). It has been estimated that more than 90% of burns are preventable, and that most are caused by carelessness or ignorance.

Significant contributions to reduced burn mortality and morbidity are less likely to come from medical scientists than from improved engineering design and more successful programs to teach burn prevention to the public.[62,66] Legislation to promote smoke detectors and interior sprinklers saves lives. Developed-world advances in burn prevention can be applied in the developing world, where burn rates remain stubbornly high. Steps to further reduce burn rates in limited-resource settings include educational campaigns to recognize burn hazards (e.g., keep children from playing around open flames, do not leave hot liquids or heaters unattended). School-based burn prevention programs in rural Malawi (i.e., Africa Burn Relief Program, www.africaburnrelief.org) and community education programs in South Africa that focused on safe use of kerosene in the home are yielding results.[89] Effective hazard reduction is neither difficult nor expensive. Simple steps work, such as encouraging stable and raised cooking surfaces, separating cooking areas from play areas, and storing fuels in well-marked, childproof containers.[45]

As with other forms of trauma, burns frequently affect children and young adults. Hospital expenses and social costs related to time away from work or school are staggering. Although most burns are limited in extent, a significant burn of the hand or foot may prevent a manual laborer from working for a year or longer and may permanently prevent return to a former activity. Outcomes for the burned patient are related to severity of injury, individual physical characteristics of the patient, quality of treatment of the acute burn, and motivation toward rehabilitation.

Most burns patients seen by U.S. physicians do so by presenting to an emergency department (ED). In the ED, judgment in triage, care plan for small burns, and initial management for major burns can influence patient survival and eventual cosmetic and functional results. Because most patients are young (about one-third are children), they will live with consequences of acute treatment for an average of 50 years.

Burns are difficult to manage even under ideal conditions. In austere settings, small burns can be exquisitely painful and debilitating. Larger and deeper injuries can be catastrophic. Burn programs are advanced in most developed countries, with effective verification programs that ensure a baseline quality of care and uniform patient experience. This is not the case in most developing countries, where burns tend to be cohorted with general surgical patients. In this setting, burns are generally treated in a nonsurgical manner, with periodic dressing changes until necrotic material has sloughed. Critical care is less well developed and integrated into burn care. Sepsis is more common.

Decisions made on initial patient evaluation require answers to the algorithm shown in Figure 15-1. This chapter describes first-responder care for major burns, guides assessment of burn severity and initial management of serious burns, and provides initial treatment plans for minor burns.

PHYSIOLOGY

For burns other than chemical burns, primary injury occurs during the period of heat contact. Coagulation necrosis takes place within cells, and collagen is denatured within dermis. Blood vessels can be completely destroyed or endothelium damaged severely enough to cause clotting. This leads to ischemic necrosis of remaining viable cells. Burn wounds are not static. Surrounding the zone of coagulation is a zone of capillary and small-vessel stasis. Blood cells collect (red cells form into rouleaux; platelets and white cells form aggregates) and circulation becomes stagnant. In the acute phase (hours to days), the ultimate fate of the burn wound depends on resolution or progression of this zone of stasis. Cells and tissue stroma release mediators (e.g., histamine, serotonin, prostaglandin derivatives, complement cascade components) and initiate an inflammatory response. In patients with burns involving less than 10% TBSA, actions of these mediators are generally limited to the burn site. Capillary permeability increases, neutrophils marginate, and additional inflammatory cells (e.g., monocytes, macrophages) are attracted by chemotaxis to the site of injury and initiate healing.

As burns approach 20% TBSA, responses becomes systemic. The capillary leak that permits loss of fluid and protein from the intravascular space into extravascular space becomes generalized. Cardiac output falls as a result of markedly increased peripheral resistance, decreased intravascular fluid volume from capillary leak, and accompanying increase in blood viscosity. Decreased blood volume and cardiac output, accompanied by an intense sympathetic response, lead to decreased perfusion to skin and viscera. Decreased blood flow to skin can convert the zone of stasis to one of coagulation. This increases the depth of burn injury. Capillary leak and depressed cardiac output lead to depressed central nervous system (CNS) function. In extreme cases, severe cardiac depression can lead to cardiac failure in healthy patients or myocardial infarction in patients with preexisting coronary artery disease. The first signs of CNS change are restlessness, followed by lethargy and finally coma. Without adequate resuscitation, burns of 30% TBSA frequently lead to acute renal failure. In a patient with a severe burn, this almost invariably leads to a fatal outcome.

Cardiovascular changes begin immediately after a burn. The extent of these changes depends on burn size and to a lesser extent on burn depth. Most patients with uncomplicated burns of less than 15% TBSA can undergo oral fluid resuscitation with salt-containing solution. As burn extent exceeds 20% TBSA,

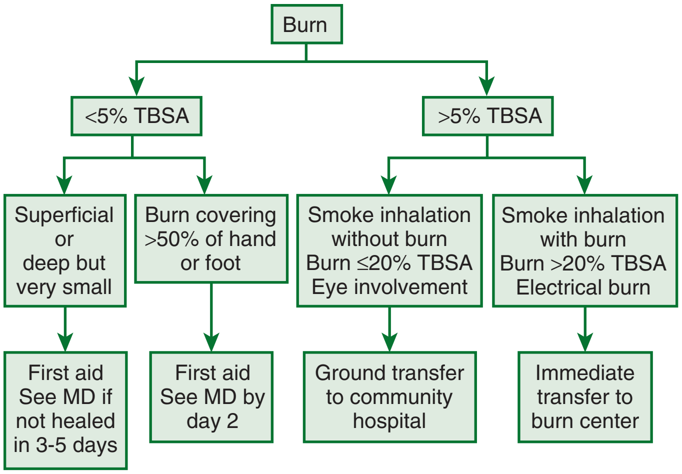

FIGURE 15-1 Algorithm for decision making at the scene. *TBSA*, Total body surface area.

massive shifts of fluid and electrolytes occur from intravascular into extravascular (i.e., extracellular) spaces. Fluid shifts begin to reverse during the second postburn day, but normal extracellular volume is not completely restored until 7 to 10 days after the burn. Unless intravascular volume is repleted, classic hypovolemic shock occurs. Insufficient fluid resuscitation can lead to irreversible acute tubular necrosis and renal failure. Untreated patients die of cardiovascular collapse.

TYPES OF BURNS

SCALD BURNS

In civilian practice, scalds, usually caused by hot water, are the most common cause of burns. Water at 60°C (140°F) creates a deep partial-thickness or full-thickness burn in 3 seconds. At 68.9°C (156°F), the same burn occurs in 1 second. Freshly brewed coffee from an automatic percolator is generally approximately 82°C (179.6°F). Boiling water always causes deep burns. Soups and sauces, which are thicker in consistency, remain in contact longer with skin and often cause deep burns. Exposed areas typically tend to be burned less deeply than areas covered with thin clothing. Clothing retains heat and keeps liquid in contact with skin for a longer time.

Immersion scalds are deep and severe burns[21,31,105] (Figure 15-2). Although water may be cooler than with a spill scald, duration of contact is longer. These burns frequently occur in small children or older adult patients with thin skin. Consequently, many states have passed legislation to set home and public hot-water heaters to maximum temperatures well below 60°C (140°F).

FIGURE 15-3 Tar burn of the hand. *(Courtesy Paul S. Auerbach, MD.)*

Scald burns from grease or hot oil are generally deep partial thickness or full thickness. Cooking oil and grease, when hot enough to use for cooking, may be approximately 204.4°C (400°F). Tar and asphalt burns are a special kind of scald. The "mother pot" on the back of a roofing truck maintains tar at a temperature of 204.4° to 260°C (400° to 500°F). Burns caused by tar directly from the mother pot are invariably full thickness. After tar is spread on the roof, its temperature has decreased enough that most burns are deep partial thickness (Figure 15-3). The initial evaluator cannot usually examine these burns because of adherent tar. Remove tar by applying a petroleum-based ointment (e.g., Vaseline) under a dressing. In the field, mayonnaise may serve this purpose (Figure 15-4). Remove the dressing and reapply ointment every 2 to 4 hours until the tar has dissolved. Only then can the extent of injury and depth of burn be accurately estimated.[43,104]

FLAME BURNS

Flame burns are the next most common burn injuries after scalds. Although injuries in house fires have decreased with the advent of smoke detectors, a significant number of burn injuries still result from careless smoking, improper use of flammable liquids, automobile accidents, and clothing ignited from stoves or space heaters. Patients whose bedding or clothes have been on fire rarely escape without full-thickness burns. Outdoor misadventures result from spilled hot water while cooking, fuel fires from cooking stoves and lanterns, fabric fire (e.g., taking lanterns into tents), smoking in a sleeping bag, tripping and falling into a campfire, and application of accelerants (e.g., gasoline, charcoal lighter fluid) to wood or charcoal fires. Most accelerants, whether gasoline, kerosene, propane, or diesel, have ignition temperatures of 210° to 280°C (410° to 536°F) and cause rapid tissue injury and full-thickness burns.

FIGURE 15-2 Immersion scald burns are often quite deep. Note popliteal flexor sparing, signifying a tightly flexed position at burning. *(Courtesy Rob Sheridan, MD.)*

FIGURE 15-4 Mayonnaise used to dissolve tar off a hand burn. *(Courtesy Paul S. Auerbach, MD.)*

FLASH BURNS

Flash burns are next in frequency after scald and flame burns. Explosions of natural gas, propane, gasoline, and other flammable liquids cause intense heat for a very brief time. Typically, unignited clothing protects skin from flash burns. Flash burns generally have a distribution covering all exposed skin, with the deepest burn areas facing the source of ignition. Flash burns are partial thickness, with depth dependent on amount and type of fuel that ignited. Although such burns generally heal without requiring extensive skin grafts, they may be very large and associated with significant thermal damage to the upper airway.

CONTACT BURNS

Contact burns result from direct contact with hot materials (e.g., metals, plastic, glass, hot coals and rocks). Such burns are usually limited in extent but are deep. Patients involved in industrial accidents typically have severe contact burns and crush injuries, because these accidents are often caused by direct contact with presses or hot, heavy objects. Toddlers may receive contact burns by touching wood-burning stoves. They most often receive deep palmar burns because the child falls with hands outstretched against the stove. Contact burns, especially in unconscious persons (e.g., narcotic- or alcohol-intoxicated person falling against a radiator) or individuals dealing with molten materials, are frequently fourth degree.[19,59,92] In wilderness settings, the most common contact burns are from hot coals, which are often as hot as 537.8° C (1000° F). These burns may occur when intoxicated campers dance around and then into campfires, architects of "river saunas" mishandle hot rocks, children fall into fires, and beach walkers sustain deep burns when coals are buried in sand overnight. Coals buried in "extinguished" campfires can remain dangerously hot for days. Falling into such ashes can cause very deep burns (Figure 15-5). Even though injured areas may be small, they can be deep and debilitating when the hiker must walk a considerable distance on burned feet.[27]

ELECTRICAL BURNS

Electrical burns are thermal burns from very-high-intensity heat. As electrical energy encounters body tissue resistance, it is converted to heat. This occurs in direct proportion to current's amperage and electrical resistance of body parts through which it passes. The smaller the body part through which electricity passes, the more intense the heat and the less it is dissipated. Therefore, fingers, hands, forearms, feet, and lower legs are frequently totally destroyed, whereas larger-volume areas (e.g., trunk) usually dissipate the current sufficiently to prevent extensive damage to viscera, unless the contact point is on the abdomen or chest (Figure 15-6). Although cutaneous manifestations may appear limited, massive underlying tissue destruction may be present because muscle, nerves, blood vessels, and bones can be burned beyond recovery.[18,36,37,77]

FIGURE 15-5 Coals buried in extinguished campfires will stay dangerously hot for days. This toddler stumbled into the ashes of a fire extinguished 24 hours earlier. *(Courtesy Rob Sheridan, MD.)*

FIGURE 15-6 This patient suffered deep localized burns to fingers from a 220-volt power source. Electricity passing through smaller body parts generates more intense heat, so less is dissipated. Fingers, hands, forearms, feet, and lower legs are frequently destroyed. *(Courtesy Rob Sheridan, MD.)*

Arc burns occur when current takes the most direct path rather than the path of least resistance. Arcs create extremely high temperatures. These deep and destructive wounds occur at joints that are in close apposition at the time of injury. Most common are burns from forearm to arm (i.e., when the elbow is flexed) and from arm to axilla (i.e., current passes from the upper extremity to trunk) if the shoulder was adducted.

Electrical burns cause a particular set of other injuries and complications that must be considered during initial evaluation. Injuries related to a fall are common. Electrical exposure can cause intense muscle contractions that lead to falls or cause fractures of lumbar vertebrae, humerus, or femur, and dislocate shoulders or hips.

Electrical cardiac damage presents with symptoms similar to those of a myocardial contusion or infarction. The conduction system may be deranged. There can be rupture of a heart wall or of a papillary muscle leading to sudden valvular incompetence and refractory heart failure. Household current (in the U.S., 110 volts) typically causes no damage or induces ventricular fibrillation. Alternating current (AC) is more likely to induce fibrillation than is direct current (DC). After exposure to shocks of 110 to 220 volts, if no cardiac abnormalities are present when a patient is first evaluated, it is very unlikely that cardiac manifestations will develop.

The nervous system is particularly sensitive to electricity. The most severe brain damage occurs when current passes through the head, but spinal cord damage is possible any time current passes from one side of the body to the other.[48,53] Myelin-producing cells are susceptible. Devastating transverse myelitis may develop days or weeks after the primary event. Conduction remains normal through existing myelin, but as myelin ages, it is not replaced and conduction stops. Peripheral nerves are frequently damaged and may demonstrate severe permanent functional impairment.[23,33] Every patient with an electrical injury must have a thorough neurologic examination as part of initial assessment. Myoglobinuria is a frequent accompaniment of severe electrical burns (Figure 15-7). Disruption of muscle cells releases cell fragments and myoglobin into circulation, from where it is filtered by the kidneys. If untreated, this can lead to permanent renal failure. Lightning strike is discussed in Chapter 5, and reviews are available.[24,25,28,29,60,77]

CHEMICAL BURNS

Chemical burns, usually caused by strong acids or alkalis, most often result from industrial accidents, use of domestic drain

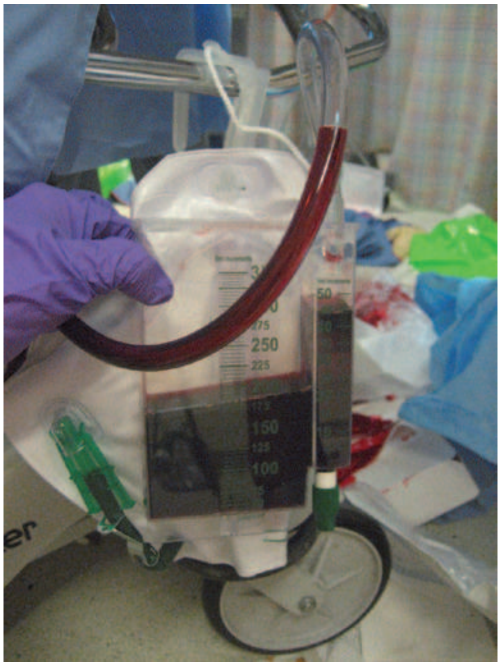

FIGURE 15-7 Evidence of myoglobinuria with "cola-colored" urine. Myoglobin pigment released from damaged muscle by electrical trauma will cause renal failure if not cleared. Administering intravenous crystalloid to an end point of 2 to 3 cc/kg/hr urine output reduces risk of renal failure. Intravenous bicarbonate (1 mEq/kg) may enhance clearance of these pigments. *(Courtesy Rob Sheridan, MD.)*

cleaners, improper use of harsh solvents, and assaults.[26,38,67,70,84,87,94] Chemical burns cause progressive damage until chemicals are inactivated by reaction with tissue or by dilution (e.g., flushing with water). Typically, acid burns tend to be more self-limited than are alkali burns. Acid tends to "tan" skin (i.e., as leather is tanned). This creates an impermeable barrier that limits further acid penetration. In contrast, alkalis combine with cutaneous lipids and saponify skin. This continues until they are removed or neutralized. A full-thickness chemical burn may appear deceptively superficial (e.g., only a mild, brownish surface discoloration). Skin may appear intact during the first few days after exposure and then begin to slough spontaneously. Unless caregivers can be absolutely certain, chemical burns should be considered deep partial thickness or full thickness until proved otherwise.

CLINICAL PRESENTATION

Cutaneous burns are caused by application of heat or caustic chemicals to skin. When heat is applied to skin, depth of injury is proportional to temperature applied, duration of contact, and skin thickness. Burn severity is related to burn size and depth and body part involved.

ESTIMATION OF BURN SIZE

Burns are a highly quantifiable form of trauma. Burn size in proportion to the patient's TBSA is the most important feature to predict mortality, need for specialized care, and expected complications. Treatment plans, including initial resuscitation and subsequent nutritional requirements, are derived directly from burn size.

A reasonably accurate estimate of burn size is provided by the "rule of nines." In adults, each upper extremity accounts for 9% TBSA, each lower extremity accounts for 18%, anterior and posterior trunk each account for 18%, head and neck account for 9%, and perineum accounts for 1% (Figure 15-8). Although the rule of nines is rapid and effective, a number of more precise charts have been developed. To establish TBSA, draw a diagram of the burn on a chart. Guided by accompanying TBSA estimates, create a relatively precise calculation of burned area. Children younger than 4 years have much larger heads and smaller thighs in proportion to body size than do adults. In an infant, the head accounts for approximately 18% of TBSA. Body proportions do not fully reach adult percentages until adolescence. To further increase accuracy in burn size estimation, especially when burns are in scattered body areas, the observer might calculate the unburned areas on a separate diagram. If calculations of burned and unburned areas do not add up to 100%, begin again with a new diagram to recalculate burned areas. For smaller burns,

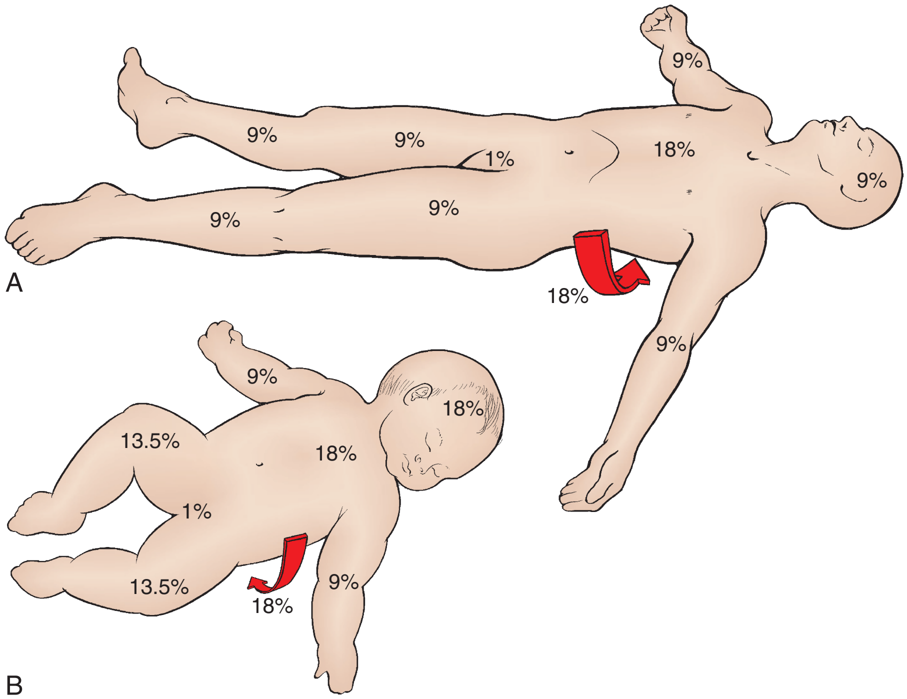

FIGURE 15-8 "Rule of nines" used for estimating burned surface area. **A,** Adult. **B,** Infant.

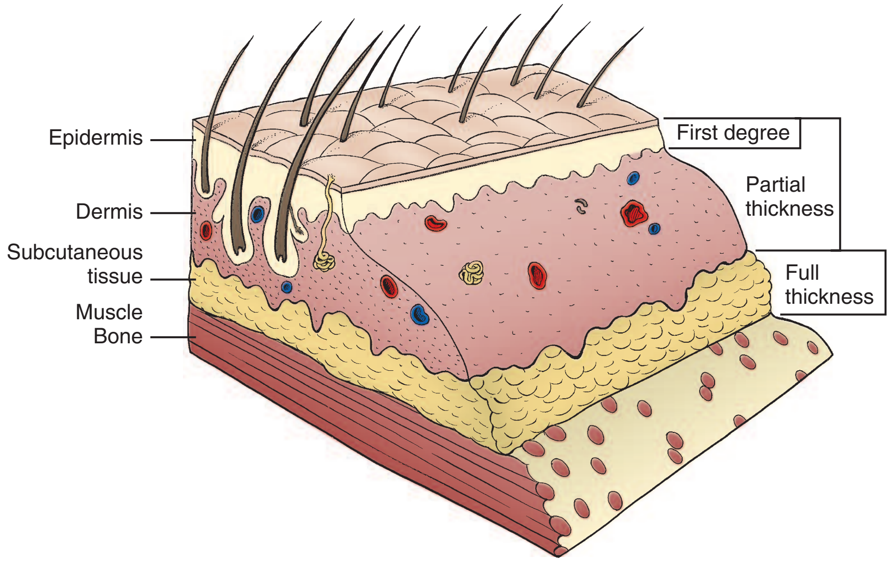

FIGURE 15-9 Skin anatomy.

accurate assessment of burn size can be made by using the patient's hand. Skin coverage on the hand amounts to 2.5% TBSA. The dorsal surface accounts for 1%, palmar surface for 1%, and vertical surface for 0.5% (including the fingers).

DEPTH OF BURN

Understanding burn depth requires awareness of skin anatomy (Figure 15-9). Epidermis is an intensely active layer of epithelial cells under layers of dead keratinized cells. It is superficial to skin's active structural framework, the dermis. Although metabolically very active, dermis has no regenerative capacity. Epithelial cells must cover the dermal surface before the burn is healed. Skin appendages (i.e., hair follicles, sebaceous glands, and sweat glands) all contain an epithelial cell lining. When surface epidermis has been killed, epithelial covering must take place from outward grown of epithelial cells lining skin appendages. As these cells reach the surface, they spread laterally and create a new epithelial surface. As a burn extends deeper into dermis, fewer and fewer appendages remain, and epithelial remnants must travel farther to produce a new surface covering, sometimes taking many weeks to produce coverage. When burns extend beyond the deepest layer of skin appendages, wounds can heal only by epithelial ingrowth from the edges, by wound contraction, or by surgical transplantation of skin from a different site.

Skin thickness varies with age, gender, and body part. Although thickness of living epidermis is relatively constant, keratinized epidermal cells can reach a height of 5 mm (0.2 inch) on palmar and plantar surfaces. Dermal thickness can vary from less than 1 mm (0.04 inch) on eyelids and genitalia to more than 5 mm (0.2 inch) on the posterior trunk. Although proportional skin thickness in each body area is similar in children, infant skin thickness in each specific area may be less than one-half that of adult skin. Skin does not reach adult thickness until adolescence. In patients older than 50 years, gradual dermal atrophy causes skin to thin significantly.

Burn treatment depends on knowledge of burn depth. Burns are classified by increasing depth as first degree, superficial partial thickness, deep partial thickness, full thickness, and fourth degree. These descriptions appear to separate burns into clearly defined categories, but many burns have a mixture of characteristics that limit diagnostic precision. Research is being conducted to devise instruments to allow more precise measurements of depth of injury.

First-Degree Burns

First-degree burns (e.g., mild sunburn) involve only epidermis. First-degree burns do not blister. Because of dermal vasodilation, they become erythematous, quite painful, and tender. Erythema and pain subside over 2 to 3 days. By day 4, injured epithelium desquamates ("peels.")

Superficial Partial-Thickness Burns

Superficial partial-thickness burns include upper layers of dermis (Figure 15-10). They characteristically form blisters with fluid collecting at the interface of epidermis and dermis. Blistering may not occur for some hours after injury. Burns initially thought to be first degree may therefore be diagnosed as superficial partial thickness by day 2. When blisters are removed, the wound is pink and wet, and it is quite painful when contacted by currents of air. The wound is hypersensitive to touch and blanches with pressure. Blood flow to dermis is increased compared with that of normal skin. If infection does not occur, superficial partial-thickness burns heal spontaneously within 3 weeks without functional impairment. They rarely cause hypertrophic scarring,

FIGURE 15-10 Superficial partial-thickness burn. Note the pink color and moist surface.

FIGURE 15-11 Deep partial-thickness burn. Note the cherry-red color.

but in pigmented individuals, healed burns may never completely match the color of surrounding normal skin.

Deep Partial-Thickness Burns

Deep partial-thickness burns also blister, but the wound surface is typically a mottled pink and white color immediately after injury (Figure 15-11). Alternatively, burned dermis may be dry, with a cherry-red color. The patient complains of discomfort rather than frank pain. When pressure is applied to the burn, capillary refill returns slowly, if at all. The wound is often less sensitive to touch than is surrounding normal skin. By the second day, the wound may be white and is usually fairly dry. If infection is prevented, such burns heal in 3 to 9 weeks, but invariably do so with considerable scar formation. Unless active physical therapy is continued throughout the healing process, joint function may be impaired and hypertrophic scarring, particularly in children and individuals with pigmented skin, becomes inevitable.

Full-Thickness Burns

Full-thickness burns involve all layers of dermis and can heal only by wound contracture, epithelialization from the wound margin, or skin grafting (Figure 15-12). Full-thickness burns are classically described as leathery, firm, insensitive to light touch and pinprick, and depressed compared with the adjoining normal skin. Difference in depth between a deep partial-thickness burn and a full-thickness burn may be less than 1 mm (0.04 inch). Full-thickness burns are easily misdiagnosed as deep partial-thickness burns, because both have many of the same clinical findings. Both may be mottled in appearance. They rarely blanch with pressure and may have a dry, white appearance. Burns may be translucent with clotted vessels visible in the depths. Some full-thickness burns, particularly immersion scalds, have a red appearance and can be confused with superficial partial-thickness burns. However, these red, full-thickness burns do not blanch with pressure. Full-thickness burns develop a classic burn eschar. An *eschar* represents structurally intact but dead and denatured dermis that, over days to weeks, separates spontaneously from underlying viable tissue.

Fourth-Degree Burns

Fourth-degree burns involve not only all skin layers but also subcutaneous fat and deeper structures. These burns almost always have a charred appearance. Frequently, only the cause of the burn gives a clue to the amount of underlying tissue destruction.

TREATMENT

CARE AT THE SCENE

Flame Burns

The first responder must remove the injured person from the source of heat. Because of potential dangers of smoke inhalation in closed areas, rescuers in a fire must take extreme caution not to become victims. Persons with burning clothing should be prevented from running and should be made to lie down (i.e., to keep flames and smoke away from the face). If water is not immediately available, flames can be smothered with a coat or blanket. If nothing is available to douse or cover flames, the victim should be rolled slowly on the ground. Once burning has stopped, clothing should be removed. Some fabrics will continue to smolder, and synthetic fabrics may melt and leave a hot adherent residue on the victim that will continue thermal injury. Even flame-retardant cloth burns or smolders when temperatures are sufficiently high (Figure 15-13).

Scalds and Grease Burns

Remove the victim of a scald or grease burn from the source of heat. Any wet clothing should be removed, because fabric retains moist heat and may continue to burn skin that is in contact with hot material. Accidents resulting from cooking indoors with grease are particularly hazardous. The startle response to a grease splatter may cause the victim to drop a pan of grease onto the fire and so ignite a kitchen fire that can rapidly become a dwelling fire.

Airway

Once flames are extinguished, direct primary attention to the airway. Any person rescued from a closed space or involved in a smoky fire should be considered at risk for smoke inhalation

FIGURE 15-12 Full-thickness burn. Note the thick, leathery, white eschar.

FIGURE 15-13 Even flame-retardant clothing will smolder if temperatures are sufficiently high. It is important to remove burning clothing promptly while protecting providers from injury. *(Courtesy Rob Sheridan, MD.)*

injury. If supplemental oxygen is not available, a patient who is coughing independently should be encouraged to continue to do so. If the patient is unconscious or airway status is in question, place the patient in a supine position and manipulate the airway manually using the chin lift or jaw thrust maneuver. When smoke inhalation is suspected, 100% oxygen should be administered by a tight-fitting mask. If the patient is unconscious or airway is compromised, and if capability (i.e., equipment and training) exists to insert an endotracheal tube, intubate the patient's trachea and attach the tube to a source of 100% oxygen. If the airway is covered with a tight mask, rescuers must be aware of significant danger of aspiration of gastric contents. Air forced into the stomach causes distention and may produce vomiting. Use of a mask prevents expulsion of emesis. The patient can rapidly aspirate vomitus into the tracheobronchial tree. Never leave an unconscious supine patient unattended. When possible, elevate the head to minimize edema.

Other Injuries and Transport

Once an airway is secured, first responders should quickly assess for other injuries and transport the patient to the nearest hospital.[9,23,77] The patient should be kept flat and warm and should be given nothing by mouth. After establishing an airway, further resuscitation is unnecessary if the patient will arrive at a hospital within 30 minutes. For transport, the patient should be wrapped in a clean, dry sheet and blanket. Sterility is not required.

Cold Application

Smaller burns, particularly scalds, may be treated with immediate application of cool water in hopes of limiting the extent of injury. Application of cold water is controversial. Immediate cooling decreases pain, possibly by decreasing thromboxane production. After several minutes have passed, or after arrival in the ED, further cooling is not likely to alter the pathologic process. Ice water should not be used except on the smallest burns. Using ice on larger burns can easily induce systemic hypothermia and associated cutaneous vasoconstriction that can extend thermal damage.

Swelling

During transport, remove constricting clothing and jewelry from burned and distal parts. Local swelling begins almost immediately. Constricting objects increase swelling and can cause vascular compromise. In addition, it is time-consuming to remove tight jewelry after distal edema occurs (Figure 15-14).

Electrical Burns

Electrical burns are particularly dangerous to both patient and rescuer. If patient remains in contact with the source of electricity, the rescuer must avoid touching the patient until the current can be turned off or wires cut with properly insulated wire cutters. Once the patient is removed from the source of current, airway, breathing, and circulation must be checked. Ventricular fibrillation (VF) or cardiac standstill is a common accompaniment to a major transthoracic current. If carotid or femoral pulses are not palpable, institute cardiopulmonary resuscitation (CPR). If pulses are present but the patient is apneic, mouth-to-mouth resuscitation alone may be lifesaving. Continue CPR until a cardiac monitor can be obtained, which will direct treatment for cardiac standstill or VF. Defibrillate VF as soon as possible. Follow advanced cardiac life support (ACLS) protocols for management of cardiac arrhythmias. Once an airway is established and pulses return, make a careful search for associated life-threatening injuries. Electrocuted patients frequently fall from heights and may have serious head or neck injuries. Intense tetanic muscle contractions associated with electrocution may fracture vertebrae or cause major joint dislocations. Until fractures can be ruled out, patients with high-voltage electrical injuries should be treated with spinal precautions and splints, if necessary.

FIGURE 15-14 Jewelry, particularly rings, should be removed promptly to protect distal circulation. Delay in removal often leads to the need later to cut away rings. *(Courtesy N. Stuart Harris, MD.)*

Chemical Burns

Whenever possible, chemical burns should be thoroughly flushed with copious amounts of water at the accident scene. Chemicals will continue to burn until removed. Wash for 5 to 10 minutes under a stream of running water to limit overall burn severity and remove gross contamination. Remove any contaminated clothing before moving the patient into the ambulance or ED. Do not attempt to apply any specific neutralizing agent. Time delay deepens the burn, and neutralizing agents may themselves cause burns. The process of neutralizing offending agents frequently generates heat. This adds thermal burn to an already potentially serious chemical burn.

Hydrofluoric acid is commonly used as a cleaning agent in the petroleum industry and for glass etching. As an acid, it causes coagulation necrosis. Fluoride ions (negatively charged) chelate positively charged ions (e.g., calcium and magnesium), which causes an efflux of intracellular calcium and results in cellular death.[76] Fluoride ion is also a metabolic poison that inhibits sodium-potassium adenosine triphosphatase (ATPase), allowing efflux of potassium.[61] Hydrofluoric acid burns are classified by National Institutes of Health Division of Industrial Hygiene standards based on the solution's concentration.[108] Concentrations above 50% cause immediate tissue destruction and pain. Concentrations of 20% to 50% create a burn that is apparent within several hours of exposure. Exposures to concentrations less than 20% may take as long as 24 hours to become apparent. Systemic symptoms of hypocalcemia or hypomagnesemia are usually absent, although cardiac dysrhythmias may develop and, once present, may be difficult to restore to a normal rhythm. QT prolongation is the most common abnormal electrocardiogram (ECG) finding. The goal of treatment for hydrofluoric acid exposure is to neutralize fluoride ion and prevent systemic toxicity. After wounds are copiously irrigated, apply topical calcium gluconate gel as 3.5 g of 2.5% calcium gluconate mixed with 5 oz of water-soluble lubricant applied to the wound four to six times a day for 3 to 4 days.[64] Pain relief with this approach is often quite rapid. Return of pain is generally a sign to repeat a dressing change.

Phosphorus can be found in both military and civilian settings as an incendiary agent found in hand grenades, artillery shells, fireworks, fertilizers, and some homemade explosives. White phosphorus ignites in the presence of air and burns until it is entirely oxidized or the oxygen source is removed (e.g., by immersion in water). Irrigate such burns with large amounts of water. Remove easily identifiable pieces of phosphorus, and place moist dressings for patient transport. Use ultraviolet light to identify embedded particles, which phosphoresce, in order to improve removal. Hypocalcemia, hyperphosphatemia, and cardiac arrhythmias have been reported.[103]

First Aid at the Scene for Smaller Burns

Not all burns need immediate medical attention. Burns less than 5% TBSA (excluding deep burns of face, hands, feet, perineum, or circumferential extremity) can be treated successfully in austere settings if adequate first-aid supplies are available and wound care is performed diligently. Except for very shallow burns that heal within a few days, most burns should be seen by a physician within 3 to 5 days after injury.

Wash burns thoroughly with ordinary, plain soap and water and dry with a clean towel. The water used should be suitable for drinking (e.g., disinfected), but it need not be sterile or bottled. After gentle cleaning and removal of loose debris, any obviously dead skin should be peeled off (which may be painful) or trimmed with sharp manicure scissors (usually painless). Large (>2.5 cm [1 inch]), thin, fluid-filled blisters should be drained and dead skin trimmed to prevent potential closed-space infection. Deep burns, as from a flame, are firm and leathery, usually do not blister, and do not require immediate debridement. Many medications are suitable to be placed on the wound before bandaging. These generally have a viscous ointment base to prevent dressings from sticking to the wound and often contain an antibiotic(s). As long as there is no allergy to the contents of the ointment, they should be useful for most second-degree burns.

Spread a thin layer of silver sulfadiazine cream or antibiotic/antiseptic ointment (e.g., bacitracin) over the wound and wrap it in dry, clean gauze that need not be sterile. Fine gauze membranes impregnated with antiseptic ointments are useful as primary burn dressings in many cases. In austere settings, clean cotton clothing can be used to improvise many effective burn dressings. Clean, white cotton T-shirts can be used to good effect. Oversize clean cotton socks can be used to reinforce dressings on hands and feet. Simple dressings (i.e., topical cream, plain gauze) are sufficient. Some patients prefer nonadherent dressings (e.g., Telfa or Adaptic, the latter sometimes known as "greasy gauze"), because they are less likely to stick to wounds during dressing changes. The same effect can be achieved by soaking (with water) a plain gauze dressing that appears stuck to wound, waiting a few minutes, and then removing the dressing with additional water if necessary. Other dressings (e.g., hydrogels, silver-coated dressings, silicone gel sheets, calcium alginate) designed to minimize frequency of dressing changes and promote healing are available but not necessary. To stock first-aid kits, we recommend simple antiseptic/antibiotic ointments (e.g., silver sulfadiazine or bacitracin) and plain gauze dressings rather than "specialty" dressings because they are simple, less expensive, and effective. A patient may prefer one dressing over another for various reasons, but no dressing has been shown conclusively to accelerate burn wound healing. First-aid kits should be stocked with general-use supplies that are easy to replenish.

Effective burn dressings can be complex and difficult to apply. Wound area mobility must be actively maintained. Every effort should be made to avoid dependent positioning, especially when patient is resting. Focal edema in a small burn wound can be painful and alarming and should be prevented with extremity elevation and active range-of-motion exercises several times a day. Wound care should be performed once a day if the outer dressing remains dry. A wet, sticky outer dressing needs more frequent wound care to keep up with wound drainage. If only the outer dressing is dirty (e.g., soiled from food or dirt), it may be changed as often as needed to maintain a clean dressing and aid in patient comfort. For quickest healing of superficial burns, perform daily wound care to remove all exudates and crust, because both significantly impair wound healing. Once a wound has epithelialized or nearly epithelialized, apply moisturizing lotion to hydrate and decrease scarring. Vitamin E, aloe, and oat beta glucan are often used for their antiinflammatory and soothing properties. Melaleuca is a topical antibacterial and antifungal tea tree oil that Australian aboriginal people have used for a variety of medicinal purposes. It is the active ingredient in Burnaid, a popular cream used for superficial partial-thickness burn injuries.

To determine which type of dressing to apply to a burn wound, consider the following:

- The dressing should cover the entire burned area (i.e., an enclosed dressing) and leave no burned skin exposed to air or air currents.
- The burn wound surface should stay moist. Unburned skin surrounding the burn should not macerate.

FIGURE 15-15 Contact burn from stepping on hot coals. Small, flat blisters do not require debridement.

- The dressing should be relatively light and not bulky. It should not limit the patient's ability to actively flex and extend all burned extremities and digits. Frequent flexion and extension prevents burned skin from tightening and assists with pain control and prevention of edema.

These principles are much more important than the choice of topical agent to cover the burn. Commonly used topical agents that might be carried in first-aid kits include antiseptic and antibiotic ointments and creams (e.g., bacitracin, double antibiotic [Polysporin: polymyxin B, bacitracin], triple antibiotic [Neosporin: bacitracin/gramicidin, neomycin, polymyxin B], silver sulfadiazine) and nonantibacterial ointments (e.g., Aquaphor, Vaseline, A+D). Any of these agents is acceptable. Using a topical antimicrobial is not essential in early postburn care.

Technique of Burn Wound Debridement. Small, intact blisters do not need debridement (Figure 15-15). Blisters serve as sterile biologic dressings to minimize desiccation and pain. Protect intact blisters from trauma, and observe every few hours to ensure that the blister has not ruptured. If the blister opens, debridement is usually recommended because leaking blister fluid may lead to crusting that can effectively "seal" the wound over entrapped bacteria, leading to a closed-space infection (Figure 15-16).

Blister debridement is essentially painless as long as blistered skin is cut and not peeled or torn. The burn should be washed with soap and water. Forceps are used to grasp blistered skin and small (e.g., manicure) scissors can be used to remove the blister roof (Figure 15-17). Remove as much blistered skin as possible, and leave a uniform surface that can be treated with a topical agent (Figure 15-18). There should no bleeding during this procedure. To ensure that the procedure will be painless, stabilize the body part to be debrided against a solid surface. This prevents patient motion and optimizes control for the person performing the procedure.

FIGURE 15-16 Contact burn from stepping on hot coals. Leaking blisters that have burst should be debrided.

FIGURE 15-17 Partial-thickness burn to dorsal hand from hot oil while cooking at camp. **A,** Blister is debrided 5 days after injury. **B,** Bacitracin ointment is applied. *(Courtesy Tim Platt-Mills, MD.)*

EMERGENCY DEPARTMENT CARE

A reasonable rule for the emergency physician in the initial assessment of a seriously injured patient is to "forget about the burn." Airway management takes priority. Although a burn is usually readily apparent and may even be a dramatic injury, a careful search for other life-threatening injuries is critical. Only after an overall assessment of patient's condition should attention be directed to specific burn care. Assessment of the nonthermally injured patient is presented in Chapter 18. The following paragraphs consider specific problems encountered in burned patients.

Resuscitation

Since the 1970s, more than a dozen resuscitation plans have been suggested. Their common goal is to complete treatment with a living patient who has normally functioning kidneys and does not develop cardiac failure or pulmonary edema. Almost all these plans use a combination of colloid and crystalloid solutions, but they vary considerably in the ratio of colloid to crystalloid, timing of colloid administration, sodium concentration of crystalloid solution, and to a much lesser extent, total volume of fluid given.[16,32,35,41,63,68,71] In recent years, a shift toward earlier administration of colloid has occurred. Data suggest it reduces overall volume requirements and morbidity related to edema. Some protocols require frequent changing of solutions, others require mixing of solutions, and some require careful monitoring of the patient's serum electrolytes. Controversy exists about which resuscitation plan is best. This need not concern the physician without a special interest in burn physiology. There is general agreement on critical facts. A patient with very large burns will probably need both colloid and crystalloid. Initially, capillaries are permeable to both crystalloid and colloid solutions. Capillary leak of albumin and other large molecules repairs itself between 6 and 24 hours after injury.

Choice of formulas for initial resuscitation is of relatively little consequence as long as the rate of fluid administration is modified according to the patient's changing requirements over time. Because of its simplicity, ease of administration, and need for little blood chemistry monitoring, the Baxter formula (also known as the Parkland formula) has been adopted by most experts and recommended officially by the American College of Surgeons Committee on Trauma.

According to this formula, crystalloid is given during first 24 hours while capillaries are still permeable to albumin. During the second 24 hours, when the capillary leak has presumably sealed, colloid is given. Rapid administration of crystalloid solution results in early expansion of depleted plasma volume, which will return cardiac output toward normal. Once the capillary leak has sealed, colloid (usually in the form of albumin) remains the most effective solution to maintain plasma volume without further increasing edema. The Baxter formula was derived to provide specific replacement of known deficits measured by simultaneous determinations of red blood cell volume, plasma volume, extracellular fluid volume, and cardiac output during burn shock.

Box 15-1 lists first and second 24-hour calculations. The Baxter formula calls for administration of lactated Ringer's solution, 4 mL/kg body weight per percentage of body surface burned during the first 24 hours after the injury. One-half of this fluid should be given in the first 8 hours and the second half during the next 16 hours. Fluid therapy during the next 24 hours consists of administration of free water in quantity sufficient to maintain normal serum sodium concentration, as well as plasma (or other colloid) to maintain normal plasma volume.

Adequacy of resuscitation can best be judged by frequent measurements of vital signs, central venous pressure, and urine output and by observing general mental and physical responses. Despite myriad new monitoring devices, urine output remains one of the most sensitive and reliable assessments of fluid

FIGURE 15-18 Burn seen in Figure 15-16, after debridement.

BOX 15-1 Baxter (Parkland) Formula

First 24 Hours—Ringer's Lactate

- 4 mL/kg/% burn in 24 hours
  One-half in first 8 hours
  One-half in second 16 hours
- Example: 70-kg (154-lb) man with 50% burn
  4 mL × 50% × (70 kg) = 14,000 mL in 24 hours
  7000 mL in hours 1 to 8
  3500 mL in hours 8 to 16
  3500 mL in hours 17 to 24

Second 24 Hours—Albumin or Plasma at Maintenance

- Maintain normal vital signs
- Adequate urine output
- Example: 70-kg (154-lb) man with 50% burn
  250 to 500 mL plasma
  2000 to 2500 mL dextrose 5% in water

resuscitation. In the absence of myoglobinuria, a urine output of 0.5 mL/kg/hr in adults and 1 mL/kg/hr in children weighing less than 10 kg (22 lb) ensures that renal perfusion is adequate. The patient's sensorium gives an indication of state of cerebral perfusion and oxygenation. The patient should be alert and cooperative. Confusion and combativeness are signs of inadequate resuscitation or warn of other causes of hypoxia. Provide supplemental oxygen in addition to fluid resuscitation.

Patients with burns that involve less than 10% TBSA generally do not require fluid resuscitation. They should stay well hydrated but should not be encouraged to force fluids. Patients with burns that involve between 10% and 20% TBSA typically do not require intravenous (IV) fluid resuscitation. They should be encouraged to drink fluids that contain electrolytes (e.g., Gatorade) and should be discouraged from drinking large amounts of plain water or sodas. Hydration status in these patients should be monitored by ensuring that oral mucous membranes are moist and urine output is brisk with light-colored urine. Patients with burns that involve more than 20% TBSA should receive IV fluid resuscitation with crystalloid solution until they reach a facility where medical professionals can evaluate need for other types of fluids.

Patients with burns of less than 50% TBSA can usually be resuscitated with a single large-bore peripheral IV line. Because of the high incidence of septic thrombophlebitis, lower extremities should be avoided as IV portals. Upper extremities are preferable, even if the IV line must pass through burned skin. Patients with burns larger than 50% TBSA or who have associated medical problems, are at the extremes of age, or have concomitant smoke inhalation should have additional central venous pressure monitoring. Because of extreme hemodynamic instability in patients with burns over 65% TBSA, these patients should be monitored in an intensive care unit (ICU) setting with a Swan-Ganz catheter to measure pulmonary capillary wedge pressure and cardiac output.

Presence of myoglobinuria alters the resuscitation plan. Myoglobinuria results from destruction of muscle cells leading to myoglobin (red muscle pigment) release. This is most often associated with crush injuries, electrical burns, or extremely deep thermal burns. Characteristic cola-colored urine indicates the need to increase the amount of fluid given and to establish diuresis of 70 to 100 mL of urine per hour (see Figure 15-7). An initial bolus of 25 g of mannitol in adults or 0.5 to 1 g/kg in children, with a repeat dose in 15 to 30 minutes, should be considered.

Escharotomy

Carefully monitor peripheral circulation in patients with circumferential full-thickness extremity burns. Edema that forms beneath inelastic eschar can increase tissue pressure beyond that of lymphatic pressure, thereby further increasing edema. When edema exceeds venous pressure and approaches arterial pressure, it can stop circulation in the extremity distal to the constricted area.

Classic findings of compartment syndrome (e.g., pain, paresthesias, pulselessness, tense swelling) may or may not be present in burned extremities. Carefully monitor distal pulses with Doppler ultrasound. If any of the classic clinical signs occur or if Doppler signals disappear, perform an escharotomy immediately.

Escharotomy performed in the hospital does not require an anesthetic, because only an insensate full-thickness burn is incised. Make an incision through eschar into subcutaneous tissue, first along the lateral aspect of the extremity and, if symptoms or signs do not improve, along the medial aspect (Figure 15-19). Incisions need not be as deep as the investing muscle fascia, and bleeding can usually be easily controlled with electrocautery and topical clotting agents. If arrival to the hospital will be in less than 6 hours, escharotomies should not be done in the field because the patient may bleed to death without proper equipment to control bleeding.

In small children, circumferential full-thickness burns of the trunk occasionally demand an escharotomy to improve pulmonary function. Chest wall escharotomies are made in the anterior axillary lines bilaterally, extending from clavicle to costal margin.

FIGURE 15-19 Deep full-thickness flame burns to the bilateral lower extremities and buttocks requiring medial and lateral escharotomies. *(Courtesy Michael J. Mosier, MD.)*

If the abdomen is involved with burn, the inferior margins of escharotomy may be connected transversely (Figure 15-20).

Fasciotomies are rarely needed in patients with thermal burns. However, if distal pulses do not return after medial and lateral escharotomies, fasciotomy should be considered. Fasciotomies can generally be done through the initial escharotomy incisions (Figure 15-21). In contrast, patients with electrical injuries frequently need fasciotomies. Careful monitoring is mandatory for all patients with electrical burns and with burns associated with soft tissue trauma or fractures. In these circumstances, loss of pulses is a strong indication for urgent fasciotomy under general anesthesia in the operating room.

Need for escharotomy in the burned hand is controversial. Fingers burned severely enough to require escharotomy are frequently mummified, and lack of muscles in the fingers puts less tissue at ischemic risk. Escharotomy done in fingers runs the risk of exposing interphalangeal joints (Figure 15-22). This can lead to subsequent infection that may ultimately require joint fusion or finger amputation. Both palmar arch and digital vessels should be monitored with Doppler ultrasound in any significant hand burn. If the signals disappear over the palmar arch or in the digital vessels, consider performing a dorsal interosseous fasciotomy.

FIGURE 15-20 Full-thickness flame burns to the anterior torso and left upper extremity. Escharotomies were performed along the flank, sternum, clavicle, costal margin, and abdomen to release the restricting eschar and allow improved chest and abdominal wall compliance. *(Courtesy Michael J. Mosier, MD.)*

PART 3 BURNS, FIRE, AND RADIATION

FIGURE 15-21 Fasciotomies are indicated in deeply burned extremities if escharotomies fail to reduce tissue tension and restore perfusion. They can generally be performed through the initial escharotomy incisions, as illustrated in this patient with deep flame burns to the leg. *(Courtesy Rob Sheridan, MD.)*

FIGURE 15-22 Full-thickness flame burns to the right hand with escharotomies in a fan pattern between metacarpals to adequately release pressure from edema formation. *(Courtesy Michael J. Mosier, MD.)*

Burn Wound Management

Clean burn wounds initially with a surgical detergent. All loose, nonviable skin should be trimmed (Figure 15-23). Debridement should be done gently. Small doses of IV narcotic are usually sufficient analgesia for this procedure. Unless other surgical procedures are necessary, general anesthesia and operating room debridement should be avoided until resuscitation is complete.

Once the wound is cleansed, apply a topical chemotherapeutic agent. Agents most often used in the United States and other industrialized countries contain silver sulfadiazine. It comes as a white cream, is soothing to the wound, has a good antimicrobial spectrum, and has almost no systemic absorption or toxicity.[7,40,88,97] Carefully question the patient about allergy to sulfa drugs before using silver sulfadiazine. Allergic reactions are encountered in approximately 3% of patients. These reactions may be manifested clinically as pain after application rather than the soothing feeling that silver sulfadiazine typically provides. If an allergy is suspected by history, a small patch (10 by 10 cm [4 by 4 inches]) of silver sulfadiazine should be applied as a test dose. The remainder of the wound can be dressed using bacitracin. If no local reaction occurs after 2 to 4 hours, an allergy is unlikely, and silver sulfadiazine is the dressing of choice. If an allergy is confirmed, refer the patient to a burn center, where the next choice of topical antimicrobial would probably be silver nitrate solution.

OUTPATIENT BURNS

The vast majority of patients with burns do not require hospitalization. In many cases, the burn, if merely kept clean, heals spontaneously in less than 3 weeks with acceptable cosmetic results and no functional impairment. Unfortunately, good results in treating superficial minor burns may entice the unwary physician to treat more complex burns by the same methods. For the patient, the consequences of such a mistake can include subsequent hospitalization, joint dysfunction, and hypertrophic scarring that may be difficult to correct, as well as considerable loss of time from work or school.

First-Degree Burns

Although first-degree burns are very painful, patients rarely seek medical attention unless the burned area is extensive. These patients do not require hospitalization, but pain control is extremely important. Aspirin or codeine may be adequate for small injuries, but for large burns, liberal use of a more potent narcotic for 2 to 3 days is indicated.

For topical medication, we recommend one of the many proprietary compounds containing extracts of the *Aloe vera* plant in concentrations of at least 60%. *Aloe vera* has antimicrobial properties and is an effective analgesic.[51,85] Anecdotal evidence suggests that it may decrease subsequent pruritus and peeling.

Burns from ultraviolet rays (e.g., sunlight, sunlamp) may initially appear to be only epidermal, but the injury may in fact be a superficial partial-thickness burn with blistering apparent only after 12 to 24 hours (Figure 15-24). Patients with such a burn should be cautioned about blisters and be asked to return if

FIGURE 15-23 Initial debridement to remove loose necrotic material should generate almost no bleeding. This can generally be done with light analgesia. *(Courtesy Rob Sheridan, MD.)*

FIGURE 15-24 Patients with apparently severe first-degree sunburn will often slough to a painful superficial second-degree burn in the ensuing 12 to 24 hours. This compromises their mobility and ability to carry gear. *(Courtesy Rob Sheridan, MD.)*

blisters form, because wound management then becomes more important because of potential for infection and subsequent scarring.

Superficial Partial-Thickness Burns

Treatment of superficial partial-thickness burns presents little problem. If the wound is kept clean, patient kept comfortable, and joints kept active, these wounds heal in less than 3 weeks with minimal scarring and no joint impairment.

First, clean and debride the wound as described previously. Small blisters may be left intact. Biochemical analysis using polyacrylamide gel electrophoresis of burn blister fluid has shown it to be similar to that of serum.[101] We suggest that blister fluid is an exudate mainly from the vascular system, provides a good environment for fibroblasts in the damaged site, and facilitates healing. Larger blisters are difficult to protect, however, and blister fluid is a rich culture medium for bacteria that live in skin appendages. Therefore, large blisters and small blisters in large burns should usually be totally removed with forceps and scissors. In some instances, blister fluid can be aspirated with a large-bore needle, allowing blistered epidermis to remain on the wound as a biologic dressing. This dead epidermis is fragile, tends to contract, and rarely stays intact except over small areas.

After debridement, the most common treatment is wound coverage with silver sulfadiazine and application of a light dressing to promote active range of motion. Some wounds can be managed with synthetic dressings that contain elemental silver (e.g., Aquacel Ag, Acticoat, Mepilex Ag). These can be applied and left in place for 1 week or until the burn is healed at approximately 2 weeks (Figure 15-25). Some very small burns do not require topical agents. For small facial burns, bacitracin ointment may be a better choice than silver sulfadiazine cream because it is less drying.

Pain is managed as for first-degree burns. Patient usually should return every 2 to 3 days until the wound heals or the patient has demonstrated ability to manage the wound without supervision.

If silver sulfadiazine is used, an appropriate home treatment regimen is to have the patient cleanse the wound once daily with tap water and reapply a topical agent and light dressing. During dressing changes, and as often as possible, put all involved joints through a full range of motion. The dressing may be unnecessary while the patient is at home, but he or she should dress the wound before leaving the house. This method is highly successful, but is inconvenient, may be fairly painful, and requires good patient cooperation.

The "exposure" method has little to recommend it. This method involves leaving the wound open, allowing wound drainage to desiccate and form a scab. Controlled studies in animals have shown that desiccation and crust formation interfere with wound healing. Our experience has also shown that crusts crack over joints, cause considerable discomfort, and can hide infection.

FIGURE 15-25 Many new silver-releasing membranes are available that provide antiseptic coverage of wounds for several days. They need to be monitored for development of submembrane infection. *(Courtesy Rob Sheridan, MD.)*

Deep Partial-Thickness and Full-Thickness Burns

Treatment of deep partial-thickness and full-thickness burns is a matter of grave concern. Full-thickness burns heal only by contraction and epithelialization from the periphery. Epithelium does not begin to migrate until eschar is removed, and the growth rate is only approximately 1 mm (0.04 inch) per day. Healing of even a small full-thickness burn may involve many weeks of discomfort and disability. Deep partial-thickness burns may take 4 to 8 weeks to heal and then leave an unacceptable scar. If a joint is involved, some loss of joint function is the rule. We have adopted a policy of early excision and grafting for such wounds.

Initial outpatient treatment can be followed by elective surgery as soon as it can be scheduled. Small wounds can be treated through day surgery. Larger wounds located over dynamically important areas can be closed with only 1 or 2 days of hospitalization. Excision and grafting procedures should be done by a surgeon experienced in tangential wound excision. Advantages of this aggressive approach are a pain-free patient with normal joint function, better cosmetic result, and a rapid return to work or school. These more than compensate for the brief hospitalization and very small risk associated with minor surgery.

Should excision and grafting be unacceptable to the patient or treating physician, use the standard method of daily cleansing and application of silver sulfadiazine cream. Most full-thickness burns need grafting at about 3 to 4 weeks after injury. Deep dermal burns should be seen by the physician frequently during healing. Active physical therapy is crucial to ensure a successful outcome.

REHABILITATION

Physicians who regularly care for burn-injured patients recognize that treatment goals extend far beyond survival of the patient and healing of wounds. The aim is to return patients at least to their preburn functional status physically and to ensure smooth and timely reentry into family and social situations. Recovery from burn injury is a team effort and depends on multiple nonphysician health care workers. Depending on burn severity and associated social situation, participation is usually required of nurses, nutritionists, occupational therapists, physical therapists, recreational therapists, social workers, vocational rehabilitation counselors, psychologists, pain management specialists, and clergy.

Burn rehabilitation should be initiated by the first physician to see the patient. Once all systemic and wound issues have been addressed, proper positioning of wounded extremities or digits should be assessed by an occupational therapist specially trained in burn management. If deemed appropriate, splints should be made immediately. Range-of-motion exercises should be started on the day of injury, and frequent follow-up by a physical therapist is essential. Best functional outcomes result from meticulous attention to early mobility. Patients almost universally choose not to move a burned body part. An active ancillary burn staff team is essential for satisfactory results. Burn scars require approximately 1 year to fade, soften, and mature. Physical therapy may be required throughout this period or longer. Pressure garment therapy may be used in certain cases in an attempt to prevent hypertrophic scar formation. The reader is referred to books dealing with acute burn care, reconstructive plastic surgery, and burn rehabilitation.[1,8,12]

INHALATION INJURY

Of the almost 40,000 fire-injured patients admitted to U.S. hospitals each year, smoke or thermal damage to the respiratory tree may occur in as many as 30%.[79] Carbon monoxide poisoning, smoke poisoning, and thermal injury are three distinctly separate aspects of clinical inhalation injury. Inhalation injury rarely occurs in an outdoor setting unless the victim is trapped in a conducive enclosed space.

CARBON MONOXIDE POISONING

Pathophysiology

Carbon monoxide (CO) is a colorless, odorless, and tasteless gas with an affinity for hemoglobin 200 times greater than that of oxygen. The simplest explanation for the mechanism of action of CO poisoning is that it reversibly displaces oxygen on hemoglobin. Although worsening hypoxia is critical and percentage of blood carboxyhemoglobin (COHb) indicates significance of hypoxia, this simple mechanism cannot account for all experimental and clinical findings seen with exposure to CO. For example, an experimental group of dogs exchange-transfused with blood containing 80% COHb showed no symptoms. In a control group with COHb levels of 80% produced by inhalation of CO, all animals died. Furthermore, degree of enzyme and muscle impairment may not correlate accurately with levels of blood COHb.[13,20,30,52]

In vitro, CO combines reversibly with cardiac muscle myoglobin and heme-containing enzymes, such as cytochrome oxidase (a_3).[13] Despite its intense affinity, CO readily dissociates according to the laws of mass action. The half-life of COHb in humans breathing room air is 4 to 5 hours. Breathing 100% oxygen, the half-life is reduced to 45 to 60 minutes.[56] In a hyperbaric oxygen chamber at 2 atmospheres (atm), the half-life is 30 minutes, and at 3 atm, it is reduced to 15 to 20 minutes.[100]

Clinical Presentation

Blood levels of COHb provide a laboratory measure to correlate with associated symptoms of CO poisoning. Levels less than 10% do not cause symptoms, although patients with exercise-induced angina may show decreased exercise tolerance. At levels of 20%, healthy persons complain of headache, nausea, vomiting, and loss of manual dexterity. At 30%, they become confused and lethargic and may show depressed ST segments on ECG. In a fire situation, this level may lead to death because victims experience diminished volition and ability to flee smoke. At levels between 40% and 60%, victims lapse into unconsciousness. Levels much above 60% are often fatal.

Therapy

Nonpregnant patients who have not lost consciousness and who have a normal neurologic examination on admission typically recover completely without treatment beyond administration of 100% oxygen. Patients who remain comatose once COHb levels have returned to normal have a poor prognosis. Hyperbaric oxygen treatment (HBOT; see Chapter 72) remains controversial for asymptomatic, moderate CO poisoning.[2,3,54,65,80,86] In one study, patients with elevated COHb levels and symptoms (e.g., loss of consciousness, confusion, headache, malaise, fatigue, forgetfulness, dizziness, visual disturbances, nausea, vomiting, cardiac ischemia, or metabolic acidosis) treated with three HBOTs in a 24-hour period appeared to have reduced risk of cognitive sequelae at 6 weeks and 12 months.[107] A follow-up meta-analysis found insufficient evidence to establish whether HBOT for CO poisoning reduces the incidence of adverse neurologic outcomes.[14] When associated with a major burn, transport to a chamber delays definitive care and is associated with numerous complications (e.g., emesis, seizures, eustachian tube occlusion, aspiration, hypocalcemia, agitation requiring restraints or sedation, arterial hypotension, tension pneumothorax, cardiac arrhythmia or arrest).[34,95] A large, multicenter trial of sufficient size to address HBOT's efficacy for CO poisoning is needed.

THERMAL AIRWAY INJURY

Pathophysiology

The term *pulmonary burn* is a misnomer. True thermal damage to the lower respiratory tract and lung parenchyma is extremely rare unless live steam or exploding gases are inhaled. Air temperature near the ceiling of a burning room may reach 540° C (1004° F) or more, but air has such poor heat-carrying capacity that most heat is dissipated in the nasopharynx and upper airway. Heat dissipation in the upper airway, however, may cause significant local thermal injury.

Clinical Presentation

Patients who have been in explosions (e.g., propane, natural gas, gasoline) and have burns of the hands, face, and upper torso are particularly at risk for pharyngeal edema (Figure 15-26).

Therapy

Maintenance of the airway is the main concern if thermal airway injury possibly occurred. Patients injured in explosions should be examined for oropharyngeal erythema and edema. Seek evidence of voice change, stridor, or singed nasal hairs. If these are present, early, empirical endotracheal intubation is prudent. Patient should be intubated for 24 to 72 hours until edema subsides. A simple test to determine if extubation should occur is to deflate the cuff to see if the patient can breathe around the endotracheal tube (ETT). If so, airway edema has probably resolved, and extubation should be safe. If doubt exists, extubation should be performed over a fiberoptic bronchoscope or nasogastric tube, which allows easy replacement of an ETT if necessary. Because there is no pulmonary parenchymal injury, the purpose of endotracheal intubation is to protect the airway and not necessarily to assist with ventilation. Ventilator settings should be adjusted accordingly and vigorous pulmonary toilet should be instituted to prevent the pulmonary problems (atelectasis and pneumonia) frequently seen in intubated patients.

SMOKE POISONING

Pathophysiology

More than 280 toxic products have been identified in wood smoke. Modern petrochemical and building industries have produced a multitude of plastic materials in homes and automobiles that when burned, produce almost all these and many other toxins not yet characterized.[46,72,93,109] Prominent byproducts of incomplete combustion are oxides of sulfur, nitrogen, and many aldehydes. One such aldehyde, acrolein, causes severe

FIGURE 15-26 Deep full-thickness flame burns to the face and neck with emergent cricothyroidotomy secondary to the inability to perform oropharyngeal intubation. *(Courtesy Michael J. Mosier, MD.)*

pulmonary irritation and edema in concentrations as low as 10 ppm. Although chemical mechanisms of injury may be different with different toxic products, overall end-organ response is reasonably well defined.* There is immediate loss of bronchial-epithelial cilia and decreased alveolar surfactant. Microatelectasis, and sometimes macroatelectasis, results in and is then compounded by mucosal edema in small airways. Wheezing and air hunger are common symptoms. After a few hours, tracheal and bronchial epithelia begin to slough, and hemorrhagic tracheobronchitis develops. In severe cases, interstitial edema becomes prominent, resulting in a typical picture of adult respiratory distress syndrome (ARDS). Pulmonary alveolar macrophages are poisoned, causing severe impairment of chemotaxis, which undoubtedly contributes to high incidence of late pneumonia seen in patients with associated cutaneous burns. Activated neutrophils release superoxides and free radicals of oxygen. This, together with other inflammatory mediators, aggravates alveolocapillary damage and leads to increased interstitial edema and impaired oxygenation.

Clinical Presentation

Any patient who has been indoors or in an enclosed space with a smoky fire and has a flame burn should be assumed to have smoke poisoning until proved otherwise. Acrid smell of smoke on the patient's clothes should raise suspicion. Rescuers are often the most important historians and should be carefully questioned.

Perform early, careful inspection of the mouth and pharynx. Hoarseness and expiratory wheezes are signs of potentially serious airway edema or smoke poisoning. Copious mucus production and carbonaceous sputum are sure signs, but their absence should not raise false hopes that injury is absent. COHb levels should be obtained. Elevated COHb or any clinical symptoms of CO poisoning are presumptive evidence of associated smoke poisoning. In very smoky fires, COHb levels of 40% to 50% may be reached after only 2 to 3 minutes of exposure.[100]

Arterial blood gases (ABGs) are drawn from patients with suspected smoke poisoning. One of the earliest indicators of smoke poisoning is an improper ratio of arterial partial pressure of oxygen (PaO_2) to fraction of inspired oxygen (FIO_2). This P/F ratio is typically 400 to 500. Patients with impending pulmonary problems have a ratio of less than 300 (e.g., PaO_2 <120 mm Hg with FIO_2 of 0.40). A ratio less than 250 is an indication for vigorous pulmonary therapy, not for merely increasing inspired oxygen concentrations.

A number of authorities suggest routine use of fiberoptic bronchoscopy for airway assessment[11,57,82,88] (Figure 15-27). It is inexpensive, quickly performed by an experienced clinician, and useful for accurately assessing edema of the upper airway. Aside from establishing evidence of tracheal erythema, it may not materially influence treatment for smoke poisoning.

We have conducted a multivariate analysis of a constellation of history, signs, and symptoms with bronchoscopic findings in 100 consecutive patients admitted with suspected smoke inhalation. If the patient had the combination of history of exposure to closed-space fire, carbonaceous sputum, and COHb level greater than 10%, there was a 96% correlation with positive bronchoscopy. Presence of two of the above features dropped correlation to 70%, and if only one was present, to 36%. As discussed previously, upper airway edema was best correlated with an explosion (i.e., flash burn) that involved the face and upper torso. Almost 50% of such patients had significant upper airway edema and underwent prophylactic airway intubation.

Therapy

All patients burned in an enclosed space or having any suggestion of neurologic symptoms should be given 100% oxygen while awaiting measurement of COHb levels. This should be administered through a tight-fitting mask in the field. If the patient demonstrates labored breathing, or if a prolonged transport time is anticipated, endotracheal intubation should be performed. Oxygen at 100% can then be administered by ventilator.

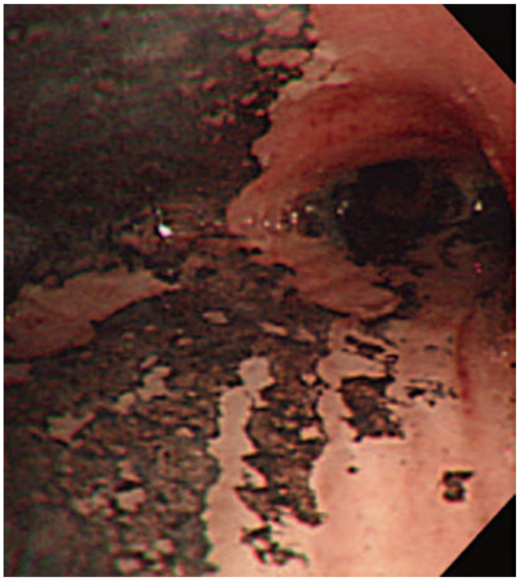

FIGURE 15-27 View of the proximal airway on bronchoscopy, demonstrating moderate erythema and carbonaceous debris, consistent with a grade 2 inhalation injury by bronchoscopic criteria. *(From Kim CH, Wool H, Hyun IG, et al. Pulmonary function assessment in the early phase of patients with smoke inhalation injury from fire. J Thorac Dis 2014;6(6):617-624.)*

Mucosal burns of mouth, nasopharynx, and larynx respond with edema formation and may lead to upper airway obstruction at any time during the first 24 hours after the burn. Red or dry mucosa or small mucosal blisters should alert the observer to the possibility of subsequent airway obstruction. These signs also should raise suspicion that significant smoke inhalation may have occurred. Carefully inspect the mouth and pharynx of any patient with facial burns. If abnormalities are found, the larynx should be examined immediately on arrival at the hospital. Presence of significant intraoral and pharyngeal burns is a clear indication for emergency endotracheal intubation. Progressive edema may make later intubation extremely hazardous, if not impossible. Mucosal burns are rarely full thickness and can be successfully managed with good oral hygiene.

Pulmonary functions early in the course of smoke poisoning may be variably affected. Typical findings include decreased lung volume (i.e., functional residual capacity) and vital capacity, evidence of obstructive disease with reduction in flow rates, increased dead space, and rapid decrease in compliance. Much of the variability in pulmonary response appears to correlate with severity of the associated cutaneous burn.[12] Without associated burns, mortality from smoke poisoning is low, disease rarely progresses to ARDS, and symptomatic treatment usually leads to complete resolution of symptoms in a few days. In the presence of burns of any size, smoke poisoning appears approximately to double the mortality rate. Pulmonary symptoms (e.g., hypoxia, rales, rhonchi, wheezes) are seldom present on admission but may appear 12 to 48 hours after exposure. In general, earlier onset of symptoms is associated with more severe disease.[98]

No standard treatment has evolved to ensure survival after smoke poisoning. Each recommended treatment modality is tempered by the opinion and individual experience of the treating physician. In the presence of increasing laryngeal edema, nasotracheal or orotracheal intubation is indicated. A tracheostomy is never an emergency procedure and certainly should be avoided as initial airway management in patients with burns to the face and neck. A cuffed ETT should be left in place for 3 to 5 days until generalized oropharyngeal edema subsides.

Mild cases of smoke poisoning are treated with highly humidified air, vigorous pulmonary toilet, and bronchodilators as

*References 10, 17, 39, 42, 55, 56, 83, 91, 106, 109.

needed. ABGs are drawn at least every 4 hours, and the P/F ratio is calculated. Worsening symptoms, difficulty in handling secretions, and falling P/F ratio are indications for intubation and respiratory assistance with a volume ventilator. If oxygenation is impaired (P/F ratio ≤250), positive end-expiratory pressure (PEEP) or continuous positive airway pressure (CPAP) is initiated and increased by increments of 3 to 5 cm H_2O until no further improvement in P/F ratio occurs or there is evidence of decreased cardiac output.

Carefully search for other mechanical causes of poor ventilation (e.g., restricted chest wall motion from full-thickness burns, pneumothorax from high ventilator pressures, or mechanical difficulties with ETT). Prophylactic antibiotics have no role in treatment of chemical pneumonitis. Early use of antibiotics can encourage development of resistant organisms and complicate subsequent burn management and treatment of bacterial pneumonia.

Corticosteroids are often used in patients with severe asthma. Clinicians dealing with smoke poisoning often use them for their spasmolytic and antiinflammatory actions. Several authors have studied use of corticosteroids, but a most convincing study comes from Moylan,[69] who showed in a prospective blinded study of patients with smoke poisoning and associated major burns that rates of mortality and infectious complications were higher in corticosteroid-treated patients. In patients with associated burns, corticosteroids did not alter the hospital course of patients admitted after the MGM Grand and Hilton Hotel fires in Las Vegas in 1981.[84]

To decide whether to admit smoke inhalation patients to the hospital for specialized care, consider severity of symptoms from smoke and presence and magnitude of associated burns. Any patient who shows symptoms of smoke inhalation and has more than trivial burns should be admitted. If the burns are greater than 15% TBSA, the patient should be referred to a special care unit. In the absence of burns, the decision to admit depends on severity of symptoms, presence of preexisting medical problems, and the patient's social circumstances. Otherwise healthy patients with mild symptoms (e.g., only a few expiratory wheezes, minimal sputum production, COHb <10%, normal ABGs) can be observed in the ED and then discharged if they have a place to go and someone to observe them. Patients with preexisting cardiovascular or pulmonary disease should be admitted for observation if they have any symptoms related to the smoke. Patients with moderate symptoms (e.g., generalized wheezing, mild hoarseness, moderate sputum production, COHb levels 5% to 10%, normal ABG levels) may be admitted for close observation and treated as for asthma. Patients with severe symptoms (e.g., air hunger, severe wheezing, copious and usually carbonaceous sputum) require prompt endotracheal intubation and ventilatory support in an ICU setting.

OTHER CONSIDERATIONS

Burns are tetanus-prone wounds. The need for tetanus prophylaxis is determined by the patient's current immunization status. If there is any doubt about the date of most recent vaccination, or time since last vaccination is more than 5 years and significant burns have occurred, update tetanus immunization.

Patients undergoing IV resuscitation should have an indwelling urinary catheter placed for hourly monitoring of urine output. Arterial lines are useful in patients who need frequent ABG determinations or who will need repeated blood sampling for other reasons. Necessary laboratory work during resuscitation phase is relatively minimal. Blood should be drawn for baseline blood chemistries. If major operative procedures, such as fasciotomy or multiple escharotomies, are expected, blood should be sent for type and crossmatching in anticipation of potential need to transfuse several units of whole blood. Determine ABG levels in any patient with a suspected inhalation injury. Arterial pH measurement is useful to help assess overall treatment of shock. If the Baxter formula is used for resuscitation, frequent electrolyte determinations are not necessary, because levels will remain in the normal range. By 48 hours, however, careful monitoring of serum sodium and potassium levels becomes important. High levels of circulating aldosterone result in an increase in renal potassium excretion. Evaporative water loss through eschar dramatically increases free-water requirements of burned patients. Hemoglobin and hematocrit levels are initially high and tend to remain high to normal until the third or fourth postburn day. Blood glucose level is typically elevated because of glycogenolytic effect of elevated catecholamines, gluconeogenetic effect of elevated glucocorticoid and glucagon levels, and relative insulin resistance.[44,90,102,110] This well-described "stress diabetes" can become a problem in normal patients if glucose-containing solutions are given during resuscitation. It is frequently a serious problem in patients with preexisting diabetes. All diabetic patients require careful monitoring of blood and urine glucose levels, and most require supplemental insulin during resuscitation.

All medications during the shock phase of burn care should be given intravenously. Subcutaneous and intramuscular injections are unreliably systemically absorbed, so their use should be avoided. Pain control is best managed with small IV doses of morphine or another suitable narcotic analgesic until pain control is adequate without affecting blood pressure.

Before the modern antibiotic era, 30% of burn patients died during the first week after their injury from overwhelming β-hemolytic streptococcal sepsis. Availability of penicillin decreased streptococcal infections but had no influence on mortality or incidence of bacterial sepsis. Patients survived the first postburn week only to die of gram-negative penicillin-resistant bacterial sepsis during the second or third week. The advent of effective topical chemotherapeutic agents applied directly to burn wounds made possible control of streptococcal infection, obviating the need for prophylactic penicillin. Use of prophylactic antibiotics in outpatient burns has not been carefully evaluated, but is unlikely to improve outcomes in patients without evidence of infection.

Stress ulceration of the stomach and duodenum was once a dreaded complication, occurring in approximately 30% of patients with burns. Protection of gastric mucosa with immediate feeding by nasogastric tube and decreasing gastric acidity (e.g., histamine-2 [H_2]) receptor antagonists, proton pump inhibitors) or coating the gastric mucosa (e.g., sucralfate) have made stress ulcers rare.[50,65,78,81,96]

Psychosocial care should begin immediately. Patient and family must be comforted, and a realistic outlook regarding prognosis of burns should be given, at least to the patient's family. In house fires, the patient's loved ones, pets, and possessions may have been destroyed. If family is not available, a member of the burn team (e.g., social worker), should find out the extent of damage in hopes of comforting the patient. If the patient is a child and circumstances suggest that the burn may have been deliberately inflicted or resulted from negligence, physicians in most states are required by law to report their suspicion of child abuse to local authorities.

BURN SEVERITY AND CATEGORIZATION

Severity of injury is proportionate to size of total burn, depth of burn, age of patient, and associated medical problems or injuries. Burns have been classified by the American Burn Association and American College of Surgeons Committee on Trauma into categories of minor, moderate, and severe.[5] *Moderate burns* are defined as partial-thickness burns of 15% to 25% TBSA in adults (10% to 20% in children), full-thickness burns of less than 10% TBSA, and burns that do not involve eyes, ears, face, hands, feet, or genitals/perineum. Because of the significant cosmetic and functional risk, all but very superficial burns of face, hands, feet, and genitals/ perineum should be treated by a physician with special interest in burn care in a facility that is accustomed to dealing with such problems (Box 15-2). Major burns (previously described), most full-thickness burns in infants and older adults, and burns combined with diseases or injuries should also be treated in a burn center. Moderate burns can be treated in a community hospital by a knowledgeable physician provided other members of the health care team have resources and

BOX 15-2 Burn Center Referral Criteria

A burn center may treat adults, children, or both.
Burn injuries that should be referred to a burn center include the following:

1. Partial-thickness burns of greater than 10% of the total body surface area
2. Burns that involve the face, hands, feet, genitalia, perineum, or major joints
3. Third-degree burns in any age group
4. Electrical burns, including lightning injury
5. Chemical burns
6. Inhalation injury
7. Burn injury in patients with preexisting medical disorders that could complicate management, prolong recovery, or affect mortality
8. Any patients with burns and concomitant trauma (such as fractures) in which the burn injury poses the greatest risk of morbidity or mortality. In such cases, if the trauma poses the greater immediate risk, the patient's condition may be stabilized initially in a trauma center before transfer to a burn center. Physician judgment will be necessary in such situations and should be in concert with the regional medical control plan and triage protocols.
9. Burned children in hospitals without qualified personnel or equipment for the care of children
10. Burn injury in patients who will require special social, emotional, or rehabilitative intervention

Excerpted from Guidelines for the Operation of Burn Centers (pp 79-86), Resources for Optimal Care of the Injured Patient 2006, Committee on Trauma, American College of Surgeons.

knowledge to ensure a good result. Adoption of early excision and grafting or creative use of local tissue rearrangement to achieve early wound closure have made burn care more complex. An increasing number of patients with small but significant burns are being referred to specialized burn care centers to take advantage of these concepts.

Criteria for admission to the hospital of patients with minor and moderate burns vary according to physician preference, the patient's social circumstances, and ability to provide close follow-up. In some circumstances, superficial burns as large as 15% TBSA can be successfully managed on an outpatient basis. In other circumstances, burns as small as 1% may require admission because of patient's inability or unwillingness to care for the wound. In general, threshold for admission of older adults and infants should be low. Any patient (child or adult) whom the physician suspects has been abused must be admitted.

TRANSPORT AND TRANSFER PROTOCOLS

Once an airway is established and resuscitation is underway, burn patients are eminently suitable for transport.[9,22,47] Resuscitation can continue en route, because patients tend to remain stable for several days. To facilitate a safe transport, stable vascular access should be ensured. If venous access is difficult or lost en route, intraosseous access is generally adequate for several hours of resuscitation (Figure 15-28). This was well proved during the Vietnam War, when burn patients were transported from Vietnam to Japan and then from Japan to the military burn center in San Antonio, Texas. The transport was generally accomplished during the first 2 weeks after the burn. Few complications occurred. More recent U.S. Army combat support hospital experience in Iraq reports that complex, definitive care was successfully provided to burned patients in austere environments.[99,58] Evacuations when more advanced care was indicated were successful.[15]

Hospitals without specialized burn care facilities should decide where they will refer patients and work out transfer agreements and treatment protocols with the chosen burn center well in advance of need. If this is done, definitive care can begin at the initial hospital and continue without interruption during transport and at the burn center. Mode of transport depends on vehicle availability, local terrain, weather, and distances involved. For distances of less than 80 km (50 miles), a ground ambulance is typically satisfactory. For distances between 80 and 241 km (50 and 150 miles), helicopter transport may be preferred. Monitoring, airway management, and changes in therapy are more difficult to achieve in a helicopter. All patients transported by air should have a nasogastric tube inserted and be placed on dependent drainage, because nausea and vomiting usually result during the flight. Two large-bore IV lines should be established in case one stops working. For distances greater than 241 km (150 miles), fixed-wing aircraft are usually satisfactory. Air ambulances may function as well-equipped, flying ICUs, and personnel are typically trained for both critical care and peculiarities of advanced burn care during a flight (see Chapter 58).

The referring physicians must ensure that patient's condition is suitable for a long transport and prepare the patient for flight. Secure the patient's airway. At 9144 m (30,000 feet), planes can be pressurized to an altitude of about 1676 m (5500 feet). Although supplemental oxygen can be administered during flight, if the patient's oxygenation is marginal, performing endotracheal intubation and initiating mechanical ventilation before transport is preferred. In-flight endotracheal intubation is difficult. If there is any question of upper airway edema, intubate the patient before transport from the referring hospital. Wrap patients to keep them warm because burned patients have difficulty maintaining body temperature. Bulky dressings, blankets, and a Mylar sheet (usually available from the flight team) can help maintain body temperature. If the patient has any cardiac irregularities, advanced cardiac monitoring must be available. In-flight noise and vibrations make clinical monitoring difficult.

Only after all other assessments are complete should attention be directed to the burn. If the patient is to be transferred from the initial hospital to a definitive care center during the first postburn day, personnel at the referring hospital can leave the burn wounds alone. They should calculate burn size for resuscitation purposes and monitor pulses distal to circumferential full-thickness burns. Wrap the patient in a clean sheet and keep him warm until arrival at the definitive care center.

INTERNATIONAL RESOURCES

Outside the United States, advanced burn care can be found at many large academic medical centers. Box 15-3 lists American Burn Association/American College of Surgeons–verified burn centers outside the United States. Dedicated burn centers are still uncommon in the developing world. Most are in large cities and therefore inaccessible to the majority of the indigenous population. Many smaller hospitals lack basic medical supplies and the

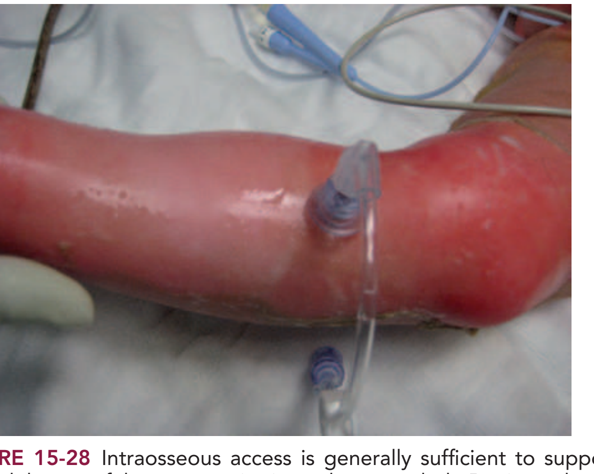

FIGURE 15-28 Intraosseous access is generally sufficient to support several hours of burn resuscitation when needed. Devices should be placed in unburned areas if possible. If placed through burned skin, they should be removed as soon as is practical. *(Courtesy Rob Sheridan, MD.)*

BOX 15-3 Burn Centers Outside the United States Verified by American Burn Association and American College of Surgeons*

Australia
Royal Adelaide Hospital Adult Burn Center, Adelaide

Canada
University of Alberta, Toronto
Firefighters Burn Treatment Unit
The Hospital for Sick Children
Pediatric Burn Center
Sunnybrook Health Sciences Centre
Ross Tilley Burn Centre
Adult Burn Center

*These burn centers have resources required for provision of optimal care to burn patients from the time of injury through rehabilitation.

clinical training needed to treat burns successfully.[49] In patients with severe burn injury, if circumstances allow, medical evacuation to a developed country or large, local city burn center will likely yield the best results. An example of a burn center in a developing country is the Nepal Cleft and Burn Center in Kathmandu, Nepal, a 501(c)3 Non-Profit Charitable Organization organized to deliver quality, deformity-correcting reconstructive surgery to the poorest patients of Nepal through a permanent, sustainable health care infrastructure.

REFERENCES

Complete references used in this text are available online at expertconsult.inkling.com.

CHAPTER 16

Exposure to Radiation from the Sun

ANDREW C. KRAKOWSKI AND ALINA GOLDENBERG

Adverse effects of sunlight overexposure are well documented.[84,139] Public attention is increasingly focused on the adverse effects of sun exposure, but sun-protective strategies are still debated. These issues are of particular concern to wilderness enthusiasts. Salutary effects of sun protection against acute phototrauma (e.g., sunburn) are more easily judged than are sequelae of chronic phototrauma (e.g., cataracts, photoaging, photocarcinogenesis). These chronic effects are increasingly relevant given the state of demographically aging populations. Economic concerns are staggering; billions of dollars are spent annually in the cosmetic and medical industries to prevent and repair photodamage, photoaging, and skin cancer. With improvements in sunscreens and photoprotective clothing, limiting skin damage while remaining active outdoors is increasingly simpler.

SOLAR RADIATION

ELECTROMAGNETIC SPECTRUM

The sun produces a continuous spectrum of electromagnetic radiation (Figure 16-1). The most energetic rays are those with wavelengths that are shorter than 10 nm: cosmic rays, gamma rays, and x-rays. These do not penetrate the atmosphere to reach Earth's surface. Phototrauma is primarily the result of ultraviolet radiation (UVR). UVR (10 to 400 nm) accounts for approximately 10% of the incident radiation at Earth's surface; visible light (400 to 760 nm) approximately 50%; and infrared (IR; 760 to 1700 nm) approximately 40%.[84] Longer-wavelength visible light and IR may also cause cutaneous phototrauma. Solar urticaria has been reported to occur with exposure to visible wavelengths. IR may produce epidermal and dermal alterations.[145]

Ultraviolet radiation has four components. Vacuum UVR (10 to 200 nm) is readily absorbed by air and does not penetrate Earth's atmosphere. Ultraviolet C (UVC; 200 to 290 nm) is almost entirely absorbed in the stratosphere 15 to 50 km (9.3 to 31.1 miles) above Earth's surface by oxygen and ozone. Man-made sources of UVC (e.g., germicidal lamps, arc-welding devices) are rarely medically relevant.

Ultraviolet B (UVB; 290 to 320 nm) is biologically active and principally responsible for tanning, burning, and nonmelanoma skin cancer formation.[139] Beneficial effects of UVB include vitamin D production from a cutaneous precursor, 7-dehydrocholesterol, to form previtamin D_3, which is quickly converted to vitamin D_3 (cholecalciferol). Cholecalciferol is first hydroxylated in the liver into 25-hydroxyvitamin D_3, then in the kidneys into the active metabolite 1,25-dihydroxyvitamin D_3, which stimulates calcium absorption from the gut.[122] Approximately 90% of 25-hydroxyvitamin D_3 is formed in this manner.[234]

At Earth's surface, approximately 10% of UVR is UVB and 90% is ultraviolet A (UVA; 320 to 400 nm). This ratio can vary with season and time of day. UVA is divided into "near UVA," or UVA II (320 to 340 nm), and "far UVA," or UVA I (340 to 400 nm). These categories are based on photobiologic responses. UVA contributes to tanning, burning, photoaging, and carcinogenesis. It is the principal trigger for photo-drug reactions. UVA penetrates skin more deeply than does UVB, with less energy lost in the stratum corneum and epidermis.

ENVIRONMENTAL INFLUENCES ON ULTRAVIOLET RADIATION EXPOSURE

Exposure to UVR varies substantially by latitude, altitude, season, time of day, solar zenith angle, albedo (reflectivity), clouds, atmospheric pollution, ozone levels, and individual factors (e.g., occupation and personal behaviors). Most UVR reaches Earth around midday when the sun is at its zenith: 80% between 9 AM and 3 PM and 65% between 10 AM and 2 PM.[84] UVB peaks at midday.[176] UVB is absorbed, reflected, and scattered by the atmosphere. During early morning and late afternoon, when the sun nears the horizon, UVB decreases considerably. Latitude and season have similar effect; peak UVB exposure is approximately 100 times greater in June than in December.[176] For each degree of latitude away from the equator, UVB intensity decreases an average of 3%. UVA varies considerably less than does UVB with latitude, time of day, and season, as predicted by Rayleigh's law:

$$\text{Atmospheric light scattering} \propto 1/\lambda$$

where λ is the wavelength. A shorter wavelength results in greater atmospheric scattering. UVB is scattered much more readily than is UVA. UVA (but not UVB) is transmitted through

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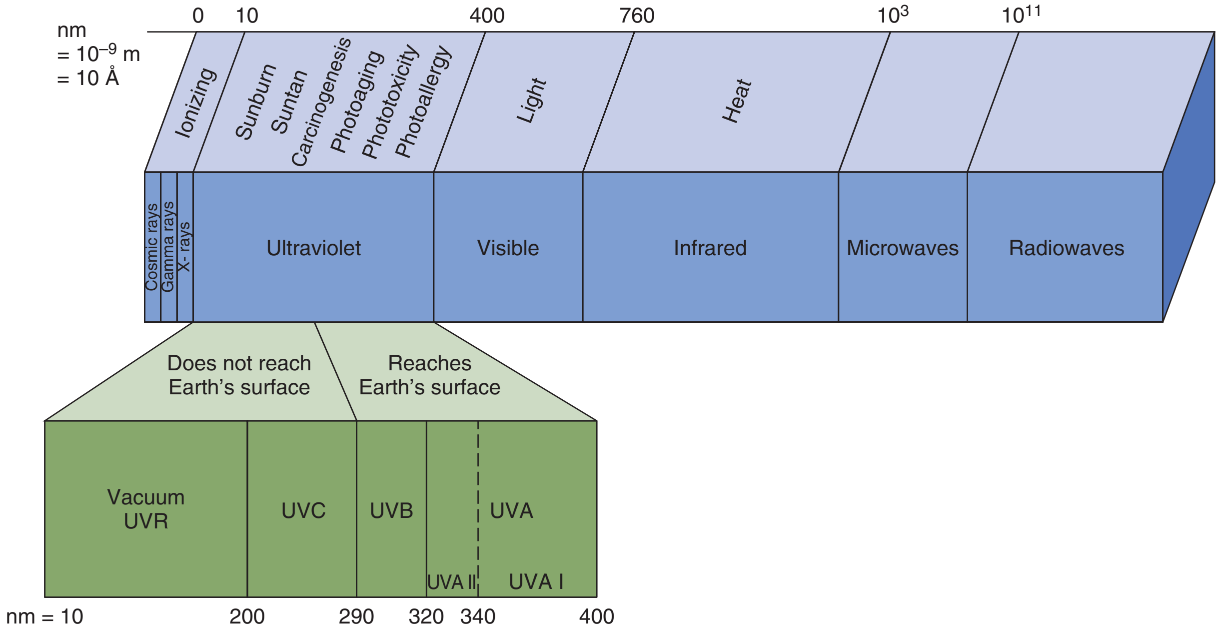

FIGURE 16-1 The electromagnetic spectrum.

window glass. Reflection increases UVR exposure. Water is a relatively poor reflector. UVR at midday penetrates water up to 60 cm (23.6 inches). Submerged skin is not well protected.[176] Ice and snow are considerably better reflectors. Clean snow may reflect up to 85% of UVR.[176] Grass, sand, metal, concrete, salt flats, and other surfaces reflect UVR to varying degrees. A 2010 study demonstrated the importance of surface reflection; while a canvas beach umbrella blocked direct UV radiation at the umbrella's base, 34% of UV was present because of reflection.[289]

Clouds absorb 10% to 80% of UVR, but typically less than 40%.[139] Polluted clouds containing the greatest concentration of hydrocarbons are the most effective at absorbing UVR. Clouds more effectively absorb heat (i.e., IR), making excessive midday UVR exposures a risk.

Wind augments sunburn. In mice, exposure to wind plus UVR results in more erythema than does exposure to UVR alone.[223] In humans, wind reduces heat perception and encourages longer exposure. Altitude profoundly influences UVB exposure. Until recently, UVB exposure was thought to rise 4% for each 305-m (1000-foot) rise above sea level. However, recent research demonstrated an 8% to 10% increase in UVB for each 305-m (1000-foot) rise above sea level.[240] This study found that UVB exposure readings in Vail, Colorado (latitude 39 degrees North) at 2591 m (8500 feet) approximated readings at Orlando, Florida (latitude 28 degrees North, elevation 18 m [60 feet]), 772 miles nearer the equator.

OZONE DEPLETION AND ULTRAVIOLET RADIATION EXPOSURE

Stratospheric ozone, which lies 15 to 50 km (9.3 to 31.1 miles) above Earth's surface, provides a thin and fragile shield against UVR. Ozone attenuates UVB and modestly reduces UVA II, but allows transmission of all UVA I.[313] Natural physicochemical processes continuously create and remove ozone from the stratosphere. Man-made pollution accelerates ozone degradation. Molina and Rowland[206] first suggested that chlorofluorocarbons (CFCs) could cause ozone depletion. Developed during the 1970s as refrigerants, CFCs contain carbon, chlorine, and fluorine. CFCs have been used in air-conditioning systems, insulation, cleaning solvents, degreasing agents, and metered-dose inhalers. *Halons*, related compounds containing bromine, also deplete stratospheric ozone. Halons arise from seawater, fire extinguishers, and various industrial processes.[117] CFCs and halons are *halocarbons*. CFCs may reside in the stratosphere for 50 to 200 years. CFCs rise into the stratosphere. Catalyzed by solar radiation, they release chlorine ions (Cl^-) and chlorine monoxide (ClO^-), which degrade ozone[117]:

$$Cl^- + O_3 \rightarrow ClO^- + O_2$$

$$O_3 + UVR \rightarrow O + O_2$$

$$ClO^- + O \rightarrow Cl^- + O_2$$

Net reaction:

$$2O_3 + UVR \rightarrow 3O_2$$

Note that Cl^- is preserved in this reaction. The half-life of Cl^- is approximately 75 years.[302] Each Cl^- ion may destroy 100,000 molecules of ozone.[302] Above Antarctica, molecular halogens coat the surface of ice clouds, making them even more reactive and able to degrade ozone.[117]

Ozone losses were first reported in 1985[74] by the British Antarctic survey. Ozone above Antarctica showed large declines in the austral springtime (September/October), and decreased 35% during the springs from 1975 to 1984.[117] Ozone depletion is now documented at all latitudes except the equator. This depletion is uneven, with more loss at the poles and less at the middle latitudes.[302] Waxing and waning occurs with the seasons. Documented ozone depletion exists over continental Europe, North and South America, South Africa, New Zealand, and Australia.[160]

Significant increases in UVB caused by ozone depletion have been documented, even near the middle latitudes. In Toronto from 1989 to 1993, Kerr and McElroy[144] documented surface UVB increases of 35% per year in winter and 7% per year in summer, corresponding with ozone decreases of 4% per year and 1.8% per year, respectively. In Scotland, similar increases in ground-level UVB caused by decreased stratospheric ozone have been documented.[208] In the northern hemisphere's middle latitudes, ozone losses are greater during winter (~6% per decade) than summer (~3% per decade).[117] Pollution (e.g., smog, particulates) may mitigate UVR increases by absorbing UVB.[302]

Ozone depletion affects the biosphere and human skin cancer rates. Data suggest that every 1% decrease in ozone causes an increased incidence of skin cancer: 1% for melanoma, 2% for basal cell carcinoma, and 3% for squamous cell cancer.[59,302] Given the paucity of direct sunlight, even if UVB triples near the poles, as suggested in worst-case scenarios, polar areas will still receive less UVB than current equatorial levels.[302] Ozone depletion may have its greatest effects on nonhuman biosystems. Plant and plankton yields may be diminished significantly, with severe detriment to terrestrial and marine life.[313]

To prevent ecologic disturbances and restore ozone levels, international agreements have been negotiated. The Vienna Convention (1985) was among the first. The Montreal Protocol (1987), ratified by all 196 countries,[291] agreed to limit and then reduce CFC production, leading to a 50% reduction by 1998.[117] The London Amendment (1990) required complete phaseout of halocarbon production. The Copenhagen Amendment (1992) accelerated the timetable for complete phaseout of CFC production, including hydrochlorofluorocarbons, by 1996 in developed countries and 2002 in undeveloped nations. Further amendments were made in Vienna (1995), Montreal (1997, 2007), and Beijing (1999).[257] The 2007 Adjustment to the Protocol calls for phaseout of hydrofluorocarbons (HFCs) by 2030. Although HFCs do not directly contribute to ozone depletion, they are considered active gases that contribute to climate change and are regulated by the Kyoto Protocol.[159]

Total atmospheric chlorine peaked in 1990 and has since declined, although only two-thirds as fast as expected.[257] This is thought to result from CFCs being released from existing, unregulated sources such as air conditioners, insulating foams, and increased production in East Asian developing countries. Because of the high cost of CFC substitutes,[40] a "black market" of illegal importation of CFCs into the United States from Mexico has emerged.[83]

Between 1988 and 2010, total ozone-depleting emissions from human activities have decreased by more than 80%. It is projected that global ozone will continue to increase and will return to pre-1980 levels by 2050.[257] Total UVB levels are expected to decrease below 1960 values by the year 2100.

ACUTE EFFECTS OF ULTRAVIOLET RADIATION ON SKIN: SUNBURN AND TANNING

The effect of UVR on skin depends primarily on wavelength, an individual's age and genetic factors, and the exposure's duration, intensity, frequency, and anatomic location. To have a biologic effect, UVR must be absorbed by molecules in the skin known as *chromophores*. Different UVR wavelengths are absorbed by different chromophores, including nucleic acids (especially pyrimidine bases), amino acids in cutaneous proteins, and lipoproteins in cell membranes. Chromophores exist at various skin depths, resulting in differing photobiologic responses to UVR. There is imprecise knowledge of how a given photochemical reaction results in a specific biochemical product and leads to an observable clinical change.

ULTRAVIOLET C RADIATION

UVC is effectively screened from Earth's surface by stratospheric ozone and oxygen. It has no known appreciable impact on human health. Even with continued ozone depletion, levels of UVC are not expected to rise. Man-made sources of UVC (e.g., germicidal lamps, arc-welding devices) are rarely associated with cutaneous pathology, because UVC is effectively absorbed by the outermost cutaneous layer, the stratum corneum.[84]

ULTRAVIOLET B RADIATION

UVB acutely induces a cutaneous inflammatory response.[127] Clinically, erythema (i.e., sunburn) is the hallmark of acute overexposure to UVB. UVB is considered to be 1000-fold more effective than UVA for induction of erythema. In a human model, 300-nm UVB is 1280-fold more effective at inducing erythema than is 360-nm UVA.[316]

Erythemogenic doses are defined as multiples of the *minimal erythema dose* (MED). MED is the lowest dose that elicits perceptible erythema. In a typical fair-skinned individual, the MED might range from 15 to 70 millijoules (mJ)/cm^2 for UVB and from 20 to 80 joules (J)/cm^2 for UVA. For a typical fair-skinned individual in San Diego, 1 MED of UVB would require 20 minutes of midsummer exposure; 1 MED of UVA would require 2 to 3 hours of exposure. A person can receive 15 MEDs of UVB in a day, but only 2 to 4 MEDs of UVA.[196] Although people are exposed to 10 to 100 times more UVA than UVB, more than 90% of sunlight-induced erythema can be attributed to UVB. The erythema action spectrum is remarkably similar to the absorption spectrum of DNA[213] and peaks in the UVB range. This suggests that DNA is a principal target chromophore for UVB-induced erythema[315] and pyrimidine dimer formation.[106]

ULTRAVIOLET A RADIATION

UVA penetrates the skin more deeply than does UVB; 95% of incident UVB is reflected or absorbed by the epidermis, whereas approximately 50% of UVA reaches the dermis.[73] UVA contributes modestly to sunburn and clinical erythema. Prolonged daily UVA exposure can approach 125 J/cm^2, which significantly exceeds the threshold erythema dose of 20 to 80 J/cm^2.[273] UVA-induced erythema has onset within 4 to 6 hours, peaks after 8 to 12 hours, and fades after 24 to 48 hours.[127,139] UVA-induced erythema may have a distinct pathophysiologic mechanism caused by keratinocyte cytotoxicity.[127] Histologically, UVA-induced erythema displays more epidermal spongiosis, fewer sunburn cells, and more dermal changes than does UVB-induced erythema, which displays a denser, deeper mononuclear cell infiltrate and more vascular damage.[127]

INFRARED RADIATION

Infrared radiation plays a less well-defined role in photodamage. Near-IR preirradiation prevents UVR-induced cytotoxicity[196] and suggests a possible evolutionary protective mechanism for IR by preparing skin cells to resist UVR-induced damage. No data indicate whether IR protects against UVR's mutagenic and carcinogenic effects.

PHOTOTRAUMA

NATURAL DEFENSES AND SKIN TYPE

Exposure to UVR causes insidious, cumulative biologic and clinical changes. UVA and UVB have distinct effects on the epidermis, dermis, extracellular matrix, cytokines, and immune response.[304] In response to UVB, the stratum corneum thickens[99] and melanin increases, mitigating further UVB photodamage. The stratum corneum (outermost layer of skin) is composed of flattened anucleate keratinocytes. Depending on its thickness, it reflects, scatters, or absorbs up to 95% of incident UVB.[112] In response to UVB, the stratum corneum can increase its thickness up to sixfold[84] and serves as the main photoprotective factor in white persons.[99] Repeated UVA exposures cause thickening to a much lesser degree.[174] UVA tans are less photoprotective than UVB tans.

Melanin reflects, scatters, and absorbs throughout the UVR spectrum. It acts as an antioxidant and reduces UVR-induced photoproducts.[148] Consequently, constitutive (racial) skin color is a principal determinant of an individual's erythema response to UVR. Although blacks and whites have similar numbers of melanocytes, these cells are differently melanized and distributed. Increased melanin in blacks can decrease dermal penetration of UVR up to fivefold[53] and increase the MED up to 30-fold. Tanning is much less protective. After an entire summer of tanning, the MED in whites increased only 2.3-fold.[53] These racial differences in melanization are reflected in lower rates of burning, photoaging, and skin cancer in blacks.

Susceptibility to photodamage is typically defined by six distinct skin types (Box 16-1). Racial pigmentation alone does not account for differences in skin type; some redheads tan easily, and some blacks burn readily. Skin type correlates well with MED. Age and anatomic site influence MED, with lower MEDs recorded in very young and very old persons.[139] Differences in stratum corneum thickness and melanocyte concentration may account for body site–specific differences in MED (e.g., the MED of the back is typically less than the MED of the lower leg).

BOX 16-1 Skin Types

I. Always burns; never tans
II. Often burns; tans minimally
III. Sometimes burns; tans moderately
IV. Burns minimally; tans well
V. Rarely burns; tans deeply; moderately pigmented (brown)
VI. Never burns; deeply pigmented (black)

Chronic suberythemal UVA exposures also cause photodamage. Repetitive low-dose exposures to UVA result in histologic changes[174]: thickening of the stratum corneum, granular and stratified cell layers; decreased elastin, vascular dilation, and inflammation.

Intrinsic mechanisms of photoprotection include antioxidants (e.g., glutathione peroxidase-reductase system mitigates damage from UVR-induced reactive oxygen species), DNA repair enzymes (correct most UVR-induced mutations), and carotenoids (stabilize biologic membranes from singlet oxygen attack).

SUNBURN

Sunburn reflects a local vascular reaction. The causes are multifactorial; DNA damage, prostaglandin activation, cytotoxicity, and other mechanisms are implicated. Onset of UVB erythema occurs 2 to 6 hours after exposure, peaks at 12 to 36 hours, and fades after 72 to 120 hours.[84,127,139] Acute histologic changes accompanying UVB exposure include edema with vasodilation of the upper dermal vasculature[127] and endothelial cell swelling, most likely caused by release of vasoactive mediators.[102] Delayed histologic changes include appearance of sunburn cells within 30 minutes after exposure. These dyskeratotic cells have enlarged nuclei and vacuolated cytoplasm. Initially, sunburn cells localize in the epidermis's lower half; after 24 hours, they are also found in the upper half. Sunburn cells may represent proliferating basal cells that cannot adequately repair UVR-induced DNA lysosomal damage.[55] Stainable Langerhans cells (i.e., cutaneous antigen-presenting cells) decrease rapidly: at 1 hour by 25% and at 72 hours by 90%.[127] In mice exposed to repetitive suberythemogenic doses of UVB, normal numbers of Langerhans cells return by 8 days. Vacuolization of melanocytes is seen after 1 hour and returns to normal 4 to 24 hours after exposure. Mast cells decrease in number and granularity within 1 hour, returning to normal after 12 to 72 hours.[127] By 24 to 48 hours after exposure, there are increases in melanin synthesis, epidermal proliferation, and thickening of stratum corneum.

Biochemical changes that accompany sunburn include increased levels of histamine,[127] which return to normal within 74 hours. Histamine is unlikely to be the principal mediator of vasodilation and erythema, because antihistamines are ineffective at preventing sunburn. UVR increases phospholipase activity, with accompanying increases in prostaglandins (PGs). PGD_2, PGE_2, PGF, and 12-hydroxyeicosatetraenoic acid are increased in blister aspirates immediately after UVB exposure, and peak after 18 to 24 hours.[127] Topical and intradermal indomethacin (a prostaglandin inhibitor) blocks UVB-induced erythema for 24 hours after exposure,[268] supporting the thesis that eicosanoids (PGs and leukotrienes) are significant mediators of UVR-induced inflammation.[151]

SUNBURN TREATMENT

Sunburn is self-limited. Treatment is largely symptomatic and involves local skin care, pain control, and antiinflammatory agents (Box 16-2). Studies of sunburn therapies include agents used immediately after UV exposure (i.e., before symptoms have manifested) and agents for treatment of acute sunburn reactions.[110]

Cool-water soaks or compresses may provide immediate relief from sunburn. Topical anesthetics are sometimes useful; use nonsensitizing anesthetics (e.g., menthol, camphor, pramoxine, lidocaine) rather than potentially sensitizing anesthetics (e.g., benzocaine, diphenhydramine). Refrigerating topical anesthetics before application provides added relief. Topical remedies include aloe, baking soda, and oatmeal, but controlled studies are lacking. Topical corticosteroids, with their vasoconstrictive effects, are often considered "first-line" treatment for acute sunburn; however, their efficacy remains controversial. A trial comparing erythema reactions in skin treated with either topical moderate-potency corticosteroid (hydrocortisone-17-butyrate) or high-potency corticosteroid (clobetasol propionate) 30 minutes before or 6 or 23 hours after exposure to UVB, found decreased erythema only in areas pretreated with high-potency corticosteroid 30 minutes before UVB exposure.[76] When applied after exposure, diclofenac gel, a topical nonsteroidal antiinflammatory drug (NSAID), alleviates pain, erythema, and edema for up to 48 hours.[145] Oral NSAIDs provide analgesia and may reduce sunburn erythema.[84] Combined use of topical corticosteroids and oral NSAIDs slightly decreases erythema during the first 24 hours if administered before sunburn becomes clinically apparent.[235] A recent metastudy found no therapy to be consistently effective, and no consensus could be made regarding treatment of sunburn.[110]

TANNING

As with sunburn, tanning is caused by UVR. Persons who seek a tan risk sunburn. Tanning is biphasic. There is immediate pigment darkening within minutes (caused by UVA), followed by *delayed* pigment darkening (DPD) in 3 days (primarily a response to UVB). *Immediate* pigment darkening results from action of UVA on preformed melanin precursors and occurs as soon as 5 minutes after exposure, peaks in 60 to 90 minutes, and then fades quickly. DPD represents new melanin synthesis within melanocytes and subsequent spread of richly melanized melanosomes into surrounding keratinocytes. DPD is notable by 72 hours after UVB exposure, peaks after 5 to 10 days, then slowly fades. Most tanning studies have been performed with erythemal doses of UVR. Multiple suberythemal UVA exposures are significantly more melanogenic than is similarly dosed UVB.[17] The mechanism of DPD is multifactorial. UVB stimulates tyrosinase release and arachidonic acid metabolites, and releases α-melanocyte-stimulating hormone from keratinocytes.[8] UVB increases binding affinity of melanocytes for melanocyte-stimulating hormone, resulting in increased melanocyte proliferation, melanization, and arborization.[24] UVB increases melanocytes in both exposed and protected skin,[276] suggesting a UVR-stimulated circulating factor that promotes melanocyte proliferation.

PHOTOAGING

Repetitive long-term exposures to sunlight result in photoaging.[80] The process termed *dermatoheliosis* is clinically and histologically

BOX 16-2 Sunburn Treatments

Pain Control
Acetylsalicylic acid
Nonsteroidal antiinflammatory drugs

Skin Care
Cool soaks and compresses
Nonmedicated moisturizers
Topical anesthetics
- Pramoxine (Prax) lotion
- Menthol plus camphor (Sarna) anti-itch lotion
- Anti-itch concentrated lotion (pramoxine) plus camphor plus calamine (Aveeno)
- Lidocaine plus camphor (Neutrogena Norwegian Formula) soothing relief moisturizer

Corticosteroids
Topical agents (e.g., triamcinolone 0.1% cream applied twice daily when erythema first appears)
Systemic agents

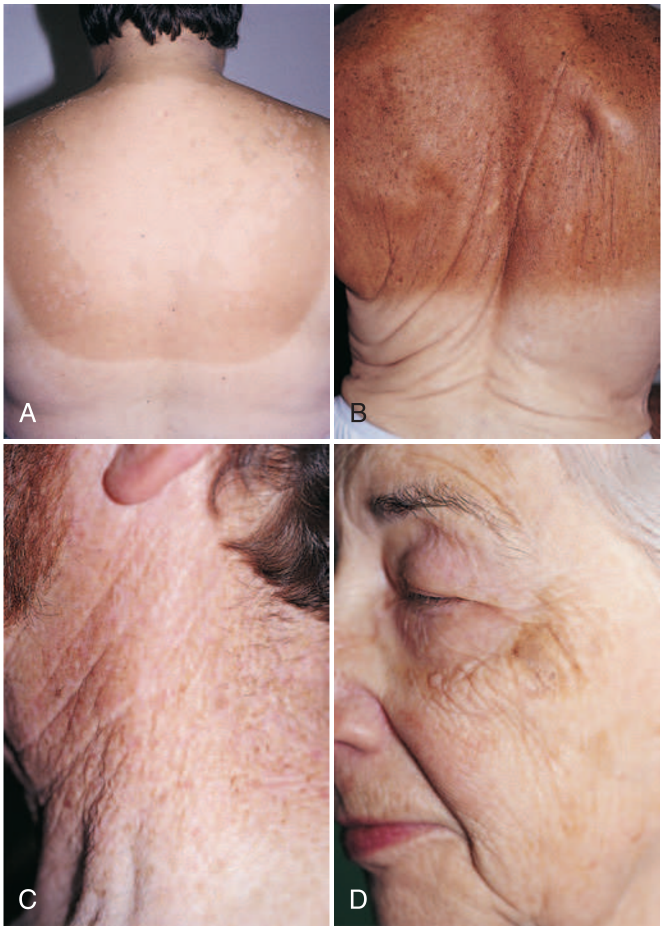

FIGURE 16-2 Phototrauma. **A,** Tan and peeling after sunburn. **B** to **D,** Dry, mottled, wrinkled, and pebbled skin with photoaging.

different from chronologic aging and does not merely represent accelerated chronoaging. Photoaged skin is characterized by dryness, roughness, mottling, wrinkling, atrophy, and pebbling and may be studded with precancers (actinic keratoses) or cancers (Figure 16-2). Photoaging contributes more to "old-looking" skin than does chronoaging. Age can be estimated from observing sun-exposed sites, but not from photoprotected sites.[300] The action spectrum for photoaging includes UVB, UVA, and IR.[174]

Chronically sun-exposed sites have fewer Langerhans cells. In culture, keratinocytes and fibroblasts from sun-damaged skin have diminished life span.[95] Chronic UVB exposure leads to deposition of thickened, amorphous elastic fibers high in the dermis, demonstrable in photoexposed white skin by age 30. In a transgenic mouse model, UVB produces this solar elastosis; UVA does not.[283] Another mouse model suggests the action spectrum for "photosagging" peaks in UVA at 340 nm,[111] and this action spectrum is remarkably similar to generation of singlet oxygen by excitation of transurocanic acid. Antioxidants may reduce free radicals. Ascorbic acid (vitamin C) stimulates collagen production in culture[229] and reduces wrinkling in UVB-treated hairless mice.[21] Vitamin E reduces wrinkling in mice and humans exposed to UVR.[21]

Tropoelastin and fibrillin synthesis diminish with chronic UVB exposure.[303] Transcription of other extracellular matrix genes is enhanced. Photoaged skin demonstrates increased matrix metalloproteinases (MMPs), which are potent mediators of connective tissue damage.[80] MMPs arise within hours of UVB exposure, even after suberythemal exposure.[78] Tretinoin inhibits induction of UVB-induced proteinases,[78,80] perhaps explaining its clinical usefulness against photoaging.[301] Tretinoin normalizes photoaltered epidermal differentiation and deposits new type I collagen in the upper dermis.[105]

There is increased demand for treatments to manage photoaging. Ablative fractional laser resurfacing vaporizes ablated microchannels through the skin, stimulates neocollagenesis within the dermis, and leads to rapid healing with minimal side effects.[129,184] Photoaging treatment pales in comparison to simple prevention. Sun-protective behaviors remain the most effective management approach.

SUN AND SKIN CANCER

MOLECULAR BASIS OF PHOTOCARCINOGENESIS

Photobiology

Nonmelanoma skin cancer (NMSC) refers to cutaneous basal cell carcinoma (BCCa) and squamous cell carcinoma (SCCa). Several photomolecular events are associated with NMSC. UVR causes characteristic changes of adjacent pyrimidines on DNA.[32,316] The 5-5 double bonds absorb UVR photons, creating 6-4 (pyrimidine-pyrimidone) photoproducts (if a single bond opens) and cyclobutane dimers (if both bonds open).[32] Cyclobutane dimers predominate 3 : 1, with thymine (T-T) dimers being the most common.[151] Even suberythemal doses of UVR can induce T-T dimers.[315] High-performance liquid chromatography can quantitatively measure these UVB photoproducts[38] and reveal 30-fold interindividual variations.[38]

Resultant UVR-induced mutations have a distinctive signature, which is that two-thirds of the mutations display cytosine → thymine (C → T) substitutions at dipyrimidine sites, and 10% show CC → TT substitutions.[32] These mutations are unique and allow UVR-induced mutations to be distinguished from chemical mutations.[32]

Data suggest that cyclobutane dimers and 6-4 photoproducts are primarily responsible for the mutagenic[162] and carcinogenic[151] properties of UVR. Many genes, including those involved in tumor suppression and promotion, may be targets for UVR mutations. Tumor suppressor genes (TSGs) that play a role in photocarcinogenesis include *p53, p16,* and protein patched homolog 1 gene *(PTCH)*.[31,123] A mutation of *p53,* the most common genetic alteration identified in human cancers, is found in approximately 50% of BCCa, 60% of actinic keratoses, and 90% of SCCa.[32,123,151,317] Although *p53* mutations may be found in non–sun-damaged skin at a low frequency, mutations are much more common in sun-exposed sites.[32]

The p53 protein is a transcription factor that regulates the cell cycle. DNA damage stimulates p53 protein production. This leads to cell cycle arrest in G_1 (a premitotic phase), allowing time for DNA repair.[32] Irreparable damage leads to apoptosis. Sunburn cells are examples of apoptotic cells.[317] Cells with mutated *p53* are more resistant to apoptosis with subsequent UVR exposures.

Within the *p53* gene, there are "hot spots" where mutations frequently occur.[32,40] Most *p53* mutations result in a single amino acid substitution, typically cytosine to thymine (C → T).[317] Normal wild-type p53 has a short half-life and is generally unstable and unstainable. Mutated *p53* is more stable and so stainable by immunohistochemical techniques.[40,240] Both UVA and UVB upregulate p53 expression in human skin.[43] After a single UVR exposure to the forearms, p53 protein expression peaks in 24 hours and returns to baseline after 360 hours.[107]

Mutations in *p53* occur as an early initiating event in photocarcinogenesis.[151] Unique *p53* mutations are present in actinic keratosis.[317] Different actinic keratoses display different *p53* mutations, supporting the role of *p53* mutations as initial causative events, followed by clonal expansion of mutated cells to form clinically visible lesions (e.g., precancerous actinic keratosis).[317] Altered *p53* provides a survival advantage to mutated cells. In response to chronic UVR, neighboring nonmutated cells become apoptotic and die, allowing space for further expansion of the mutated clone and ultimately resulting in development of actinic keratosis or SCCa.[32]

The *p53* mutations alone may be insufficient to produce NMSC. Patients with Li-Fraumeni syndrome inherit a mutated form of the *p53* gene and have increased incidence of sarcomas, adenocarcinomas, and melanomas, but not NMSC.[151] Other factors (e.g., decreased DNA repair, UVR-induced immunosuppression) likely play a permissive role. Patients with xeroderma pigmentosum (XP) have increased numbers of *p53* mutations,[32] defective gene repair mechanisms, and greatly increased NMSC incidence. Cutaneous lymphomas show a higher frequency of UVR signature *p53* mutations.[193] In mycosis fungoides, mutations are found in the tumor stage but not the plaque stage,[193] suggesting that UVR promotes clinical progression of this lymphoma. Epidemiologic data demonstrate increased incidence of non-Hodgkin's lymphoma among persons who live closer to the equator.[1]

Other TSGs are less well studied but have increasingly defined roles in photocarcinogenesis. In melanoma, *p16* is frequently inactivated[130] and increasingly downregulated as melanoma progresses.[271] Another TSG, *PTCH,* which is also located on chromosome 9, is frequently mutated in both familial and sporadic BCCa. Mutations of *PTCH* are especially notable in patients with XP and multiple BCCa[130]

In addition to downregulating TSGs, UVR can activate proto-oncogenes (e.g., *bcl*-2, c-*fos,* and *ras)* to form functional oncogenes.[130] In response to UVR, *bcl*-2 protein is overexpressed, suppressing apoptosis and permitting expansion of malignant clones. UVR alters c-*fos,* disrupting transcription of nuclear proteins involved in cell proliferation. UVB causes mutations in *ras,* disrupting mitogenic signaling pathways. Mutations in *BRAF,* a critical component of the *ras* protein kinase pathway, are found in a large percentage of nevi[158] and melanomas,[227] especially melanomas that arise on intermittently sun-exposed skin.[182] *BRAF* mutations occur only rarely in melanomas arising in chronically sun-exposed or completely sun-protected skin,[182] suggesting multiple genetic pathways for melanoma induction. Mutations of *BRAF* and *p53* may interact to form melanoma.[227]

UVR-related oxidative damage is another mechanism contributing to photocarcinogenesis. Although UVA causes fewer direct mutations than does UVB, it is a more potent cause of cellular oxidative damage, producing reactive molecular oxygen and nitrogen species. Oxidative damage to DNA, proteins, and lipids contributes to carcinogenesis through inflammation, immunosuppression, and ultimately mutation.[109] The MMPs, a group of zinc-dependent enzymes, increase in response to UVR to favor tumor invasion and spread.[34,130]

Photoimmunology

Ultraviolet radiation produces local and systemic immunosuppression.[216] UVB depletes immunocompetent antigen-processing cells (Langerhans cells) for up to 2 weeks after exposure.[204] UVB alters Langerhans cells by interfering with their ability to present antigens to T cells.[101] UVB diminishes type 1 helper T cell responses (which promote contact hypersensitivity) while preserving type 2 helper T cell responses (which suppress contact hypersensitivity), converting Langerhans cells from immunogenic to tolerogenic. As a consequence, UVR exposure diminishes contact hypersensitivity and mixed-lymphocyte reactions. This may explain why UVR-induced skin cancers, which are antigenic, progress to clinical lesions. UVR-induced immunosuppression can be transferred in mice with irradiated T lymphocytes.[216]

Immunoregulatory failure contributes to formation of skin cancer.[156] In immunosuppressed patients, skin cancer is often more aggressive and occurs at an earlier age.[71] In kidney transplant patients in Australia, 45% develop skin cancer within 11 years and 70% within 20 years.[28] For heart transplant patients in Australia, the incidence of skin cancer is 31% at 5 years and 43% at 10 years. In immunosuppressed patients, the ratio of SCCa to BCCa is 4 : 1, the opposite of the ratio in immunocompetent patients.[72] Of note, although kidney transplant patients are taking higher doses of immunosuppressive drugs than are heart transplant patients, skin cancer rates appear higher in heart transplant patients. Chronic sun exposure and fair complexion further increase risk of skin cancer in transplant patients, possibly as a result of overexpression of p53.[93]

NONMELANOMA SKIN CANCER

Americans[240] have a 20% lifetime risk of developing NMSC. The incidence continues to rise.[98] Factors that play a role include a "sun-worshiping" lifestyle (sunbathing, tanning), poor preventive behaviors (e.g., insufficient use of sunscreen, hats, and covering bathing suits), aging population, and depletion of the ozone layer.

Exposure to UVR causes the majority of precancerous actinic keratoses and true skin cancers (Figure 16-3). Laboratory data confirm UVR induces and promotes NMSC in mammalian animal models.[139] Ninety percent of all NMSC are attributed to sunlight exposure alone.[251] NMSC has a much greater incidence in whites than in blacks and occurs primarily on sun-exposed areas. Risk for NMSC increases with increasing sun exposure. Repeated sunburn is an independent risk factor.[155] Patients with XP have impaired ability to repair UVR-induced DNA damage and 1000-fold greater risk of developing NMSC, typically at a very early age.[151]

Development of NMSC in humans is related to time and intensity of UVR exposure. British immigrants to Australia assume the much higher Australian risk of NMSC only if they emigrate before age 18 years; after that time, immigrants retain the lower British risk.[187] Another study suggests NMSC risk decreases for UVR exposure after age 10 years.[154]

Basal Cell Carcinoma

Basal cell carcinoma is associated with sun exposure up to the age of 19 years but is not associated with mean annual cumulative summer sun exposure.[87] Risk for BCCa is associated with fair complexion and freckling. Intermittent (rather than continuous) sun exposure in poor tanners may be the most important factor in development of BCCa.[155]

Basal cell carcinoma includes a heterogeneous group of low-grade malignant cutaneous tumors characterized by markers associated with hair follicle development. BCCa is the most common cancer in the United States and is most often found on the head and neck (Figure 16-4). In contrast with SCCa, BCCa is relatively uncommon on the dorsal surface of the hand, where solar radiation exposure is high. While locally aggressive, BCCa is rarely metastatic. Several clinical morphologies of BCCa exist; diagnosis depends on the astute clinician. *Nodular* BCCa, the most common form, manifests as one or a few small, pearly papules with a central depression. Telangiectasias may be seen. Lesions are usually friable and frequently bleed when rubbed vigorously with a cotton-tipped swab. *Pigmented* BCCa is similar to nodular BCCa but appears brown or black because of pigmentation. *Cystic* BCCa manifests as bluish gray, dome-shaped cystic papules or nodules similar in appearance to hidrocystomas. *Morpheaform* BCCa manifests as a white sclerotic plaque, usually without the characteristic findings of a pearly border, leading to this morphologic lesion often being overlooked or misdiagnosed as a benign scar. *Superficial* BCCa, the most common pattern in patients with human immunodeficiency virus (HIV), favors the trunk and distal extremities. It typically manifests as superficial, dry, scaly lesions that may resemble patches of slow-growing eczema or psoriasis; close examination typically reveals the characteristic raised border. "Rodent ulcer" is a neglected BCCa that has ulcerated; consequently, the "rolled" border of the lesion may not be present or recognizable (Figure 16-5).

Squamous Cell Carcinoma

Both UVC and UVB are effective inducers of SCCa in mice.[127] SCC may begin as an actinic keratosis, appearing clinically as an irregularly bordered, pink, rough papule or plaque. Actinic keratoses may be successfully treated with cryotherapy, topical imiquimod, topical 5-fluorouracil (5-FU), and surgical removal. True SCCa, the second most common form of skin cancer, may manifest clinically as dull-red, superficial, indurated, well-demarcated papules and plaques arising on sun-exposed areas (i.e., the face and dorsal surfaces of the hands). Lower-lip lesions may develop with actinic cheilitis; a history of repeated sunburns and tobacco use are predisposing factors. As the lesions grow over the course of months, they become deeply nodular and ulcerated (Figure 16-6). The ulcer may be hidden by an overlying crust that, when removed, reveals a discrete, indurated, and elevated base. Careful examination of regional lymph nodes is warranted in suspected cases. Rate of metastasis ranges from

FIGURE 16-3 **A,** Actinic keratoses: thin, vague, and scaly papules. **B,** Basal cell carcinoma: smooth, pearly papule. **C,** Squamous cell carcinoma: keratotic red and tan papule. **D,** Melanoma: note the asymmetry, border irregularity, color variegation, and diameter of more than 6 mm (0.24 inch).

0.5% to about 5%; risk factors for metastasis include location on the temple, scalp, ear, or lip; recurrence after prior treatment; size and depth of the primary lesion; aggressive histologic findings; and host immunosuppression.

The relationship of photoexposure and SCCa is different than that between photoexposure and BCCa. SCCa and cumulative lifetime photoexposure do not appear to be associated, but SCCa risk increases with chronic occupational exposure, especially during the 10 years before diagnosis.[87] SCCa risk factors include periodic recreational exposure, pale complexion, and red hair. In select mouse models, suberythemal UVR has caused SCCa, and gradual suberythemal exposures may be more carcinogenic than erythemal doses.[86,213] This may explain why persons with no prior sunburns may develop SCCa. In SCCa exposed to in vitro UVR, a gene segment *(KNSTRN)* was the target of point mutations in 19% of reviewed SCCs. The presence of such a mutation may predispose to aggressive tumor behavior; mutated *KNSTRN* drives cells toward aneuploidy and tumor development. UV-activated mutations and their lasting tumorigenesis effects may be prevented with UV blockers, such as sunscreen.[163]

FIGURE 16-4 Pink, pearly papule with a rolled border and overlying telangiectasias located on the right pectoral area of a 55-year-old surfer from San Diego; biopsy revealed a basal cell carcinoma.

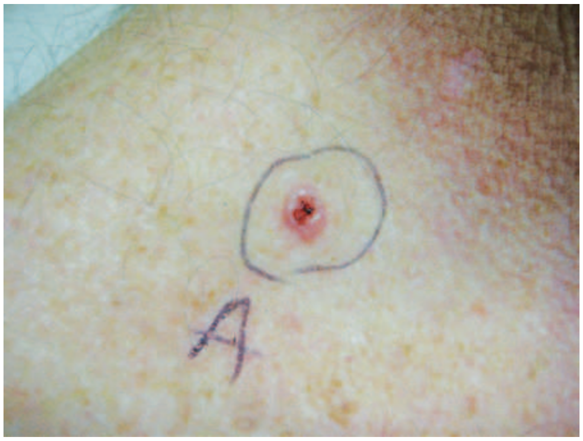

FIGURE 16-5 Basal cell carcinoma demonstrating characteristic "rolled" borders and central ulceration.

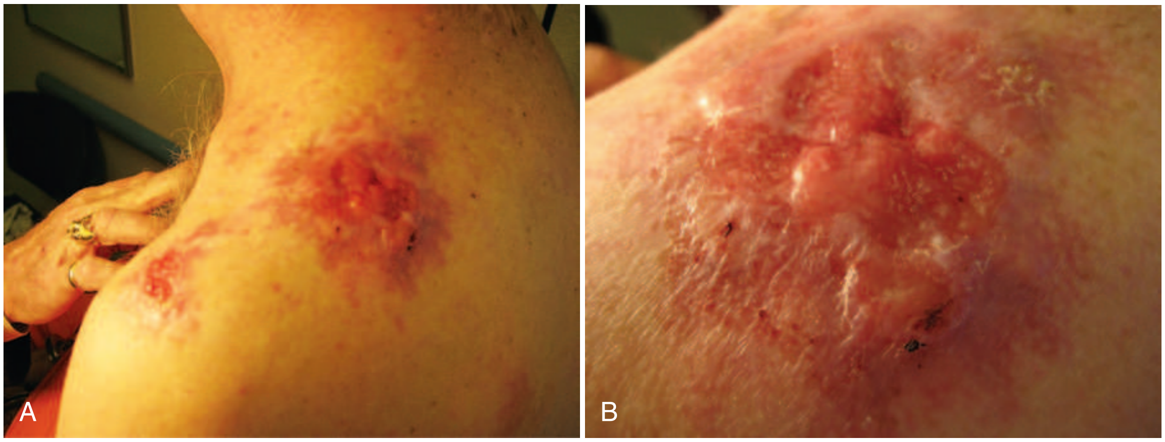

FIGURE 16-6 Squamous cell carcinoma. **A,** Neglected squamous cell carcinoma on lateral and posterior shoulder. **B,** Closer image of the same carcinoma.

MELANOMA

Melanoma is a skin cancer derived from melanocytes, cells found within the basement membrane of epidermis. It results from environmental and genetic factors. In the United States, incidence of melanoma has increased since records were first kept in the 1930s, rising 121% in the 20 years between 1973 and 1994.[108] Between 2002 and 2011, incidence of melanoma has been rising on average 1.8% each year.[4] Melanoma is the most common cancer for persons 25 to 29 years old and the second most common for those 15 to 29 years old.[23] Approximately 76,100 Americans were diagnosed with new cases of invasive cutaneous melanoma in 2014.[4] Large increases in melanoma incidence have been noted in Europe, Australia, and even Japan.[142] Melanoma mortality rates show signs of stabilizing, possibly as a result of improved sun-protective behaviors. Survival with melanoma increased to 92% in 2003, from 49% in the 1950s.[238] The total estimated cost of treating melanoma was $2.36 billion in 2010.[280]

Melanoma includes different clinicopathologic types. *Nodular* melanomas are typically smooth, dome-shaped, and friable lesions occurring most frequently on sun-exposed areas of the head, neck, and trunk. They are twice as common in men as in women. *Lentigo maligna* manifests as a tan macule on sun-damaged skin that may darken and spread so slowly that patients are often unaware of changes (Figure 16-7). It typically occurs among older patients who live in sunny climates. *Superficial spreading* melanoma has no preference for sun-damaged skin and affects adults of all ages. Color variegation (i.e., dark brown, black, red, white, blue) is common (Figure 16-8). Lesions may arise de novo or in association with preexisting nevus. A new papule or nodule may develop as the vertical growth phase develops. *Acral lentiginous* melanoma, the most common type of melanoma in dark-skinned and Asian populations, may begin as a light brown, uniformly pigmented macule that gradually darkens, thickens, and ulcerates. Subungual or plantar lesions are often present, and Hutchinson's sign (i.e., black discoloration of the proximal nailfold at the end of a hyperpigmented linear streak) portends melanoma in the matrix of the nail. *Amelanotic* melanoma is difficult to discern clinically. It lacks pigment and mimics pyogenic granuloma or BCCa.

Ultraviolet radiation contributes significantly to melanoma and is believed to be the only modifiable risk factor.[7,103] The UV action spectrum for melanoma remains uncertain. The 1000-fold increased incidence of melanoma in humans with XP strongly supports UVB as a causative agent.[152] UVB induces melanocytic hyperplasia, atypia, and melanoma in newborn human foreskin xenografts on RAG-1 (immunodeficient) mice.[8]

Melanoma incidence increases with proximity to the equator in white populations[142] in the United States, Australia, Scandinavia, and the nonwhite population of India.[157] Intermittent intense exposures pose a particularly high risk for melanoma.[69] A 2005 meta-analysis of 57 studies associates increased risk of melanoma with a history of intermittent sun exposure and sunburn.[89] There is only a small increased risk for total sun exposure, and a decreased risk with heavy occupational exposure.[70,89] Patients with melanoma are twice as likely to relate a history of prior sunburn than are age-matched controls, and are three times as

FIGURE 16-7 Melanoma on the posterior helix, which made early self-detection difficult.

FIGURE 16-8 "Yin-yang"–shaped melanoma on back demonstrating asymmetry, color variegation, and a diameter of more than 6 mm (0.24 inch). The location made early self-detection difficult.

likely to relate a history of multiple prior sunburns.[70] Persons who tan poorly and burn readily are at higher risk for melanoma.[178] Distribution of melanomas on the trunk (in both genders) and the lower legs (in women) is consistent with the hypothesis that intermittent sun exposure is provocative. Melanomas also arise in sun-protected sites, especially in nonwhite populations, suggesting an additional cause.

Occupational UVR exposure likely plays a role in melanoma incidence. Servicemen who served in the Pacific theater during World War II have a higher risk of melanoma than do those who served in Europe.[36] A meta-analysis of 19 studies and 266,431 participants found airline pilots and cabin crew had an almost twofold higher incidence of melanoma than the general population (standardized incidence ratio [SIR] for pilots 1.83 and cabin crew 2.09).[248] Pilots and air crew had a 42% higher mortality rate compared with the general population. Although cosmic radiation exposure for air crews was not found to be above the allowed limit, the total amount of UVR exposure has not been quantified and may be a factor in their rising melanoma rates. Glass windshield materials allow 54% of UVA radiation to pass through, and for every 900 m (2970 feet) of altitude increase, the level of UVR increases by 15%. Cumulative UVR exposure for pilots and cabin crew may be staggeringly high.[210] Pilots have higher rates of cataracts than the general population[214] The Federal Aviation Association has not issued any special regulations for sun protection for pilots and crew.

Sunburns in childhood may be particularly relevant to the later development of melanoma. Celtic migrants to Australia who arrived before age 10 years assume the high melanoma risk of native Australians; migrants more than 15 years old on arrival have only one-fourth that risk.[246] Europeans who live more than 1 year in a sunny climate have an increased relative risk (2.7) of melanoma. Risk increases substantially (4.3 times) if they arrive before age 10.[11] One study suggests childhood sun exposure contributes a serious risk only if there is subsequent and significant sun exposure as an adult.[9]

Association of increased melanoma risk with sun exposure during youth may be attributable to the effect of sun on the development of melanocytic nevi (moles) in children. The most important risk factors for melanoma are number of nevi and the number of atypical nevi.[90] Numbers of benign acquired nevi increase with increasing acute and chronic sun exposure.[33,90,113,294] In Australia, the number of nevi (up to 12 years old) increases with increasing proximity to the equator.[143] Sun-related increased nevus counts are demonstrable at early ages. In Queensland preschoolers less than 36 months old, increased nevus counts are associated with more time spent outdoors and a history of sunburn.[113] Established nevi may develop histologic changes transiently, simulating melanoma after a single UVR exposure.[281] Data suggest sunburn can induce malignant transformation in benign nevi.[44]

Efforts have been made to educate and protect populations at risk; improved photoprotection and early detection have been widely promoted. In Australia, sunscreen sales are tax free, hats are typically required for children when they are playing outdoor sports, and public parks increasingly feature artificial shade. The Skin Cancer Foundation encourages monthly self-examinations, with special attention to pigmented lesions that display atypical clinical features: the *ABCDEs of melanoma*[232]: *a*symmetry; *b*order irregularity; *c*olor variegation; *d*iameter of more than 6 mm (0.24 inch); and *e*volving features (Figure 16-9). Nevi with these clinical features, symptomatic nevi, or nevi that bleed or ulcerate should be evaluated by a dermatologist. Notably, conventional ABCDEs may fail to detect a majority of pediatric melanomas, especially in prepubertal children. For this reason, any de novo, amelanotic, bleeding, or rapidly enlarging "bump" should be treated as highly suspicious in this uniquely vulnerable population.[52]

PHOTOPROTECTION

SUNSCREENS

Sunscreens are topical temporary protectants against UVR. They are classified into two distinct types based on the chemical nature

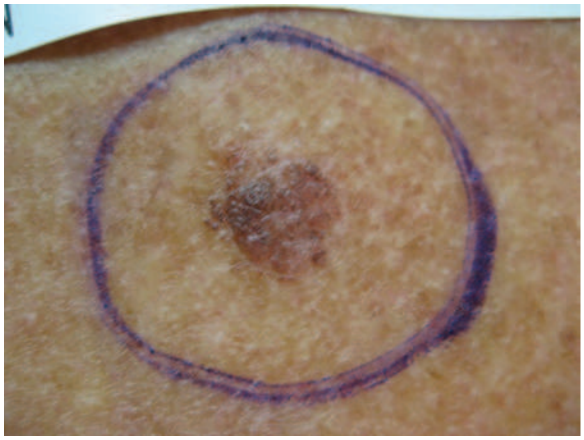

FIGURE 16-9 Melanoma on the back demonstrating the ABCDEs: asymmetry, border irregularity, color variegation, diameter of more than 6 mm (0.24 inch), and evolving features (i.e., the patient's wife had noticed that the area at 9 o'clock was "growing out from the rest of it").

of their components: *organic* (i.e., chemical) and *inorganic* (i.e., physical) UV filters. Both absorb UVR; inorganic filters can also reflect and scatter UVR.[183]

Organic sunscreens were first discovered in 1926. By 1928, the first commercial sunscreen, which contained benzyl salicylate and benzyl cinnamate (organic filters), was marketed in the United States.[82] Subsequent sunscreen evolution focused on UVB protection to mitigate against development of sunburn.

Table 16-1 lists current sunscreening ingredients approved by the U.S. Food and Drug Administration (FDA). Two names are sometimes given for the same agent, because the *U.S. Pharmacopeia* changed the names of several sunscreening agents (effective September 1, 2002) to conform better to international standards.[289]

Paraaminobenzoic acid (PABA) was patented in 1943 and became commercially available in 1960. PABA is an effective UVB

TABLE 16-1 Sunscreening Agents Approved in the United States

Sunscreen	Maximal Screen (%)	Ultraviolet Radiation
Organic		
Aminobenzoic acid	15	UVB
Avobenzone	3	UVA I
Cinoxate	3	UVB
Dioxybenzone	3	UVB, UVA II
Ecamsule*	2	UVB, UVA
Homosalate	15	UVB
Menthyl anthranilate (meradimate)	5	UVA II
Octocrylene	10	UVB, UVA II
Octyl methoxycinnamate (octinoxate)	7.5	UVB
Octyl salicylate (octisalate)	5	UVB
Oxybenzone	6	UVB, UVA II
Padimate O	8	UVB
Phenylbenzimidazole sulfonic acid (ensulizole)	4	UVB
Trolamine salicylate	12	UVB
Inorganic		
Titanium dioxide	25	UVB, UVA
Zinc oxide	25	UVB, UVA

Modified from US Food and Drug Administration: *Sunscreen drug products for over-the-counter human use* [stayed indefinitely]. 21 CFR 352. www.gpo.gov/fdsys/pkg/CFR-2002-title21-vol5/pdf/CFR-2002-title21-vol5-sec352.10.pdf. Revised April 1, 2013. Effective June 4, 2004.
*Approved by the U.S. Food and Drug Administration on July 21, 2006.

absorber but provokes contact and photocontact dermatitis in approximately 4% of exposed persons and can permanently stain fabrics a dull-yellow color. PABA has been largely replaced by PABA esters (e.g., amyl dimethyl PABA [padimate A] and octyl dimethyl PABA [padimate O]). These absorb UVB well and are less staining and less allergenic.

Cinnamates are the next most potent class of UVB absorbers, often replacing PABA in PABA-free sunscreens. Octyl methoxycinnamate (octinoxate; Parsol MCX) is an order of magnitude less potent than padimate O.[167] Octocrylene, which is a cinnamate derivative, is a weak UVB absorber that also absorbs UVA modestly up to 360 nm. Cinnamates may cause contact dermatitis. Cinoxate is the most frequent contact sensitizer, with cross-sensitization to related cinnamates in coca leaves, balsam of Peru, and cinnamon oil.[64]

Salicylates (e.g., homosalate, octyl salicylate [octisalate]) are relatively weak absorbers of UVB. They are most often used in combination with other sunscreening agents. Salicylates are nonsensitizing and water insoluble and help to solubilize benzophenones in commercial products.[84]

Anthranilates (e.g., methyl anthranilate [meradimate]) are similarly weak UVB absorbers, which also filter UVA. They display peak absorption at 340 nm.[167]

Phenylbenzimidazole sulfonic acid (ensulizole) is a unique UVB absorber, in that it is water soluble. It is increasing used in oil-free cosmetic sunscreens.[167]

Benzophenones (e.g., oxybenzone, dioxybenzone, sulisobenzone) are broader-spectrum sunscreening agents, with good absorption in the UVB and UVA ranges up to 360 nm.[167]

As UVA photodamage is increasingly appreciated, UVA-blocking agents (e.g., avobenzone, ecamsule) have been introduced. Avobenzone (Parsol 1789, butyl methoxydibenzoylmethane) is a potent UVA absorber and the only organic filter approved as a long-range UVA protectant.[167] Its absorption peak at 358 nm falls almost to zero at 400 nm.[243] Photodegradation may limit its effectiveness. Under simulated solar light, avobenzone can be degraded 36% within 15 minutes,[250] but a patented complex known as Helioplex, a combination of avobenzone, oxybenzone, and diethyl 2,6-naphthalate, is remarkably photostable.[50] Select stabilizing compounds (e.g., vitamin C, vitamin E, iron chelators) may additionally retard photodegradation.[194]

Ecamsule (Mexoryl SX) is the newest sunscreening agent to be approved by the FDA. It has been available in Europe for several years. It is an excellent UVA filter and modest UVB filter. Ecamsule is highly photostable and thermostable. It protects skin from repeated UVA exposures and prevents histologic changes associated with photoaging.[258]

Inorganic filters, historically known as inorganic sunscreens, are opaque agents that include calamine, ichthammol, iron oxide, kaolin, red veterinary petroleum, starch, talc, titanium dioxide (TiO_2), and zinc oxide (ZnO). Of these, only TiO_2 and ZnO are FDA approved. Inorganic filters protect throughout the UVR and visible spectra and may even protect against IR-induced erythema.[224] Classic inorganic blockers tend to be messy, uncomfortable, and cosmetically undesirable.

Preparations of TiO_2 and ZnO with a submicron (i.e., nano) particle size are now widely available. Classic TiO_2 and ZnO particle size ranges (150 to 300 nm for TiO_2 and 200 to 400 nm for ZnO) permit light to be reflected and scattered. Submicron dimensions (20 to 150 nm for TiO_2 and 40 to 100 nm for ZnO) make these particles more soluble and minimally reflective of visible light. This makes them nearly transparent in thin coats. ZnO's lower refractive index in the visible range makes it more transparent than TiO_2.[203] Submicron-sized preparations significantly absorb UVR, providing broad-spectrum protection from UVB and UVA, and blur the distinction between organic and inorganic sunscreens.[63,167,249] TiO_2 and ZnO are sometimes marketed as "chemical-free" sunscreens, which is clearly a misnomer.

No studies have shown percutaneous penetration of the nanoparticles into human adult skin or any cellular damage.[39,217] The ecologic impact of large amounts of metal oxide nanoparticles in the environment is unknown.[222]

Eight different UV filters (e.g., quinolone derivatives and novel UVA filters) are currently in the FDA application process. Already in use in Australia and Asia, these filters will greatly broaden the U.S. sunscreen market if approved.[37,231,287,298]

Sunscreen Vehicles

Sunscreen vehicles affect efficacy and acceptability. The ideal vehicle spreads easily, maximizes skin adherence, minimizes interaction with active sunscreening agent, and is noncomedogenic, nonstinging, nonstaining, and inexpensive. The best vehicle is highly dependent on personal preference. Creams and lotions (emulsions) are most popular. Lipid-soluble sunscreening agents result in an objectionable greasy feel. "Dry lotions" minimize the lipid component(s) and often include water-soluble sunscreening agents to reduce oiliness.[167] Sunscreen oils contain only a lipid phase and are cosmetically less acceptable.

Gels tend to be nongreasy but wash or sweat off easily. Gels produce more stinging and irritation. Sticks typically incorporate sunscreening agents into wax bases but are difficult to apply to larger areas. Aerosols cover large areas quickly but tend to disperse spray into the air and form an uneven film.[167] Aerosols need to be rubbed in to provide uniform protection.[14] Sunscreens are increasingly being incorporated into cosmetics (e.g., foundations, lipsticks, moisturizers).

Sun Protection Factor

A sunscreen's ability to protect skin from UVR-induced erythema is measured by the sun protection factor (SPF). SPF is defined as the ratio of UVR required to produce minimal erythema (1 MED) in sunscreen-protected versus unprotected skin.[139,284] Multiplying the time required to burn an individual's unprotected skin by the sunscreen's SPF factor provides the time skin would be protected from burning with sunscreen. It can be represented by the following formula:

$$\text{SPF} = \frac{\text{MED of sunscreen-protected skin}}{\text{MED of unprotected skin}}$$

Testing conditions are standardized by the FDA.[284] The agent to be tested is applied at a standard concentration of 2 mg/cm^2. Testing is performed indoors with a solar simulator on the back between the beltline and the scapulae. SPF is typically determined on a panel of 20 (or a maximum of 25) individuals with skin types I, II, or III (see Box 16-1). The mean determines the sunscreen's SPF. Although indoor testing with a solar simulator is more reproducible than outdoor natural sun exposure, it may yield a falsely high SPF value. In outdoor testing of more than 30 sunscreens labeled SPF 15, none was found actually to have an SPF of more than 12.[226] Factors responsible for lower SPF values with outdoor testing include sweating, clothing, toweling off, sand abrasion, and application variability. Solar simulators generally have less UVA output than does sunlight.[250]

Determinations of SPF use erythema as the measurable end point. Erythema is predominantly a result of UVB and not UVA exposure. Consequently, SPF is primarily a measure of UVB protection. Tables 16-2 shows the relationship of SPF to UVB absorption.

How high an SPF is necessary? Given that SPF 15 blocks 93% of UVB, some argue SPF 15 is sufficient,[185] and that higher labeling claims are misleading and costly for consumers. In several studies, higher SPF sunscreens conferred clinical and histologic benefits. In one study, a single application of SPF 25 sunscreen protected just as well as did multiple applications of SPF 15 for up to 6 hours of exposure.[220] Histologically, an SPF 30 sunscreen provides better protection against sunburn cell formation than does an SPF 15 sunscreen.[137]

Sunscreen Application

Sunscreen underapplication, uneven application, and delayed application result in unnecessary photoexposure and photodamage.

TABLE 16-2 Skin Protection Factor and Ultraviolet B Radiation Absorption

Sun Protection Factor	Ultraviolet B Radiation Absorption (%)
2	50.0
4	75.0
8	87.5
15	93.3
30	96.7
50	98.0

The most persuasive argument favoring higher-SPF sunscreens is that there are variations in application technique. Protection provided by sunscreen is related to amount of product applied.[253] Typically, sunscreens are applied at much lower concentrations (0.5 to 1 mg/cm^2) than they are tested (2 mg/cm^2).[252] Resultant SPF is thereby reduced to as low as 20% to 50% of the labeled value SPF for organic sunscreens.[35,277] Inorganic sunscreens tend to be applied even more thinly, most likely because of their cosmetic visibility.[32] For TiO_2 products, application concentrations of 0.65 mg/cm^2 result in SPF values of only 20% to 30% of labeled value.[277] Persons who burn more easily tend to apply thicker concentrations of sunscreen.[61]

Uneven application further reduces sunscreen protection. Individuals typically cover the forehead adequately, but temples, ears, and posterior neck are often undertreated or missed entirely.[172] Sunscreens containing disappearing colorants are popular because they provide visible assurance of complete coverage. Adequate coverage of only chronically exposed areas (face, ears, dorsal surfaces of hands) requires 2 to 3 g (0.07 to 0.11 oz) of product per day.[167] This requires using an 8-oz bottle of sunscreen every 80 to 120 days.

Application delay imposes a further decrease in protectiveness. In one study,[241] sunscreen was applied only after arriving at the beach in 98% of families. Median delay from arrival at the beach to sunscreen application to the entire family was 51 minutes.

Ultraviolet A Radiation Protection Factors

With increased understanding of UVA-induced photodamage and the recent addition of better UVA-blocking agents (e.g., avobenzone, ecamsule, micronized TiO_2 and ZnO), more attention has been focused on measuring UVA protection. Several measures of UVA protectiveness (e.g., the UVA protection factor) have been suggested. None has been widely accepted.[244]

Sunscreen Regulation

In the United States, sunscreens are regulated over-the-counter (OTC) drugs. The FDA's *Final Over-the-Counter Drug Products Monograph on Sunscreens* (1999) established allowable sunscreening agents, testing procedures, and labeling claims for efficacy, water resistance, and safety.[284] In 2011 the FDA updated labeling claims and testing procedures.[285] The final rule establishes labeling and effectiveness testing for OTC sunscreen products marketed without an approved application under Section 505 of the Federal Food, Drug, and Cosmetic Act. It does not address determinations for substances *generally recognized as safe and effective* (GRASE) in sunscreen products. The new rule provides the following services to the public:

- Helps ensure products will be appropriately labeled and tested for both UVA and UVB protection
- Promotes proper use of sunscreens and greater consumer protection from damaging effects of UVR
- Identifies claims that render a product "misbranded" or claims that are not allowed on any OTC sunscreen drug product marketed without an approved application (e.g., "sunblock," "sweatproof," and "waterproof" have been deemed misleading and are no longer permitted)

The final regulations reduce the number of individuals required in SPF testing from 20 to 10 and require only a single in vitro test to demonstrate broad-spectrum protection. Performance is on a pass/fail basis using a critical wavelength of 370 nm. *Critical wavelength* is defined by FDA as the wavelength at which the integral of the spectral absorbance curve for a particular sunscreen product reaches 90% of the integral over the UV spectrum from 290 to 400 nm:

$$\int_{290}^{\lambda_c} A(\lambda)d\lambda = 0.9\int_{290}^{400} A(\lambda)d\lambda$$

where λc = critical wavelength, $A(\lambda)$ = mean absorbance at each wavelength, and $d\lambda$ = wavelength interval between measurements.[289]

Labeling. Products that pass testing (i.e., possess a mean critical wavelength ≥370 nm) will be labeled *broad spectrum* and *SPF 15 (or higher)*, and demonstrate protection against both UVB and UVA radiation. New labeling will also inform consumers that these sunscreens not only protect against sunburn, but also can reduce risk of skin cancer and early skin aging. For these broad-spectrum products, higher SPF values also indicate higher levels of overall protection.

Sunscreen products that are not broad spectrum, or that are broad spectrum with SPF values from 2 to 14, will be labeled with a warning such as, "Unlike broad-spectrum products and those higher SPF values, this product has been shown only to help prevent sunburn, not skin cancer or early skin aging."

The FDA requires labels to include a new "direction statement":

Sun Protection Measures: Spending time in the sun increases your risk of skin cancer and early skin aging. To decrease this risk, regularly use a sunscreen with a Broad Spectrum SPF of 15 or higher and other sun protection measures including:

- Limit time in the sun, especially from 10 a.m.-2 p.m.
- Wear long-sleeved shirts, pants, hats, and sunglasses.

Required warnings on all covered OTC products will also include the following (Figure 16-10):

- "Do not use on damaged or broken skin."
- "When using this product, keep out of eyes. Rinse with water to remove."
- "Stop use and ask a doctor if rash occurs."

Issues Not Finalized. Products containing inorganic sunscreen agents can no longer be marketed as "sunblocks,"[284] but other marketing issues remain. The "Advance Notice of Proposed Rulemaking (ANPR): Sunscreen Drug Products for Over-The-Counter Human Use; Request for Data and Information Regarding Dosage Forms" has approved gels, oils, lotions, creams, butters, pastes, and ointments, but not powders, body washes, shampoos, or wipes, which no longer may be able to be marketed in the United States.[288] Sprays continue to be marketed and are not mentioned in the regulations.

Proposed FDA rules would limit maximum SPF value on sunscreen labels to "50+," because data are insufficient to show that products with SPF values higher than 50 provide greater protection.

Substantivity

Substantivity is the ability of sunscreens to resist being washed off by water. The FDA's 2011 final rule changed testing and labeling requirements to make it easier for consumers to understand water resistance.[285] Data indicate that individuals at the beach or pool spend an average of 21 minutes in the water and go into the water an average of 3.6 times per outing.[285]

Sunscreens newly labeled "water resistant (40 minutes)" or "water resistant (80 minutes)" will have passed testing requirements that include water immersion (with moderate activity) for 20 minutes with 15-minute drying times (no towel drying), repeated once or thrice, respectively.[285]

Substantivity testing is an imperfect science. Numerous factors (e.g., relative humidity, amount applied, immersion time, activity level) must be considered. MED for skin in salt water is less than the MED for skin in fresh water; both are lower than the MED of dry skin.[88] Cold churning water, sand abrasion, and toweling add to sunscreen loss. It is not clear if water-resistant sunscreens are truly surf resistant. The concerns about saltwater substantivity have led to marketing of "surf shop" sunscreens. Few published data indicate whether these products are more substantive.

The PABA and PABA esters are intrinsically substantive as a result of bonding to stratum corneum proteins. Other sunscreens must be incorporated into vehicles that confer substantivity. Substantivity can be increased by applying sunscreen 15 to 30 minutes before water exposure. Reapplication after swimming or sweating increases protection. Affordable UVA- and UVB-protective water-resistant sunscreens are widely available (Table 16-3).

Stability

Photostability is a sunscreen's ability to remain intact and effective after sun exposure. Questions regarding photostability have been raised about avobenzone, octyl dimethyl PABA, and octyl methoxycinnamate. Photodegradation of octyl methoxycinnamate allows histologic and enzymatic injury to the skin.[188] Failure of a photolabile sunscreen may result in genotoxicity.[189] In a study of 27 photoprotective lipsticks, 14 became partially photoinactive after moderate UVR exposure.[181] Twelve were photolabile in the UVA range, one in the UVB range, and one in both UVA and UVB ranges.

Photostability can be improved by using combinations of sunscreening agents. Octocrylene stabilizes avobenzone in a number of sunscreen formulations; 4-methylbenzylidene camphor stabilizes octyl methoxycinnamate.[25] Vehicle formulations also affect stability.[25]

There are few published data regarding packaging, storage, and shelf life of sunscreens. Packaging may affect sunscreen acceptability and stability. Shelf life of at least 1 year is presumed for most commercially available sunscreens. Sunscreens exposed to extremes of temperature for long periods (e.g., glove compartments) may be degraded.

Sunscreen Prevention of Chronic Photodamage

Sunscreens prevent sunburns and mitigate UVR-induced histologic damage, UVR-induced immunosuppression, photoaging, and photocarcinogenesis. Sunscreens reduce UVR-induced DNA damage,[41] decreasing pyrimidine photoproducts in humans[41] and UVR-induced *p53* mutations and skin cancer in mice.[5] Sunscreen nearly eliminates overexpression of p53 in mice after acute[233] and chronic[88] UVR exposure. In humans, an SPF 15 sunscreen reduces p53+ cells by 33% after chronic UVR exposure.[18]

Published effects of sunscreen on immunosuppression are contradictory, largely resulting from the complex relationships of UVR dosing and sensitivity in different experimental models. Overall, sunscreens mitigate UVR-induced immunosuppression. SPF is not a reliable measure of a sunscreen's ability to block UVR-induced immunosuppression; two sunscreens with identical SPF values may vary considerably in their immunoprotectant effects.[16,237,314] A broad-spectrum SPF 15 sunscreen prevents the UVR-induced suppression of contact hypersensitivity to dinitrochlorobenzene, a potent topical allergen, in humans.[259] In susceptible mice injected with melanoma, sunscreens fail to adequately suppress UVB enhancement of melanoma growth.[305] This finding has been used to support a peculiar antisunscreen stance. A

FIGURE 16-10 Sunscreen labeling according to 2011 final rule. *(From US Food and Drug Administration: Sunscreen drug products for over-the-counter human use: Final rule,* Fed Reg *76:35620, 2011.)*

FIGURE 16-10, cont'd

reasonable interpretation is that sunscreens by themselves are not sufficient to prevent all immunosuppressive sequelae of UVR exposure.

Sunscreens reduce sunburn cell formation and solar elastosis[29] in humans. Histologic changes of photoaging in mice are prevented by pretreatment with SPF 15 sunscreen.[146,147] Higher-SPF sunscreens provide increasing protection against UVB-induced wrinkling in mice.[22] Histologic and clinical signs of UVA-induced photoaging are prevented by broad-spectrum sunscreens.[114]

Sunscreens and Nonmelanoma Skin Cancer

Daily sunscreen use is associated with prevention of AKs, SCC, and melanoma.[103,56]

Actinic Keratoses and Squamous Cell Carcinoma. Sunscreen use reduces formation of precancerous actinic keratosis and promotes resolution of preexisting lesions.[48,212] In a 2-year trial of sunscreens, persons who benefited most had the greatest number of keratoses at enrollment,[212] underscoring the value of continuing sunscreen use in adults. A trial in Australia comparing an SPF 16 sunscreen (2% avobenzone and 8% octinoxate) against a sunscreen of the participants choosing, found a 24% reduction in actinic keratosis development and acquisition at 4.5 years and a 38% reduction in SCCa.[104] Liquid-base makeup provides an approximate SPF 4 because of pigments used in the foundation.[167] Women who use lipstick have a lower incidence of SCCa than those who do not use lipstick.[120,167]

Basal Cell Carcinoma. Daily use of SPF 15 sunscreen in adults reduces the incidence of SCCa but not of BCCa.[104] One study estimated that using an SPF 15 sunscreen from birth until age 18 years would reduce the lifetime risk of NMSC by 78%, but did not show a significant decline in BCCa.[275]

Sunscreens and Melanoma

Controversy exists regarding the effects of sunscreen use on melanoma incidence. Previous epidemiologic studies have failed to demonstrate conclusive evidence of decreased melanoma incidence with sunscreen use. Several studies have suggested an increased risk of melanoma with sunscreen use.[12,62] A 1996 meta-analysis evaluated melanoma risk in sunscreen users;[62] one study showed decreased risk,[124] and seven showed increased risk. Subsequent studies have continued to show contradictory results. Confounding these studies are the following:

- Persons at the highest risk for melanoma (i.e., those with fair complexions who burn easily) may be the same persons who use sunscreens.
- Prior sunscreen products were inferior (e.g., lower SPFs and narrower spectra). Modern sunscreens are more substantive, with higher SPFs and substantially broader and better UVA protection.
- Because sun exposure during childhood appears to be the most provocative for melanoma, surveying adults about their current sunscreen habits may be irrelevant and misleading.

A large, community-based 2011 study in Australia provides strong evidence that daily application of sunscreen may directly reduce melanoma risk.[103] During 15 years of follow-up, in persons provided with broad-spectrum (SPF 16) sunscreen for daily use, risk for any first primary melanoma was reduced by 50% (p = 0.051) and for invasive melanoma by 73% (p = 0.045).

TABLE 16-3 Select Sunscreen Products

Product	Sun Protection Factor	Active Ingredients
High Sun Protection Factor Waterproof Broad-Spectrum Creams and Lotions		
Banana Boat Sport 50	30	B, C, OC, S
Banana Boat Sunscreen Sport Family Size Broad Spectrum Sun Care Sunscreen Lotion	50	A, S, B, C
Blue Lizard Australian Sunscreen Lotion	30+	B, C, OC, ZO
Blue Lizard Australian Sunscreen, Sensitive	30+	ZO, TI
Coppertone Sport Sunscreen	30	B, C, S
Coppertone Water Babies Sunscreen Lotion	45	B, C, S
Dermatone Sunscreen Lotion	36	C, PBSA, ZO
EltaMD UV Clear	46	ZO, C
EltaMD UV Physical	41	ZO, TI
Hawaiian Tropic Sunscreen Silk Hydration	30	A, B, C
Kiss My Face Sensitive Side	30	ZO, C
Neutrogena Ultra Sheer Dry-Touch Sunscreen	55	A, B, OC, S
Neutrogena Age Shield Face Lotion Sunscreen	110	A, C, S, B
Ocean Potion Broad Spectrum, Anti-Aging Lotion	50	A, B, C, S
Ombrelle Complete Extreme Lotion	50	A, B, OC, S
Panama Jack Sunscreen Lotion	50	B, C, OC, S
SolBar PF Cream	50	B, C, OC, S
High Sun Protection Factor Gels		
Bullfrog Land Sport With Breathable Sweat TECH Quik Gel	50	B, C, OC, S
High Sun Protection Factor Sprays		
Banana Boat Sunscreen Sport Performance Quik Dri Broad Spectrum Suncare Sunscreen Spray	30	A, S, B, C
Banana Boat Sunscreen Sport Performance CoolZone Broad Spectrum Suncare Sunscreen Spray	30	A, OC, B
Coppertone Sport Continuous Sunscreen Spray	30	B, C, S
High Sun Protection Factor Sticks		
Neutrogena Sunscreen Ultra Sheer Stick	70	A, S, OC, B
Shade Stick	30+	B, C, S
Specialty Sunscreens		
Australian Gold Spray with Bronzer	30	A, S, B, C
Babyganics Mineral-Based Baby Sunscreen Lotion	50	S, ZO, TI
Loreal Paris Sublime Sun Advanced Sunscreen Crystal Clear Mist	30	A, S, C
Lip Screens		
Dermatone Medicated Lip Balm	23	B, PB
Neutrogena Lip Moisturizer	15	B, C
Inorganic (Physical) Sunscreens		
Neutrogena Sensitive Skin Sunscreen Lotion	30	TI
Vanicream Sunscreen	30	TI, ZO
Moisturizers Containing Higher-SPF Sunscreens		
Anthelios SX Daily Moisturizing Cream	15	A, E, OC
Aveeno Positively Radiant Daily Moisturizer Broad Spectrum SPF	15	A, C, S
Eucerin Daily Protection Moisturizing Face Lotion	30	ZO, TI, S, PBSA
Lubriderm Daily Moisture Lotion with Sunscreen Broad Spectrum SPF	15	B, C, S
Neutrogena Healthy Defense Daily Moisturizer Broad Spectrum SPF	30	C, OC, PBSA, ZO
Neutrogena Oil-Free Moisture	35	OC, S, A, B
Purpose Dual Treatment Moisture Lotion	15	C, MA, TI

Data from Shuai X, Kwa M, Agarwal A, et al: Sunscreen product performance and other determinants of consumer preferences. JAMA Dermatol 2016;152(8):920-927.
A, Avobenzone; *B,* benzophenones; *C,* cinnamates; *E,* ecamsule; *MA,* methyl anthranilate (meradimate); *OC,* octocrylene; *PB,* paraaminobenzoic acid or paraaminobenzoic acid ester; *PBSA,* phenylbenzimidazole sulfonic acid (ensulizole); *S,* salicylates; *TI,* titanium dioxide; *ZO,* zinc oxide.

Limitations of the study include borderline significance of the risk reduction.[97] Results of this study support sunscreen use to help reduce risk of melanoma.

The effect of sunscreens and clothing protection on numbers of nevi in children and adolescents (a prominent risk factor for melanoma)[90] is uncertain. In one study of children younger than 36 months, sunscreen use is associated with decreased nevus counts,[113] whereas in another, sunscreen increased benign nevi in adolescents.[294] Protective clothing had no effect.[165] It is not clear why intermittent sun exposure, especially during childhood, is associated with increased risk of melanoma, whereas chronic occupational exposure may be partially protective.[89]

Sunscreen Side Effects

Sunscreen side effects are generally mild and limited. In one study, participants applied SPF 15 sunscreen or vehicle control;[81] 19% of both groups had adverse reactions. Most were irritant in nature, fewer than 10% were allergic, and more than 50% of persons who developed irritation were atopic. Allergic reactions to sunscreens are more often the result of preservatives and fragrances than of active sunscreening agents.[64,261]

While uncommon, most sunscreening agents may cause allergic or photoallergic contact dermatitis.[139] Benzophenone-3 and octyl methoxycinnamate are leading UV filters triggering allergic responses.[116] In children with allergic contact dermatitis with a photodistribution, patch testing to evaluate their sunscreens may be helpful to determine the allergic trigger. PABA is now rarely used because it sensitizes approximately 4% of exposed persons. After an individual is sensitized, cross-sensitization with thiazides, sulfonamides, benzocaine, and hair dyes that contain paraphenylenediamine may occur.[239]

Stinging or burning without accompanying erythema, scaling, or dermatitis is common, especially in periocular areas and in patients with rosacea. Addition of skin protectants (e.g., cyclomethicone) to the sunscreen vehicle can mitigate this.[215] Certain vehicles (e.g., alcoholic gels) may be more stinging. Even when periocular application is avoided, perspiration, water immersion, and rubbing may cause sunscreen to migrate, thus producing symptoms.

Comedogenicity is primarily related to ingredients in the vehicle base. Certain common excipients (e.g., almond oil, cocoa butter, isopropyl myristate, isopropyl palmitate, olive oil) are possible comedogens.

Both TiO_2 and ZnO can generate reactive molecular species, called free radicals, with sun exposure.[63] TiO_2 is more photoactive than is ZnO.[203] Photoactivated TiO_2 can damage DNA in vitro.[119] In vivo, it is unlikely that TiO_2 particles penetrate the stratum corneum to reach underlying epidermal cells that contain DNA. Transmission electron microscopy fails to demonstrate TiO_2 penetration of the stratum corneum.[65] Data demonstrate that ZnO is not absorbed and Zn levels are unchanged after application.[92] Coating TiO_2 or ZnO with silicone halts photoproduction of reactive species.[63] Concerns have been raised regarding use of these agents on broken skin.

Some sunscreening agents may have weak estrogenic or antiandrogenic activity.[256] Benzophenone-3, octyl-methoxycinnamate, and 3-(4-methylbenzylidene) camphor may have estrogenic effects on human breast cancer cells in culture.[255] In one study, whole-body application of these three sunscreening agents was tested. Plasma and urine levels of these agents were detectable in men and postmenopausal women; luteinizing hormone and follicle-stimulating hormone were unchanged, and there were only minor changes in testosterone and estradiol (in men only). The authors concluded that these endocrinologic alterations are clinically insignificant, and that these sunscreen products are safe for use in adults. With chronic use, oxybenzone may have estrogenic and antiandrogenic activity.[118,177,255,297] Oxybenzone is not concentrated in plasma after use and does not have high affinity for estrogen receptors.[133]

ROLE OF VITAMIN D

The relationship among sun exposure, skin cancer, and vitamin D has garnered media attention. Skeletal effects of vitamin D are well established in the literature.[138] Extraskeletal effects of vitamin D began to be studied after discovery of vitamin D receptor (VDR) within skin, pancreas, breast, prostate, and colon cancer cells.[138] Additionally, VDR has been found on immune system cells.[47,263,290] A 2001 Institute of Medicine report stated evidence was insufficient to provide recommendations on vitamin D for extraskeletal disease prevention.[131] A 2011 meta-analysis by the U.S. Preventive Services Task Force (including 19 randomized controlled trials and 28 observational studies) found no significant benefits of vitamin D in prevention of cancer.[48]

Other studies show a possible protective effect of vitamin D against systemic malignancies. Mortality rates of several common cancers in the United States (e.g., breast, colon, prostate) increase with increasing latitude, and thus with decreasing sun exposure.[68] Sunlight reduces the risk of non-Hodgkin's lymphoma.[267] Among men in the U.S. Navy, regular sun exposure reduces melanoma risk.[91] In patients with melanoma,[19] sun exposure is associated with increased survival. Melanoma may be among the tumors for which vitamin D has a salutary effect. Supporting this hypothesis are laboratory data demonstrating VDRs on melanoma cells and growth inhibition in response to vitamin D.[51] A case-control study found that diets rich in vitamin D and carotenoids were associated with reduced melanoma risk.[198] Long-term studies of vitamin D assessing causation and dose-response in skin cancer prevention are necessary.

Sunscreen's role in reduction of systemic vitamin D levels has been extensively studied. Although regular sunscreen use can decrease cutaneous synthesis of vitamin D_3[191] and circulating levels of measurable 25-hydroxyvitamin D,[192] even the most conscientious sunscreen users appear to maintain normal levels of vitamin D.[186] Individuals using SPF 15 sunscreen for 2 years maintained normal parathyroid hormone levels and normal bone metabolic markers.[75] Patients with XP maintained normal vitamin D levels over 6 years, despite rigorous photoprotection with sunscreens, clothing, and sun avoidance.[270] The NHANES 2003-2006 questionnaires showed that frequent sunscreen use was not associated with lower vitamin D levels in Caucasians.[170]

Controversy surrounding vitamin D and sunscreen may stem from inadequacies in sunscreen application in real-life settings. Appropriately thick application of sunscreen allows for 1/SPF% of UVR to be absorbed, providing a source of vitamin D production. Most adults do not apply sufficient sunscreen (at 0.5 mg/cm^2 instead of the recommended 2 mg/cm^2). This can decrease the labeled SPF by a factor of 8. Sunscreen alone is not sufficient to be the sole predictor of vitamin D insufficiency in the general population.[219]

The recommended dietary allowance (RDA) has varied. American Academy of Pediatrics 2008 guidelines recommending a daily intake of vitamin D of 400 international units (IU) per day effectively doubled the dose recommended in the 2003 guidelines.[295] Some authors advocate for more aggressive supplementation to meet physiologic need, particularly for individuals who are deprived of sun exposure.[254] Given that only brief sun exposures are needed to synthesize vitamin D,[121] Holick[122] suggests an approach of sensible sun exposure, which involves 5 to 10 minutes of exposure two or three times weekly in conjunction with the dietary intake of vitamin D and vitamin supplements. This recommendation has raised considerable controversy and concern in the dermatologic community.[213]

In 2010, the Institute of Medicine concluded that bone health was the only outcome for which causality and sufficient dose-response evidence are established. Vitamin D's role in cancer prevention was not found to be conclusively demonstrated. The new RDA for vitamin D assumes *minimal* sun exposure and suggests the following:

- 1 to 70 years, 600 IU per day
- 71 years or older, 800 IU per day

The committee continued to recommend 400 IU per day as adequate intake (AI) for infants up to 12 months of age. The group also established tolerable upper intake levels (UL) for vitamin D, taking into account emerging evidence of U-shaped associations (i.e., increased risk at both low and high levels and lowest risk at moderate levels of serum 25-hydroxyvitamin D) for all-cause mortality, cardiovascular disease, vascular calcification, pancreatic cancer, falls, frailty, and fractures. The recommended UL for vitamin D follows[131]:

- 9 years and older, 4000 IU per day
- 4 to 8 years, 3000 IU per day
- 1 to 3 years, 2500 IU per day
- 6 to 12 months, 1500 IU per day
- 0 to 6 months, 1000 IU per day

These recommendations have been upheld by the U.S. Preventive Services Task Force Unit in its 2013 recommendations, with a goal of 800 IU for asymptomatic adults older than 65.[209]

OTHER SOURCES OF SUN PROTECTION

Clothing Protection

Clothing provides substantial sun protection to broad surface areas. The United States has the most stringent UV-protective clothing standards in the world and assesses fabrics using the ultraviolet protection factor (UPF). UPF measures both UVB and UVA radiation blocked. Approved fabrics must undergo 40 simulated launderings, must be exposed to 100 fading units of simulated sunlight (equivalent to 2 years of sun exposure), and must be exposed to chlorinated water if marketed for water use.[272] Although the FDA was initially involved, the Federal Trade Commission now reviews clothing applications.

Several manufacturing strategies are used to achieve high SPFs. Solumbra is made of tightly woven nylon with an SPF of 30 or more (Figure 16-11). In hairless mice, this fabric is significantly better than cotton for reducing formation of UVR-induced SCCa.[197] SolarKnit uses chemically treated cotton and cotton-synthetic blends to achieve an SPF of 30 or more. Rayosan, a UVR-absorbing agent, bonds to various fabrics and increases the SPF by up to 300%.[176] Tinosorb FD, a unique organic UVR protectant, may be incorporated into detergents to increase the SPF of clothing with each wash.

Unregulated clothing varies considerably in ability to block UVR. The SPF fabrics range from 2 (polyester blouse) to 1000 (cotton twill jeans).[242] A typical dry white cotton T-shirt has SPF of 5 to 9.[242] The most important factors for determining SPF are tightness of the weave[176,242] and the actual fabric. Lycra is an extreme example of this; it blocks almost 100% of UVR when lax and only 2% when maximally stretched.[176] Other determinants include wetness and color. Dry and dark fabrics have a higher SPF than do wet and white fabrics.

Clothing prevents chronic photodamage and is associated with fewer nevi.[10] Blue denim reduces UVR-induced p53+ cells twice as effectively as does an SPF 15 sunscreen.[18] Denim greatly reduces formation of skin cancers in patients with XP.[17] Wearing long sleeves was associated with lower 25(OH)D levels.[169] However, 100% cotton clothing transmits 15% of UVR. Adequate vitamin D levels can be achieved even if only the face and palms are exposed.[269]

Ladies' hosiery provides surprisingly low SPF: black hose have SPF of 1.5 to 3, and beige hose SPF of less than 2.[262] Hat protection varies as a function of brim diameter and style. Small-brimmed (<2.5 cm [1 inch]) hats adequately protect the forehead and the upper nose; medium-brimmed (2.5 to 7.5 cm [1 to 3 inches]) and wide-brimmed (>7.5 cm [3 inches]) hats protect proportions of the nose, cheeks, chin, and neck.[60] Wide-brimmed hats provide SPF of 7 for the nose, 3 for the cheeks, and 2 for the chin. Baseball-style caps are especially useful for children. They protect the forehead well, allowing sunscreen application below the cheekbones, thus mitigating the risk of stinging from application near the eyes.

Glasses, contact lenses, and sunglasses protect the corneas from most UVB and from variable amounts of UVA.[247] A complete discussion of this is provided in Chapter 48.

FIGURE 16-11 Photoprotective clothing. **A,** Solumbra hiking apparel. **B,** Coolibar swimwear. *(**A** courtesy Sun Precautions; **B** courtesy Coolibar.)*

SUN AVOIDANCE

An indoor lifestyle is undesirable for most persons. More practical is avoidance of excessive midday sun (i.e., 10 AM to 3 PM), which significantly reduces UVB exposure.[172] Shade provides variable protection. In one study, shade beneath leafy trees provided SPF of less than 4.[225] Shade cloths allow significantly more UVB exposure than does clothing of the same fabrics, largely because of atmospheric scattering and surface reflection.[306]

Automobile windshields block UVB and some UVA. Side windows typically block only UVB.[282] This may explain why photodamage is more prominent on the left side of the face of Americans (and on the right side of the face of Australians) who drive a great deal.[58] Factors that affect UV-protective properties of glass include color, type, coating, and interlayers between layers of glass. Transparent plastic films that meet legal requirements in all 50 states can be applied to block more than 99% of UVR (e.g., LLumar UV Shield).

SUNLESS TANNING

Bronzers

Most artificial tanners and bronzers contain dihydroxyacetone (DHA). DHA reacts with amino groups of keratin proteins by the Maillard reaction to form brown-pigmented products known as *melanoidins*.[166] With DHA, bronzing can occur within 1 hour. It often requires multiple applications to achieve the desired depth of color. Maintaining this bronzed look requires reapplication every few days, because stained stratum corneum is shed from the skin surface. Depth of color is related to thickness of the stratum corneum and amount and frequency of application.[167] Cosmetic complaints include difficulty with obtaining an "even" tan and yellowing of the palms.

Dihydroxyacetone alone is an inadequate sunscreen. It does not absorb UVB; rather, DHA absorbs higher-wavelength UVA I and lower-wavelength visible light,[85] which makes it useful for certain photosensitivity disorders, such as porphyrias and polymorphous light eruption. Some commercial bronzing products now contain sunscreen in addition to DHA. Although the artificial tan produced by these combination products lasts for days, photoprotection lasts for only hours. The FDA requires bronzers without sunscreens to display a warning that they do not protect against sunburn.

Other products to promote indoor tanning have been used. Few are safe and effective. Tan accelerators containing melanin precursors (e.g., tyrosine) that have no discernible benefit.[134] Sunscreen preparations that containing psoralens (most often 5-methoxypsoralen [oil of bergamot]) are available in Europe. These stimulate melanin synthesis, but are tumorigenic in mice.[45] Psoriasis patients treated with psoralen plus UVA (PUVA) have a higher incidence of SCCa[275] and melanoma.[274] Psoralen-containing sunscreen is associated with increased risk of subsequent melanoma.[12] Oral carotenoids (e.g., canthaxanthin) are potentially toxic and consequently not approved in the United States.

Spray Tan

Spray tanning consists of topical application of DHA by a spray applicator. Literature on the adverse effects of spray tanning are lacking.[153] Oral or ophthalmic absorption of DHA by the spray technique warrants further review.

Tanning Booth

Ultraviolet radiation from artificial sunbeds is a human carcinogen.[211] Approximately 30 million North Americans (including 2.3 million adolescents) use tanning salons each year.[79] Caucasian women (18 to 21 and 22 to 25 years old) have the highest use (31.8% and 29.6%, respectively).[150] A 2011 Youth Risk Behavior Surveillance System report found 29% of high school girls have used indoor tanning.[66] A recent study found daily doses of UVR increased serum levels of β-endorphins that act in the same brain pathways as opioid drugs. When this stimulus was removed, the mice showed signs of withdrawal. This mechanism suggests "tanning addiction" may play a role in tanning bed use.[96]

Damage from tanning salons is insidious. Links between indoor tanning and melanoma risk have been reported (relative risk [RR] 1.20). First use of sunbeds before age 35 was associated with 1.87 times the risk of melanoma.[27,49] In adults 18 to 29 years old, 76% of all melanoma cases can be attributed to tanning bed use alone.[54] Approximately 25% of BCC can be attributed to indoor tanning.[77] Relative risk of squamous carcinoma is 2.5 times higher among tanning bed users.[140] An estimated 170,000 yearly cases of NMSC can be attributed to indoor tanning alone.[299]

The dangers of indoor tanning prompted the World Health Organization, American Academy of Dermatology, and American Medical Association to recommend legislation to ban indoor tanning for minors under 18 years old. A number of states have banned indoor tanning for minors. In 2014, the FDA reclassified UV tanning devices from class I (moderate risk) to class II (moderate to high risk), which allows for more regulatory control.[221] Indoor tanning lamps are now required to include a black-box warning stating that use should be avoided in persons less than 18 years old, if skin lesions or open wounds are present, or if there is a personal or family history of skin cancer. Users should receive regular evaluations for skin cancer.[286] As of 2015, only Brazil and Australia have banned tanning salons ("commercial solariums").[126]

Until 1980, most sunlamps emitted mostly UVB.[12] Current tanning salons make use of high-output UVA tanning beds and market their services as a way to tan without burning, with a subtle but incorrect message that such tans are safe. Chronic suberythemal UVA contributes to photoaging, immunosuppression, and carcinogenesis. There is significant variation in radiation output of tanning beds. In one study,[307] UVA output varied by a factor of 3, and UVB output by a factor of 60. Typical tanning bed outputs are contaminated with 2% to 10% UVB,[296] more than the average UVB content of natural sunlight. In another study in Scotland, 10 minutes of exposure yielded the same carcinogenic risk as did 30 minutes of peak summer sun at the same latitude.[208]

UNIQUE PHOTOPROTECTANTS

Antioxidants

Exposure to UVR creates reactive oxygen species (ROS) that contribute to DNA damage[228] and peroxidative destruction of membrane lipids.[127] Various natural antioxidants (e.g., vitamins A, C, and E; reduced glutathione; urocanic acid; melanin) and enzymatic systems (e.g., catalase, superoxide dismutase) protect skin from ROS.[127] Chronic exposure to UVR depletes the skin of these antioxidants.[179]

Animal studies have found applying antioxidants (e.g., tocopherol sorbate and vitamins C and E) before UVR exposure delays skin damage.[58,136,164,213] Although vitamin C does not act as a sunscreen (it does not absorb UVR), it protects against erythema and sunburn cell formation by quenching free radicals that are at least partially causative.[57] Routine use of antioxidants (e.g., topical vitamin E) may provoke contact sensitization and serve as a tumor promoter.[202]

Oral antioxidants may also be of value for preventing photodamage.[67] A combination of oral vitamins C and E decreased clinical signs of sunburn and thymine dimer formation after UVB irradiation.[230]

Botanicals

Botanical sunscreens are gaining attention due to potential photoprotective, photoabsorbant, antioxidative, antimutagenic, antiinflammatory, and anticarcinogenic properties.[171]

Camellia sinesis (i.e., green tea) contains polyphenols that are potent antioxidants. Polyphenols remove UVR-produced ROS and protect skin from further damage.[161] Green tea can be used orally and topically. Green tea polyphenol's antiphotocarcinogenic effects are believed to be mediated through interleukin-12 (IL-12). The use of the phenol in IL-12 knockout mice did not result in photocarcinogenic protection, but it did in IL-12 intact mice.[3,195]

Resveratrol, which is a potent antioxidant found in grapes, nuts, and red wine, mitigates the UVB-associated damage in mouse skin. It reduces UVB-induced edema, inhibits lipid peroxidation, and decreases production of enzymes associated with tumor promotion.[2]

Silmarin, which is a flavonoid derived from milk thistle, also has antioxidant, antiinflammatory, and salutary immunomodulatory effects when applied topically.[141] Topical applications of aloe and tamarind xyloglucan protect against UVR-induced immunosuppression by acting as antioxidants rather than sunscreens.[278]

Cucuma longa (i.e., turmeric containing curcumin) possesses rich antiinflammatory and antioxidant properties.[132] Curcumin induces apoptosis of BCCa cells.[135] Curcumin is noted for its chemopreventive and chemotherapeutic effects in various cancer types, including the skin, lung, breast, gastrointestinal, and genitourinary areas.[173]

Flowers of *Spathodea campanulata,* a tree endemic to roadsides of tropical Africa, possess flavonoids that strongly absorb in the 205 to 252 nm range and moderately in the 280 to 330 nm range.[293] Topical application may help avoid sunburn and UVR skin damage.

Ferulic acid is found in grains, fruits, and vegetables. Combining ferulic acid with vitamin C and E antioxidants in a topical solution doubled its photoprotective properties and was found to inhibit thymine dimer formation.[168]

Capparis spinosa (i.e., caper bush, Flinders rose), endemic to the Mediterranean countries, contains ferulic acid, cinnamic acid, and other derivatives with significant antioxidative and photoprotective effects. It reduces UVB-induced erythema, suggesting it may be a potential sunscreen additive.[26]

Root and flowers of *Pongamia pinnata* (i.e., Indian beech nut tree, Karanja), a tree found along the coast or rivers in India, contain a bioflavonoid that possesses many differing properties, including antiinflammatory and antisolar effects. Aqueous extract was most absorbent in the UVB range of 300 to 320 nm and UVA range of 335 to 400 nm. Acetone extract exclusively absorbed within the UVA region, with the maximum wavelength of absorbance at 337.9 nm.[260] This additive could also serve as a potential sunscreen ingredient.

Synthetic Molecular Structures

Postexposure therapy for sunburn with topical application of the DNA repair enzyme T4 endonuclease V (T4N5) is of interest. When applied in liposomes, T4N5 localizes in the epidermis and epidermal appendages,[309] and it enhances repair of UVR-induced DNA damage in mice and humans.[311] T4N5 prevents UVR-induced immunosuppression[156] and reduces UVR-induced skin cancer in mice.[308] In a study of patients with XP, T4N5 in a liposomal base significantly reduced the incidence of new actinic keratoses and BCCa after 1 year.[310]

ATTITUDES TOWARD PHOTOPROTECTION

During the 20th century, a tan was equated with health, wealth, and stylishness. Coco Chanel's 1929 pronouncement that "a golden tan is the index of chic" characterized the times. This attitude led to dangerous behaviors and created cultural norms that remain challenging to overcome. Numerous recent studies document continued skepticism toward photoprotection.[15,149,194,318]

Even patients with sun-related problems often do not adopt adequate sun protection habits. One study documented that patients with dysplastic nevus syndrome, at high risk for melanoma, do not avoid sunburning.[30] Among patients 1 year after treatment for BCCa, only 49% wore hats or long sleeves in the summer, and 62% used less than two bottles of sunscreen per year.[115] Studies found that organ transplant recipients did not considerably improve sun-protective behaviors after their transplant,[197a,265] and only 40% reported using sunscreen.[279]

Sunscreen use correlates with knowledge of the harmful effects of sun exposure and understanding of SPF values.[20] In a survey of American adults, 42% were aware of the term *melanoma,* and 34% knew it was a type of skin cancer.[199] Some use sunscreens in the belief that sunscreens will promote tanning. More education is needed. In college students in Southern California, a 12-minute videotape about photoaging in conjunction with UV facial photography resulted in improved sun-protective behaviors 1 month after the education.[180] In Australia, where there are significant educational efforts about UV-related skin injury, three-fourths of adults visiting family physicians reported using sunscreens.[190] Australian state-sponsored and privately sponsored programs stress sun avoidance and clothing protection over sunscreens, and Australian fashion magazines feature more hats and models who are less tan.[46] For information regarding sun protection, patients rely on the Internet as much as on their physicians. Utilizing electronic media and social networking tools to promote sun-protective behaviors is an option for policy makers, public health officials, and medical professionals.[100]

Photoprotection education needs to begin during childhood. Considerable sun exposure occurs by the age of 18 years, and childhood exposure may be more significant than lifetime exposure for determining subsequent risks of BCCa and melanoma. Children who use sunscreens at an early age are more likely to use sunscreens as adolescents.[13] Sun protection policies in U.S. schools are lacking. In one study, only 10% of 484 secondary schools in 27 cities surveyed had a formal policy in place.[38]

Education of parents is required to alter parental behavior, beginning with the first well-baby visit. Sun avoidance and clothing protection should be advocated for infants who are less than 6 months old, and sunscreen should be added to the photoprotective regimen for older toddlers and children.

Advertisers and the fashion industry continue to glorify tanning and offer an oxymoronic message: you can get a "healthy tan" while protecting your skin.[236] In a review of American fashion magazine models, there was a trend toward lighter tans, more sunscreens, and more articles about sun awareness. Men's magazines did not demonstrate this trend.[94]

PHOTOSENSITIVITY DISORDERS

ENDOGENOUS PHOTOSENSITIVITY DISORDERS

Sun protection is especially important for persons with endogenous photosensitizing disorders, who take photosensitizing medications (Box 16-3), and who are exposed to topical photosensitizers (Box 16-4). For each of these conditions, use of broad-spectrum sunscreens, sun avoidance, and clothing protection provide appropriate prophylaxis.

The most common endogenous photodermatosis is polymorphous light eruption, affecting 10% to 14% of whites, predominantly females less than 30 years old. This manifests with pruritus, erythema, macules, papules, or vesicles on sun-exposed skin arising 1 to 2 days after exposure and resolving spontaneously over the next 7 to 10 days. It is most common with initial sun exposures during the spring or early summer. "Hardening" of the skin may occur with subsequent exposures. Patient education is very important. Sun avoidance and protective clothing are critical. Liberally applied sunscreens are helpful; a broad-spectrum sunscreen that contained padimate O and avobenzone was quite effective.[85] For medication-related photosensitization disorders, identifying the specific causative agent is crucial, and discontinuation or substitution should be considered.

Treatment for polymorphous light eruption includes super- or high-potency topical corticosteroids for several daily to weekly pulses, frequently in combination with systemic antihistamines (e.g., diphenhydramine, hydroxyzine, doxepin). Hardening of the skin in the spring with UVB, narrow-band UVB, or PUVA can be very effective. Systemic antimalarials (e.g., 200 to 400 mg/day of hydroxychloroquine sulfate, started in late winter) are generally less effective than phototherapy. For patients with severe issues, azathioprine, cyclosporine, thalidomide, and mycophenolate mofetil may be considered.

BOX 16-3 Common Oral Photosensitizing Medications

Antihistamines
Fluoroquinolones
Nonsteroidal antiinflammatory drugs
Oral contraceptives
Phenothiazines
Sulfonamides
Sulfonylureas
Tetracyclines
Thiazides
Tricyclic antidepressants

BOX 16-4 Topical Phototoxins and Photoallergens

Topical Phototoxic Compounds

- Dyes
  - Eosin
  - Methylene blue
- Medications
  - Phenothiazines
  - Sulfonamides
- Psoralens
  - Methoxypsoralen
  - Trimethylpsoralen
- Tars
  - Creosote
  - Pitch

Topical Phototoxic Plants

Angelica
Carrot
Celery
Cow parsley
Dill
Fennel
Fig
Gas plant
Giant hogweed
Lemon
Lime
Meadow grass
Parsnip
Stinking mayweed
Yarrow

Topical Photoallergenic Compounds

- Antiseptics
  - Chlorhexidine
  - Hexachlorophene
- Fragrances
  - Methylcoumarin
  - Musk ambrette
- Phenothiazines
- Salicylanilides
- Sulfonamides
- Sunscreens
  - Benzophenones
  - Cinnamates
  - Dibenzoylmethanes
  - Paraaminobenzoic acid
  - Paraaminobenzoic acid esters

Sunlight may exacerbate lupus erythematosus. UVB is typically causative; UVA can contribute. Broad-spectrum sunscreens, sun avoidance, and clothing protection are appropriate. A broad-spectrum sunscreen diminished clinical severity in a 4-week study.[42] Systemic antimalarials may be used in more serious cases.

Porphyrias are caused by inherited abnormalities in heme synthesis. Clinical manifestations vary with genetic subtype, but photosensitivity is common. Sunscreens other than inorganic blockers are generally inadequate. Topical DHA and oral beta-carotene may be useful adjuncts to sun avoidance.

Chronic actinic dermatitis manifests as persistent macules and plaques that are often infiltrated and lichenified on chronically sun-exposed sites on older men. Patients may demonstrate dermatitic flares with even modest exposure to UVR and shorter-wavelength visible light. The disorder can progress from dermatitis to T cell lymphoma. Broad-spectrum sunscreens, sun avoidance, and clothing protection (including wearing brimmed hats) are essential. For advanced cases, therapy with azathioprine, cyclosporine, PUVA, and retinoids has been used.

Persistent light reaction is a peculiar and persistent overreaction to sun exposure resulting from prior topical photoallergy. Musk ambrette, found in many perfumes, may provoke persistent light reaction.[239] UVB is most often causative.

For disorders in which melanocytes are defective or absent (e.g., albinism, vitiligo) and for disorders in which DNA repair mechanisms are deficient (e.g., XP), the protective triad of sunscreens, sun avoidance, and clothing protection is required.

PHOTOTOXICITY

Most oral photodrug eruptions are phototoxic and clinically manifest as exaggerated sunburn on exposed skin with sharp cutoffs at the neck and short-sleeve line. Less common is photo-onycholysis, in which the distal fingernails separate from their underlying beds. Photodrug eruptions are usually triggered by UVA. The most common offending drugs are listed in Box 16-3.

Topical photosensitizers may cause phototoxicity, photoallergy, or both. Phototoxicity results in exaggerated sunburn, typically followed by postinflammatory pigmentation. Phototoxicity is nonimmunologic and typically caused by UVR.

Many plants can produce phototoxic reactions in exposed skin (see Box 16-4), resulting in *phytophotodermatitis*. Common chemical precipitants are furocoumarins, especially psoralens, which are found in limes, lemons, and certain other plants (Figure 16-12). Phytophotodermatitis is common among farmworkers, bartenders, cannery packers, and vacationers to sunny climates. Oil of bergamot, which contains 5-methoxypsoralen, is a frequent cause of phototoxicity related to perfumes (berloque dermatitis). This eruption manifests as streaks of erythema and subsequent pigmentation on exposed skin of the face, neck, and wrists. Meadow-grass dermatitis among hikers is caused by contact with various common weeds (e.g., meadow parsnip) containing furocoumarins. This leads to whip-like erythematous streaks and postinflammatory hyperpigmentation after exposure to sunlight.

FIGURE 16-12 Phytophotodermatitis on a teenager after a "lime fight" that took place during an outdoor summer picnic.

Psoralens have been incorporated into sunscreens in Europe to promote tanning, although their use is associated with increasing risk of burns and carcinogenicity.[45] PUVA is used therapeutically for psoriasis and other select dermatoses.

PHOTOALLERGY

Photoallergic reactions occur only in previously sensitized individuals and are uncommon. Provoked by interaction of UVA with a topical proallergen, they result in contact dermatitis within 48 hours. Unlike phototoxic reactions, which are limited to exposed skin, photoallergic reactions can spread to adjacent sun-protected sites. Sunscreens are paradoxically the current leading cause of photoallergy.[125] Prevention requires excellent UVA protection, including use of broad-spectrum sunscreens.

TIPS FOR THE WILDERNESS ENTHUSIAST

Moist skin (e.g., swimmers and hikers in humid environments) reflects less UVR, resulting in greater absorption of UVB.[84] Snow, wind, and altitude augment UVB exposure for skiers and climbers. One study reported 36% of climbers (24 of 67) developed significant sunburns during expeditions up to 7000 m (23,400 feet) despite application of sunscreen.[264] A year-long study using continuous dosimetry monitoring of professional alpine mountain guides confirmed exceedingly high cumulative UVR exposure.[205]

Acute UVB overexposure may cause photokeratitis (snowblindness) in skiers and climbers.[312] Chronic exposure to UVR may cause or contribute to pterygia, cataracts, and macular degeneration (see Chapter 48).

To prevent cutaneous manifestations of toxic sun exposure, use a broad-spectrum sunscreen. Ointments and waxes may be desirable for climbers and winter campers because these reduce the risk of chapping and frostbite. Concomitant use of sunscreen and insect repellent containing diethyltoluamide (DEET) lowers the effective SPF by 34%.[207] If no commercial sunscreen can be obtained, extemporaneous inorganic blockers can be made from ashes, mud, and leaves. Clothing, such as long sleeves, pants, hats, and polarized sunglasses, grant significant UVR protection without need for topical sunscreens.

Sunburn treatments can include application of cold teabags, especially green tea, on the involved areas; temperature, antioxidative, and antiinflammatory properties help soothe and decrease erythema. Cool compresses with cotton material and oatmeal soaks can help relieve pain associated with sunburns. Topical analgesics such as *Hamamelis* (witch hazel), as well as the botanicals discussed earlier, may be used.[128]

UVB is a potent stimulus for reactivation of herpes labialis in outdoor enthusiasts.[266] Sun exposure leads to immune system depression. UVR suppresses herpes simplex virus (HSV) antigen presentation by the epidermal cells and decreases immune detection of the virus. Ample viral replication allows for a recurrence.[292] UVB induces HSV recurrence in animal models[218] and humans.[245] A recent study found spending 8 or more hours per week outdoors without eye UVR protection resulted in increased risk of ocular HSV recurrence.[175] Sunscreen is ineffective for preventing recurrences in outdoor skiers,[200] but it effectively prevents recurrences in the laboratory.[245] This may reflect a difference in application techniques. Zinc oxide inhibits the first step of HSV-2 pathogenesis, entry into target cells, spread among infected cells, and ability to neutralize virions of both HSV-2 and HSV-1.[6,201]

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CHAPTER 17

Volcanic Eruptions, Hazards, and Mitigation

JOANNE FELDMAN AND ROBERT I. TILLING

Volcanic eruptions are spectacular, violent, and often quite dangerous expressions of Earth's dynamic internal processes (Figure 17-1). More than 80% of the earth's surface above and below sea level is of volcanic origin, and gaseous emissions from volcanoes helped form Earth's oceans and atmosphere.[24] On average, about 60 to 70 eruptions occur worldwide each year; half of these are continuations of previously erupting volcanoes, and the others are new eruptions.[70,79] There are approximately 600 active volcanoes in the world and probably another 800 that have erupted at least once during the past 10,000 years.[79] Some volcanoes erupt only once in their lifetime, whereas others erupt repeatedly or even continuously. The largest explosive eruptions occur infrequently; in general, the longer the time interval between eruptions, the larger the next eruption tends to be. Some of the worst volcanic catastrophes in history have occurred at volcanoes believed to be extinct, including the famous eruption of Vesuvius in AD 79, which destroyed the cities of Pompeii and Herculaneum (see later).[79] In fact, in the past two centuries, 12 of the 17 largest eruptions were the first eruptions known in historical times.[66,70] Table 17-1 lists some notable historical eruptions, including the one at Chaitén Volcano in southern Chile, coming back to life after being inactive for 9400 years.[43] The Chaitén eruption, which began in May 2008, continued nonexplosively through 2009 before ending in early January 2010, constructing a new lava dome (0.8 km^3).[49] This eruption has special volcanologic significance because it is the world's first major rhyolitic eruption since the 1912 eruption of Novarupta, Alaska—the largest of the 20th century (Figure 17-2; see Table 17-1).

Volcanic eruptions have been responsible for the deaths of approximately 300,000 people in the past 400 years. In recent years, the average is two to four fatal volcanic events per year. Causes of death and number of fatalities are not well documented.[73] As the most deadly volcano hazards, pyroclastic flows have claimed the most lives, whereas tephra is the most common killer (Box 17-1). Long after the eruption, famine and disease epidemics are responsible for up to one-third of the total fatalities attributed to explosive eruptions[73] (Tables 17-2 and 17-3).

Compared with other natural disasters, volcanic eruptions occur infrequently, affect few people, and are responsible for only a small percentage of fatalities. Only about 2% of all natural disasters are from volcanic activity.[38,74] The deadliest volcanic eruption in history, Tambora, Indonesia in 1815, killed approximately 60,000 people, whereas 1 million people were killed in the worst hurricane (Ganges Delta in Bangladesh, 1970) and 830,000 were killed in the worst earthquake (Shaanxi earthquake in China, 1556).[41,71,79] Nevertheless, volcanoes have the potential to unleash one of the most destructive forces on Earth. Approximately 74,000 years ago, an Indonesian volcano named Toba

FIGURE 17-1 Eruption of Mt St Helens on May 18, 1980. *(Courtesy Robert M. Krimmel, U.S. Geological Survey.)*

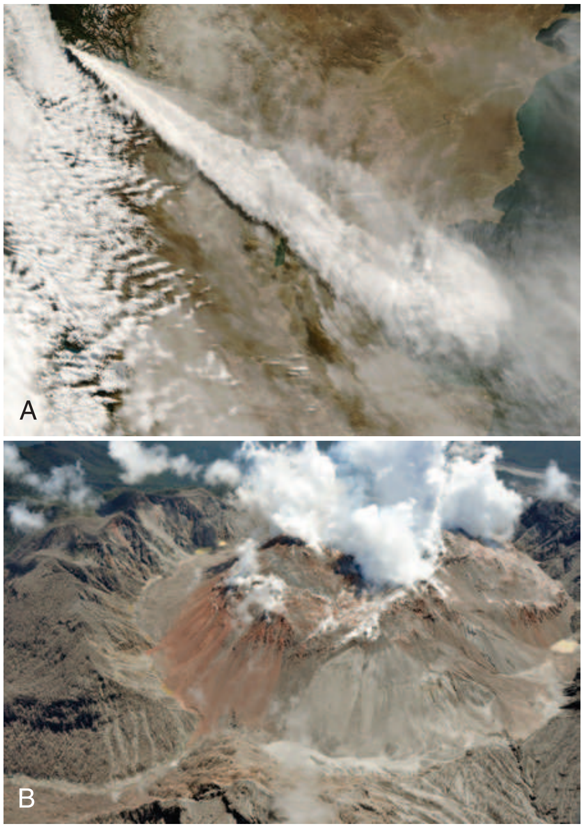


FIGURE 17-2 **A,** Satellite view of an ash plume produced during the explosive phase of the 2008-2010 eruption of Chaitén Volcano, southern Chile; plume is drifting downwind across Argentina and dissipating over the Atlantic Ocean. **B,** Aerial oblique view in January 2010 of the new lava dome constructed within Chaitén's 3-km (1.9-mile)–wide summit caldera. *(**A,** MODIS/NASA image, May 3, 2008; **B** courtesy John Pallister, U.S. Geological Survey.)*

TABLE 17-1 Some Notable Historical Volcanic Eruptions

Volcano	Country	Year	Significance
Santorini	Greece	1650 BC	One of the largest explosive eruptions on Earth; may have contributed to the decline of Minoan civilizations
Mt Vesuvius	Italy	AD 79	First major historical eruption to occur within range of major cities; first eruption to be well documented by an eyewitness (Pliny the Younger)
Laki	Iceland	1783	Largest historical lava flow eruption on Earth; catastrophic impact on Iceland's population from famine caused by loss of livestock from poisoning by hydrogen fluoride emissions
Mt Tambora	Indonesia	1815	Largest historical volcanic eruption on Earth; highest estimated eruption column (43 km [27 miles]); largest known death toll of over 60,000 (12,000 directly by pyroclastic flows* and tephra*; 48,000 indirectly from starvation and disease); global sulfuric acid aerosols caused worldwide climate change resulting in the "Year Without a Summer" in 1816; abnormally low temperatures in the northern hemisphere caused famine from widespread crop failure
Krakatau	Indonesia	1883	First large eruption of the modern age; two-thirds of the island destroyed; tsunami* killed 36,000 people living in adjacent coastal areas
Montagne Pelée	Martinique	1902	Classic example of a moderate-sized eruption causing severe loss of life: 29,000 people died
Novarupta	U.S.	1912	Largest eruption in the world in the 20th century; occurred in uninhabited part of Alaska; no fatalities
Mt St Helens	U.S.	1980	First major explosive eruption to be monitored intensively with modern technology; worst volcanic disaster in U.S. history; $1 billion worth of damage but only 57 people died because timely forecasting prompted evacuation
El Chichón	Mexico	1982	Erupted violently three times; first eruption came as a complete surprise; pyroclastic flows killed 2000; worst volcanic disaster in Mexican history
Nevado del Ruiz	Colombia	1985	Example of small eruption causing severe loss of life; lahar* caused 23,000 deaths and $212 million of damage; worst volcanic disaster in Colombian history; disaster demonstrates that in densely populated areas, even very small eruptions can cause widespread devastation and kill thousands
Mt Pinatubo	Philippines	1991	Second-largest eruption of the 20th century; major societal impact in Philippines; important but temporary global atmospheric effects; despite its huge size, eruption directly caused only 300 deaths because of timely evacuations prompted by precise forecasts by scientists
Chaitén	Chile	2008	Largest eruption in the 21st century to date; volcano had been dormant for 9400 years before abrupt onset of eruption in May 2008; activity is continuing nonexplosively through mid-June 2010; lahars and ashfalls caused relatively few deaths but severe socioeconomic impacts in southern Chile and downwind neighboring Argentina
Eyjafjallajökull	Iceland	2010	Major flight disruptions across northern Europe; the ash cloud both drifted over the Atlantic and for considerable intervals passed directly over Europe, halting flights of most commercial aircraft for almost a week in a controversial shutdown with economic impacts in the billions of dollars
Mt Merapi	Indonesia	2010	Over 350,000 people were evacuated from the affected area due to ash plumes, pyroclastic flows, and lahars; ash plumes caused major disruption to aviation across Java; 353 deaths
Bardarbunga	Iceland	2014	Subglacial stratovolcano beneath Vatnajökull ice cap has erupted continuously since late August 2014 and was ongoing as of early February 2015; the lava flow field formed to date is the largest in Iceland since that of the Laki eruption in 1783-1784
Mt Ontake	Japan	2014	A phreatic eruption occurred with no warning at this volcano; pyroclastic flows, ashfall, and ballistic ejecta killed more than 56 hikers and visitors; Japan's deadliest eruption since 1926 at Tokachi Volcano

Data from Sigurdsson H: The history of volcanology. In Sigurdsson H, Hougthon BF, McNutt SR, et al, editors: *Encyclopedia of volcanoes*, San Diego, 2000, Academic Press; Tilling RI: Volcanic hazards and their mitigation: Progress and problems, *Rev Geophys* 27:237, 1989; Clemens JA: Volcano! Evacuation and military medical implications, *ADF Health* 3:25, 2002; Major JJ, Lara LE: Overview of Chaitén Volcano, Chile, and its 2008-2009 eruption, *Andean Geology* 40:196, 2013; and Smithsonian Institution Global Volcanism Program http://www.volcano.si.edu/.
*See definitions in Box 17-1.

BOX 17-1 Glossary of Volcano-Related Terms

Lahar	Volcanic mudflow
Lava	Magma that has erupted at the earth's surface
Magma	Molten rock inside the earth
Pumice	Lightweight solidified fragments of magma ejected explosively from an eruption
Pyroclastic flow	Ground-hugging ash and rock clouds that sweep down slopes at hurricane speeds
Tephra	Explosively erupted airborne volcanic material such as ash, pumice, and rocks
Tsunami	Seismic sea wave generated by an earthquake or eruption
Volcanologist	Scientist who studies volcanoes

exploded and ejected 2800 km^3 (672 cubic miles) of ash, dust, and volcanic gases high into the stratosphere, where it was carried around the world by high-altitude winds. The particulate matter interfered with solar radiation and is thought to have led to a 10° C (22° F) temporary global cooling of the earth's surface.[71,88] Such a degree of cooling today would be catastrophic on a global scale.

We can expect more fatalities from volcanic eruptions as human settlements inexorably encroach on areas with high-risk volcanoes.[4] Current estimates suggest that about 500 million people, or 10% of the world's population, live within 100 km (62 miles) of a volcano that has been active in the historical record.[4,60] Auckland, New Zealand, occupies an area of young volcanoes. Seattle-Tacoma, Washington, is on land that could be devastated by mudflows from an eruption of Mt Rainier. Naples, Italy, is built on the flanks of Mt Vesuvius, where in the first minutes of

TABLE 17-2 Causes of Fatalities from Notable Volcanic Disasters Since 1000 AD

			Number of Deaths According to Primary Cause				
Volcano	**Country**	**Year**	**Pyroclastic Flow**	**Lahar**	**Tsunami**	**Lava Flow**	**Posteruption Starvation**
Mt Merapi	Indonesia	1006	1000	—	—	—	—
Kelut	Indonesia	1586	—	10,000	—	—	—
Mt Vesuvius	Italy	1631	—	—	—	18,000	—
Mt Etna	Italy	1669	—	—	—	10,000	—
Mt Merapi	Indonesia	1672	300	—	—	—	—
Mt Awu	Indonesia	1711	—	3200	—	—	—
Oshima	Japan	1741	—	—	1480	—	—
Cotopaxi	Ecuador	1741	—	1000	—	—	—
Makian	Indonesia	1760	—	3000	—	—	—
Mt Papadayan	Indonesia	1772	2960	—	—	—	—
Laki	Iceland	1783	—	—	—	—	9340
Mt Asama	Japan	1783	1150	—	—	—	—
Mt Unzen	Japan	1792	—	—	15,190	—	—
Mayon	Philippines	1814	1200	—	—	—	—
Mt Tambora	Indonesia	1815	12,000	—	—	—	48,000
Mt Galunggung	Indonesia	1822	—	4000	—	—	—
Nevado del Ruiz	Colombia	1845	—	1000	—	—	—
Mt Awu	Indonesia	1856	—	3000	—	—	—
Cotopaxi	Ecuador	1877	—	1000	—	—	—
Krakatau	Indonesia	1883	—	—	36,420	—	—
Mt Awu	Indonesia	1892	—	1530	—	—	—
La Soufrière	St Vincent	1902	1560	—	—	—	—
Montagne Pelée	Martinique	1902	29,000	—	—	—	—
Santa María	Guatemala	1902	6000	—	—	—	—
Taal	Philippines	1911	1330	—	—	—	—
Kelut	Indonesia	1919	—	5110	—	—	—
Mt Merapi	Indonesia	1951	1300	—	—	—	—
Mt Lamington	Papua New Guinea	1951	2940	—	—	—	—
Mt Hibok-Hibok	Philippines	1951	500	—	—	—	—
Mt Agung	Indonesia	1963	1900	—	—	—	—
Mt St Helens	United States	1980	57	—	—	—	—
El Chichón	Mexico	1982	>2000	—	—	—	—
Nevado del Ruiz	Colombia	1985	—	>25,000	—	—	—
Mt Merapi	Indonesia	2010	353				
Mt Ontake	Japan	2014	≥56				
	Totals:		>65,606	>57,840	53,090	28,000	>57,340
	GRAND TOTAL				>261,876		

Modified from Tilling RI: Volcanic hazards and their mitigation: Progress and problems, *Rev Geophys* 27:237, 1989; and Tanguy J-C, Ribière C, Scarth A, et al: Victims from volcanic eruptions: A revised database, *Bull Volcanol* 60:137, 1998; and Smithsonian Institution Global Volcanism Program http://www.volcano.si.edu/.

TABLE 17-3 Fatalities from Volcanic Eruptions, 1783-2000

	Fatalities	
Volcanic Hazard	**Number**	**%**
Posteruption famine and disease epidemics	75,000	30
Pyroclastic flows	67,500	27
Lahars	42,500	17
Volcanogenic tsunamis	42,500	17
Debris avalanches	10,000	4
Volcanic ash	10,000	4
Volcanic gases	1750	<1
Lava flows	750	0.3
TOTAL	250,000	—

Modified from Baxter PJ: Impact of eruptions on human health. In Sigurdsson H, Hougthon BF, McNutt SR, et al, editors: *Encyclopedia of volcanoes,* San Diego, 2000, Academic Press.

a major eruption, more than 100,000 people could be killed[4,10,66] (Figure 17-3). Latin America and the Caribbean are areas of particularly high risk because of population density. During the 20th century, 76% of all fatalities from volcanic eruptions and one-half of the most powerful eruptions occurred in this region. To date, eruptions during the 21st century have been moderate in size, occurred in diverse locales, and luckily caused relatively few deaths. In general, most fatalities occur in densely populated, less developed countries[60] (Table 17-4).

Although volcanic eruptions constitute a significant natural hazard, other processes and products of volcanism can be highly beneficial to society, explaining in part why so many people live on or near volcanoes.[71] Volcanic ash rejuvenates soil and can prevent loss of phosphorus, resulting in highly productive agricultural land (Figure 17-4). Volcanic ore deposits supply diamonds, copper, gold, silver, lead, and zinc. Products of volcanic activity are used as building materials, as abrasive and cleaning agents, and for many chemical and industrial uses.[24] Geothermal heat and steam can drive turbines to generate electricity, heat homes and industries directly, and be enjoyed by people at hot-spring resorts (Figure 17-5). The beauty of volcanoes and volcanic activity also generates income for communities through tourism.

FIGURE 17-3 **A,** Mt Eden, one of 50 geologically young but dormant volcanoes in the Auckland Volcanic Field, within the city of Auckland, New Zealand. **B,** Mt Rainier sits just 137 km (85 miles) southeast of Seattle-Tacoma, Washington. **C,** Bay of Naples, Italy, with Mt Vesuvius in the background. *(**A** courtesy Lloyd Holmer, Institute of Geological and Nuclear Sciences, New Zealand; **B** courtesy Lyn Topinka, U.S. Geological Survey; **C** courtesy Robert I. Tilling, U.S. Geological Survey.)*

FIGURE 17-4 Farmer plowing a lush rice paddy in central Java, Indonesia. Sundoro Volcano looms in the background. The most highly prized rice-growing areas have fertile soils formed from breakdown of young volcanic deposits. *(Courtesy Robert I. Tilling, U.S. Geological Survey.)*

MT VESUVIUS, AD 79

The best-known volcanic eruption was Mt Vesuvius on August 24, AD 79. This eruption killed thousands of people, devastated the surrounding countryside, and destroyed at least eight towns, most notably Pompeii and Herculaneum. Before this eruption, Mt Vesuvius was seen as a benign mountain with lush vineyards planted on the slopes and human settlements on the mountain's flanks. Unlike the nearby often-erupting volcanoes Mt Etna and Stromboli, Mt Vesuvius was not considered volcanic. Even a series of pre-eruption earthquakes, as typically occurs before an eruption, did little to raise concern that Mt Vesuvius was an active volcano. The eruption was witnessed and documented by Pliny the Younger. In two letters to the Roman historian Tacitus, Pliny wrote that the first explosion began in the early afternoon and ended the evening of the following day. At first, Vesuvius produced an enormous eruption cloud that ejected ash, pumice, and volcanic gases vertically up to 30 km (19 miles) high. Then, from a darkened sky, ash and pumice rained down on the towns of Pompeii and Straide, causing roofs to collapse under the weight of the ashfall and burying the towns (Figure 17-6).

The town of Herculaneum, lying at the foot of Mt Vesuvius on a cliff overlooking the sea, was initially spared from burial. The prevailing wind blew away from the town and toward Pompeii. In the early hours of August 25, however, Vesuvius exploded again, this time ejecting hot gases, ash, and pumice down the mountain's slopes as a pyroclastic flow. Herculaneum was destroyed, buried beneath more than 20 m (66 feet) of pumice and ash. Whatever remained of Pompeii was also

TABLE 17-4 Fatalities From Volcanic Eruptions by Region, 1600-1982

	Fatalities	
Region	**Number**	**%**
Indonesia	161,000	67
Caribbean	31,000	13
Japan	19,000	8
Iceland	9400	4
Everywhere else	19,000	8
TOTAL	239,400	100

Modified from Blong RJ: *Volcanic hazards: A sourcebook on the effects of eruptions*, Orlando, Fla, 1984, Academic Press.

FIGURE 17-5 Blue lagoon in Iceland, with Svartsengi power plant in the background. Clean geothermal energy heats 87% of the homes in Iceland, including the entire capital city, Reykjavík. Excess geothermal water (which is absolutely clean) is ejected into the lagoon, and where there is swimming, the temperature averages about 40°C (104°F). The lagoon is a very popular tourist destination. *(Courtesy Mary Dagold.)*

FIGURE 17-6 View from the main square of the well-preserved ruins of Pompeii, with Vesuvius in the background. *(Courtesy Harvey E. Belkin, U.S. Geological Survey.)*

destroyed at that time.[65] Pliny the Younger wrote of the death of his uncle, Pliny the Elder, who probably died of asphyxiation from being caught too close to a pyroclastic flow.[4]

The remains of more than 2000 people found amid the ruins offer clues as to the causes of death. People unwilling or unable to flee their homes were instantaneously suffocated as hot volcanic ash and gases entered buildings. Others had multisystem trauma as the force of the explosion and pyroclastic flows scooped up rocks and building materials and smashed them into anything in their path. Skeletons recently uncovered in beach caves in Herculaneum suggest that the cause of death was the intense heat, about 500° C (932° F)[13,51,77] (Figure 17-7).

FIGURE 17-7 The "Garden of the Fugitives," in Pompeii, Italy, reveals 13 adults and children huddled together in a futile attempt to shield themselves from pyroclastic flows from the eruption of Vesuvius in AD 79. The human casts are obtained by filling cavities left in hardened ash with liquid chalk. *(Courtesy Lancevortex.)*

VOLCANOES AND THEIR GLOBAL DISTRIBUTION

Different images are associated with the word *volcano*—for example, a violently erupting Mt St Helens, a peaceful-looking snow-capped Volcán Villarrica in Chile, or rivers of lava flowing down the flanks of Kilauea Volcano in Hawaii (Figure 17-8). *Volcano* also means the opening, or vent, in the earth's crust through which molten rock, ash, and gases are ejected. Molten rock, while underground, is called *magma*. It becomes *lava* once it reaches the surface. Whether a volcano erupts explosively (e.g., Vesuvius, Mt St Helens) or nonexplosively (e.g., lava flows of Kilauea) depends on the magma: its composition, temperature, gas content, viscosity, and crystal content.[71] Magma that is fluid

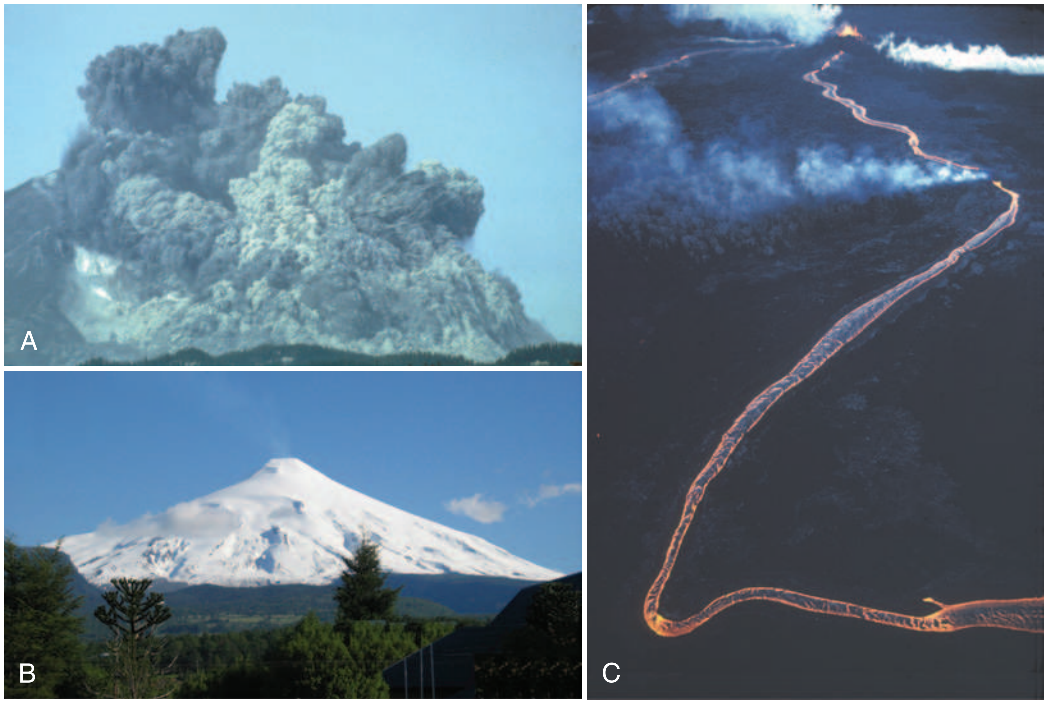


FIGURE 17-8 **A,** Violently erupting Mt St Helens on May 18, 1980. **B,** Villarrica Volcano, Chile, looks peaceful and even has a ski lift on its flanks, but the mountain is actually the most active volcano in Chile. **C,** A long river of lava flowing downhill from Kilauea Volcano in 1983. It ultimately enters the ocean 12 km (7.5 miles) away. *(**A** courtesy Keith Ronnholm; **B** courtesy Robert I. Tilling, U.S. Geological Survey; **C** courtesy J. D. Griggs, U.S. Geological Survey.)*

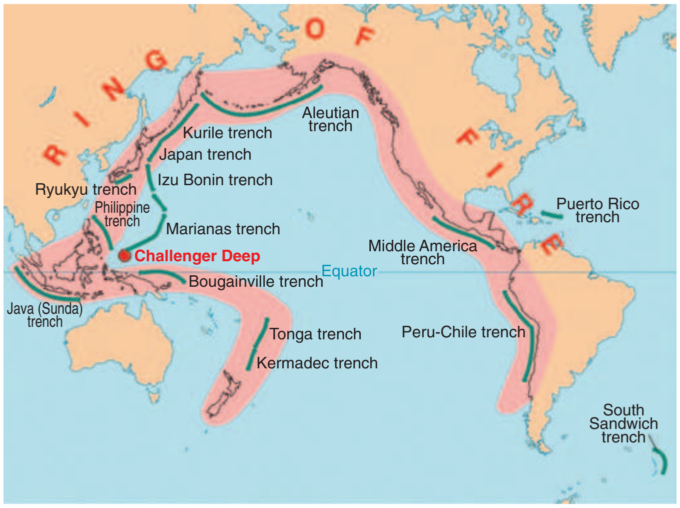


FIGURE 17-9 The Ring of Fire, a zone of frequent earthquakes and volcanic eruptions encircling the Pacific Ocean. Where the plates come together, they form deep oceanic trenches *(green). (From Kious WJ, Tilling RI:* This dynamic Earth: The story of plate tectonics, *Washington, DC, 1996, US Government Printing Office.)*

and hot tends to erupt frequently (every few years) and generally nonexplosively. This type of volcano most commonly produces fountains or rivers of red-hot lava.[83] In contrast, magma that is less fluid and cooler, and that contains trapped gases, tends to rise sluggishly and can plug up the volcanic vent. If enough pressure builds up as trapped gases expand during ascent, the pent-up pressure can blow the plug, abruptly unleashing the expanding gases and producing a violent eruption.[40]

The most volcanically and seismically active zone in the world, called the Ring of Fire, coincides roughly with the borders of the Pacific Ocean (Figure 17-9).[40] The volcanically active countries in this zone include Russia, Japan, the Philippines, Indonesia, Papua New Guinea, New Zealand, and the countries on the Pacific coasts of North, Central, and South America. Volcanoes are also scattered in the Atlantic and Pacific Oceans—in Hawaii, Iceland, and the Galápagos.

THEORY OF PLATE TECTONICS

The global distribution of volcanoes, as well as the origin and distribution of mountain ranges and earthquakes, are explained by plate tectonics.[63,79] This theory states that the earth's outermost layer is broken into a number of rigid plates that move relative to one another as they float atop the hotter, semisolid, and more mobile material of the mantle. The nature and distribution of volcanic activity depend on formation, movement, and destruction of these plates at their margins (Figure 17-10).

When two tectonic plates move away from each other, or diverge, new crust is created as molten rock pushes up from the mantle and oozes out onto the earth's surface or the seafloor. One well-known, mostly oceanic, divergent boundary, the Mid-Atlantic Ridge, is a submerged mountain range in the Atlantic Ocean that extends from the Arctic Ocean to beyond the southern tip of Africa. Along the Mid-Atlantic Ridge are numerous volcanoes, including those that rise above sea level in Iceland (Figure 17-11). Another prominent divergent boundary, entirely continental, is the 11,000-km-long (6835-mile-long) Great African Rift. About 75% of Earth's volcanism occurs unseen along divergent boundaries, deep on the ocean floor.

Two plates can also move toward one another, or converge. How two converging plates interact depends on the type of crust—continental or oceanic. Continental parts of plates, composed largely of granitic rocks, are relatively lightweight compared with the much denser and heavier oceanic parts of plates, which are composed of basalt. When two continental plates collide, both buckle upward to form a mountain range. The Himalaya Mountains are the result of the Indian plate colliding against the Eurasian plate (Figure 17-12). Few volcanoes are located in zones of continental collisions.

Many of the world's volcanoes are located at the convergent boundary between a continental plate and an oceanic plate. When these plates converge, the heavier oceanic plate dives, or subducts, below the lighter continental plate. This produces tremendous pressure and heat, melting the rock deep in the mantle. This molten rock, or magma, traps gases, such as carbon dioxide (CO_2) and sulfur dioxide (SO_2), making it buoyant in the surrounding denser, solid rock, and it begins to rise through the surrounding solid rock. Magma movement causes earthquakes that can be recorded with sensitive volcano-monitoring equipment. If the rising magma finds an area of weakness at the earth's surface, a volcano is created either just inland from the coast—for example, the volcanoes in eastern Russia, the Cascades in North America, and the Andes in South America—or just off the coast, such as the volcanic island arcs of the Aleutian Islands in Alaska, and Indonesia (Figure 17-13). Because of their proximity to a continent's coastline or to an island, subduction volcanoes are often near populated regions and thus can have a significant human impact. Eruptions tend to be violent and explosive, such as the 1980 eruption of Mt St Helens or the 1991 eruption of Mt Pinatubo in the Philippines.[71]

Some volcanoes are found far from plate boundaries. The Hawaiian volcanoes are more than 3200 km (1988 miles) from

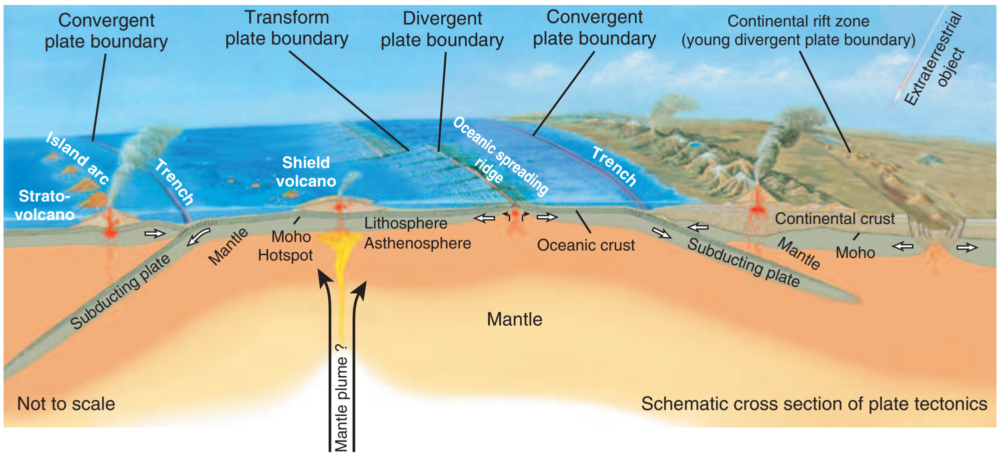


FIGURE 17-10 Cross section of the main types of plate boundaries. *(From "This Dynamic Planet," a wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and the U.S. Naval Research Laboratory.)*

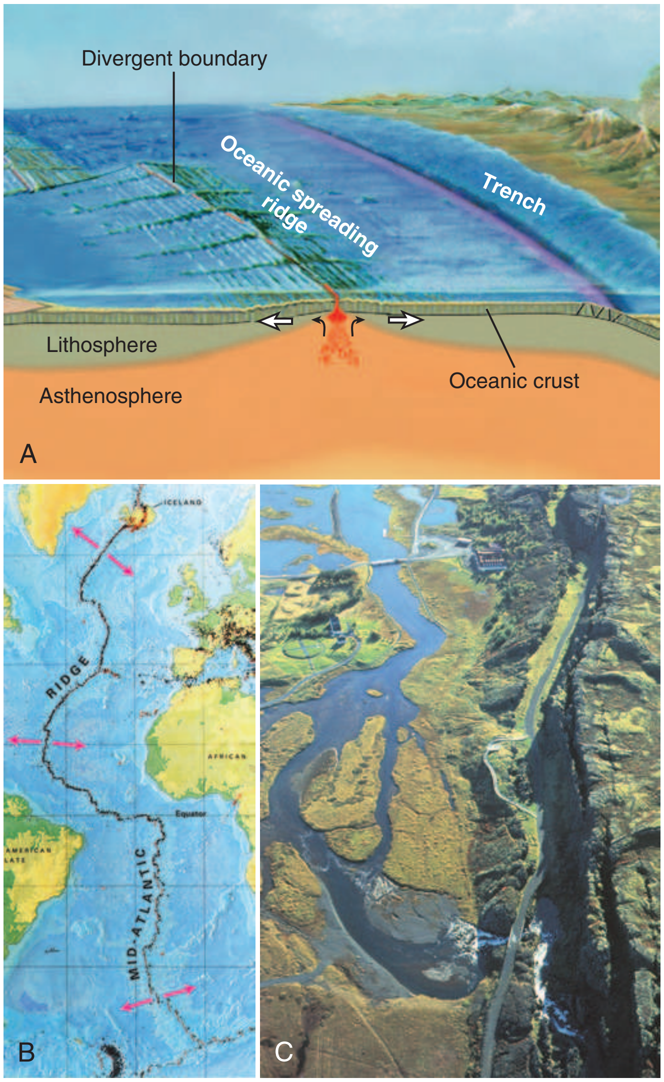


FIGURE 17-11 **A,** Cross section of an oceanic divergent boundary. **B,** Map of the Mid-Atlantic Ridge, along which the Eurasian and African plates are pulling away from the North American and South American plates. Note the ridge rising above sea level in Iceland. **C,** Exposed segment of the Mid-Atlantic Ridge at Thingvellir, Iceland. Left of the fissure, the North American Plate is pulling westward away from the Eurasian Plate (right of the fissure). *(**A** from "This Dynamic Planet," a wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and the U.S. Naval Research Laboratory; **B** and **C** from Kious WJ, Tilling RI:* This dynamic Earth: The story of plate tectonics, *Washington, DC, 1996, US Government Printing Office.)*

the nearest plate boundary, and Yellowstone, with more than 10,000 geysers, hot springs, and boiling mud pools, is located in the interior of the North American plate. At both these locations, an inferred *hot spot* below the plate melts overriding rock to produce magma that can rise toward the surface and ultimately erupt onto the seafloor or land. It has been assumed that the hot spot is stationary, whereas the tectonic plate above it moves. However, recent studies have questioned the fixedness of hot spots, prompting substantial debate among Earth scientists.

Examination of oceanic hot spots shows that in a series of islands created by plate movement, the islands farthest from the hot spot are the oldest. For example, a 6000-km (3728-mile) chain of volcanoes stretches from the older Emperor Seamounts (underwater sea mountains) off Alaska to the younger Hawaiian Islands. These were all created by passage of the Pacific Plate over the Hawaiian hot spot. This hot spot, currently located under the Big Island of Hawaii, has remained stationary for about 45 million years, whereas the Pacific Plate has been slowly moving to the northwest. According to the stationary-hot-spot model, as the plate continues to move over the hot spot, a new Hawaiian island will eventually emerge above sea level. In fact, just 35 km (22 miles) southeast of the Big Island there is an underwater volcano, Loihi, that has risen 3 km (1.9 miles) above the seafloor and is within 1 km (0.6 mile) of the ocean surface (Figure 17-14). At hot-spot volcanoes, eruptions tend to be nonexplosive and are rarely life threatening.[40] Huge volumes of fluid lava pour out, often creating large volcanic mountains, such as Mauna Loa, the largest single volcano in the world, standing 8851 m (5.5 miles) above the sea floor.

TYPES OF VOLCANOES

As erupted material accumulates around a volcanic vent, a volcano is formed and progressively grows. Classified by structure, the most common types of volcanoes are composite volcanoes, calderas, shield volcanoes, subglacial volcanoes, and flood basalts. These can be roughly grouped as either explosive or nonexplosive volcanoes. However, volcanoes can show both explosive and nonexplosive behavior during their life span. For example, in recorded history, Kilauea typically has erupted nonexplosively, spewing out fountains and rivers of lava, yet its 1790 and 1924 eruptions were spectacularly explosive. New studies show that if activity in the geologic past is taken into account, Kilauea's explosive eruptions are as frequent as those of Mt St Helens.

GENERALLY EXPLOSIVE VOLCANOES

Composite Volcanoes

Composite volcanoes, or *stratovolcanoes,* have steep sides and are typically associated with subduction zones at converging plate boundaries. Mt Fuji in Japan, Mt Pinatubo in the Philippines, and Mt Rainier in the United States are classic examples. However,

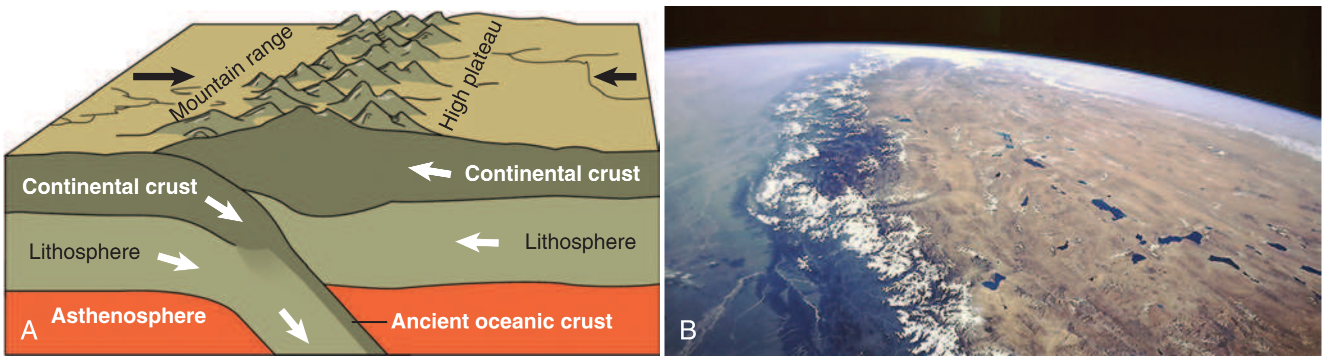


FIGURE 17-12 **A,** Cross section of two continental parts of plates converging, resulting in formation of a mountain range. **B,** The snow-capped Himalayas and the Tibetan Plateau are produced by collision of the Indian-Australian Plate *(left)* against the Eurasian Plate *(right)*. *(**A** from Kious WJ, Tilling RI:* This dynamic Earth: The story of plate tectonics, *Washington, DC, 1996, US Government Printing Office; **B** courtesy NASA, photo STS41G-120-22.)*

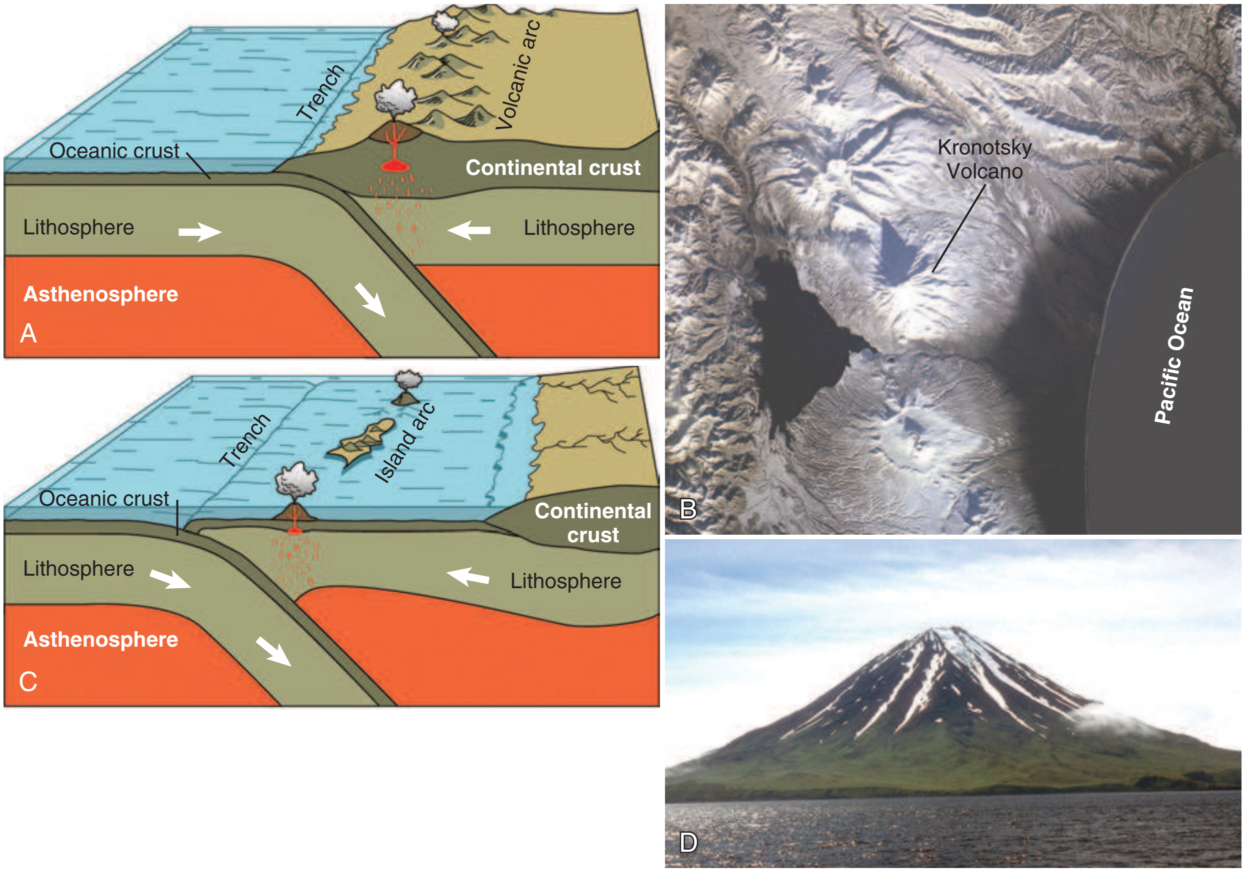


FIGURE 17-13 **A,** Cross section showing subduction of an oceanic plate resulting in formation of continental volcanoes and mountains. **B,** Kronotsky Volcano, at 3525 m (11,570 feet) above sea level, lies at the margin of the Pacific Ocean on the Kamchatka Peninsula of Russia. It was formed from subduction of the Pacific Plate *(right)* under the Eurasian Plate *(left)*. **C,** Cross section illustrating subduction of an oceanic plate with formation of volcanic island arcs. **D,** View of steep-sided, symmetric Carlisle volcano on Carlisle Island in the central Aleutian Islands. The 1620-m (5315-foot)–high stratovolcano has erupted several times since the late 1700s. *(**A** and **C** from Kious WJ, Tilling RI:* This dynamic Earth: The story of plate tectonics, *Washington, DC, 1996, US Government Printing Office; **B** modified from NASA, photo STS61A-45-0098; **D** courtesy M. Harbin, University of Alaska Fairbanks, U.S. Geological Survey.)*

composite volcanoes can also be formed at divergent plate boundaries (e.g., Hekla in Iceland, Mt Kilimanjaro in Tanzania) or at hot spots (e.g., Mt Erebus in Antarctica, Tenerife of the Spanish Canary Islands).[65,66] The steep-sided shape results from deposition of viscous lava flows alternating with pyroclastic flows and ashfall deposits. The explosive nature of composite volcanoes comes from high viscosity and volatility of the magma (Figure 17-15).

Calderas

Formed by collapse of a volcanic structure, calderas are circular or elliptical depressions, generally more than 1 km (0.62 mile) in diameter. Crater Lake in the U.S. Cascade Range is a large, partially filled caldera 10 km (6.2 miles) in diameter and 600 m (1970 feet) deep, formed when Mt Mazama exploded 7700 years ago. Krakatau, in Indonesia, was created by an 1883 eruption that involved rapid emptying of the magma chamber and subsequent collapse of the volcano.[65] Kilauea Crater is another well-known caldera (Figure 17-16).

Very large calderas fed by huge active magma chambers have been called *supervolcanoes* and are capable of producing enormously explosive eruptions. Yellowstone Caldera, 85 km (53 miles) long by 45 km (28 miles) wide, the largest and most worrisome in the United States, has a magma chamber that is 40 km (25 miles) long, 20 km (12 miles) wide, and 10 km (6 miles) deep.[66] Yellowstone has produced explosive eruptions 1000 times larger than the 1980 Mt St Helens eruption. Two other geologically young, large calderas located in the United States are Long Valley Caldera in California and Valles Caldera in New Mexico. Outside the United States, very large calderas include Campi Flegrei in Italy, Kamari Caldera on the island of Kos in the eastern Aegean Sea, and Rabaul Caldera in Papua New Guinea. Fortunately, very large caldera-forming eruptions were rare events, occurring approximately once in hundreds of thousands of years (Figure 17-17).[66]

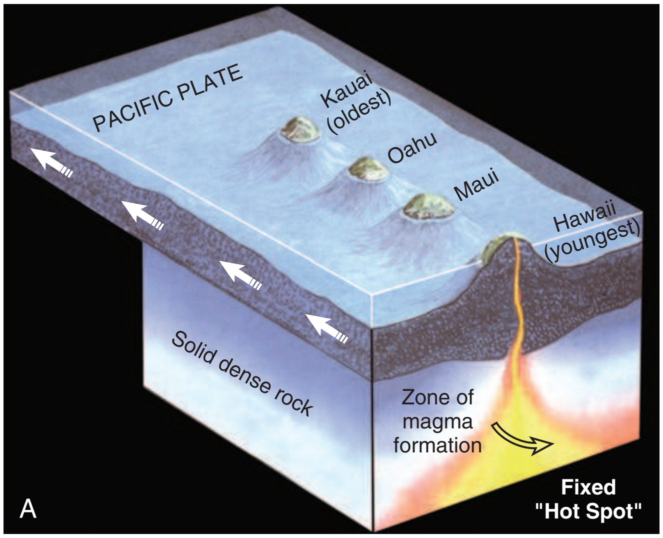
GENERALLY NONEXPLOSIVE VOLCANOES

Shield Volcanoes

Shield volcanoes have gentle slopes and are formed almost exclusively of layers of lava that have often flowed great distances from the eruptive vents. The magma, unlike that of explosive volcanoes, is predominantly of low viscosity and low volatility. Shield volcanoes are mostly formed at hot spots, although some are located at convergent or divergent plate boundaries—for example, Erta Ale in Ethiopia and Mt Etna in Italy. The largest volcanoes on Earth, Mauna Loa and Mauna Kea of Hawaii, are classic examples of shield volcanoes (Figure 17-18).

Subglacial Volcanoes

Historically active volcanoes located under glaciers, called subglacial volcanoes, are known only in Iceland and Antarctica. They can erupt explosively, but thick glacial ice cover generally inhibits material from being ejected high into the atmosphere. Instead, lava generally is erupted effusively, forming flows that often melt ice to create subglacial lakes and rivers. If this subglacial water



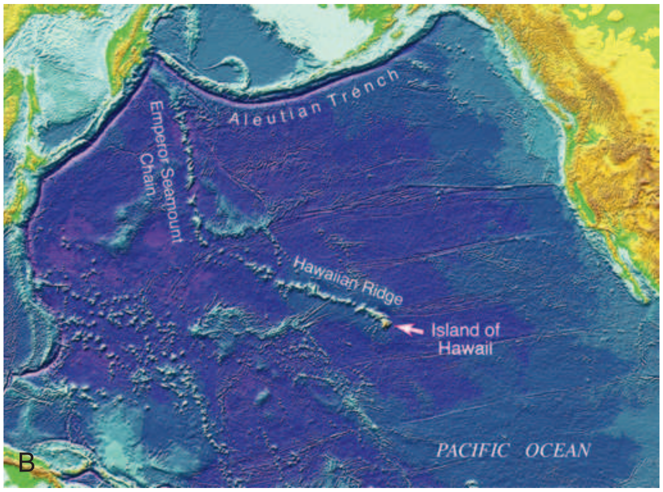


FIGURE 17-14 **A,** Cross section of the Hawaiian hot spot. **B,** Map of the 6000-km (3728-mile)–long Emperor Seamount–Hawaiian Ridge formed by passage of the Pacific Plate over the Hawaiian hot spot over a span of 70 million years. *(**A** from Kious WJ, Tilling RI:* This dynamic Earth: The story of plate tectonics, *Washington, DC, 1996, US Government Printing Office; **B** from "This Dynamic Planet," a wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and the U.S. Naval Research Laboratory.)*

suddenly escapes onto the glacier's surface (a *glacial burst,* or jökulhlaup), a huge river can form and destroy anything in its path. Grímsvötn, historically the most active volcano in Iceland, lies largely beneath the vast Vatnajökull icecap. The caldera lake is covered by an ice shelf 200 m (656 feet) thick, and only the southern rim of the 6- by 8-km (3.7- by 5-mile) caldera is exposed (Figure 17-19).[66] Its most recent eruption was in May 2011, which was the largest in Iceland in 50 years and included an explosive phase that produced a high ash plume that impacted air travel in Europe. Eyjafjallajökull, another subglacial volcano 120 km (75 miles) from Reykjavik, Iceland, began to erupt on March 20, 2010, after being dormant since 1823. During the eruption, hot lava melted the overlying glacial ice and generated jökulhlaups (see Figure 17-19C) that caused destructive flooding and prompted evacuation of more than 800 inhabitants. Then, on April 14, the eruption entered a much more explosive phase and propelled an enormous ash plume more than 8 km (5 miles) into the atmosphere.[72] This plume drifted easterly over northern Europe for the next several weeks, causing massive disruption of international air travel. This drifting Eyjafjallajökull ash cloud in 2010 and the one from the more powerful, but shorter-lived, 2011 Grimsvötn eruption provide illustrative examples of the potential hazards of volcanic ash for aviation safety (see Volcanic Ash, later). The Eyjafjallajökull eruption ended in October 2010.

Flood-Basalt Plateaus

Flood-basalt plateaus are massive areas of hardened lava produced from the largest volcanic events known on Earth.[34] Found on all continents and ocean floors, flood-basalt plateaus are created when basaltic magma erupts rapidly from fissures to form sheets of lava flows, typically tens of meters thick and covering tens of thousands of square kilometers.[34] Good examples are the Columbia River Plateau (Figure 17-20) and the Deccan Plateau of India. The rate of erupting lava can be 20 times the average eruption rate of a hot-spot volcano, and the eruption is on average 1000 times larger than that of a supervolcano.[66] Not surprisingly, the copious release of volcanic gases during the eruptions of flood basalts can severely affect the climate, and there is strong correlation between mass extinction on Earth and eruption of flood basalts.[66]

Undersea Volcanoes

Most undersea volcanoes are found at oceanic divergent plate boundaries. Others are found at undersea hot spots or near island arcs at convergent plate boundaries. Where two plates diverge, magma is injected along the space created. If magma reaches the seafloor, pillow lava (from slow effusions) or sheets of lava (from more rapid effusions) form. Sometimes, if the magma supply to a single point is sufficiently large and persistent, a cone-shaped volcano, called a *seamount,* rises from the seafloor. Seamounts found at undersea hot spots become island shield volcanoes, such as the Hawaiian volcanoes, if they rise above sea level. Seamounts at subduction zones become island-arc volcanoes, such as the volcanoes of Indonesia, above sea level. Hot-spot seamounts can emerge above sea level and then later sink as the seamount moves away from the hot spot and the seafloor subsides under the weight of the lava. Atolls, found in equatorial regions, are the coral reefs around drowning island volcanoes, after they become inactive and sink below sea level (Figure 17-21).[66]

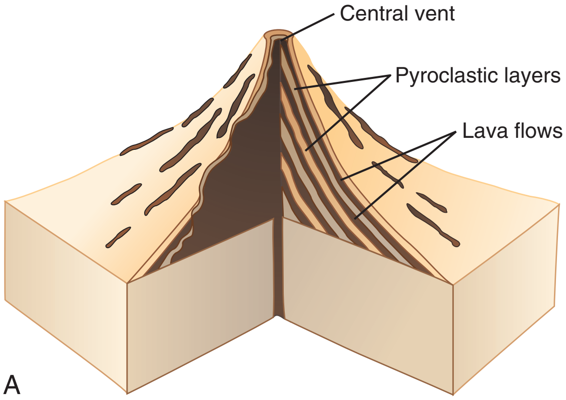


FIGURE 17-15 **A,** Cross section of a composite volcano (stratovolcano). **B,** Mt Fuji, Japan, is a perfect example of a composite volcano. *(Courtesy Thomas C. Pierson, U.S. Geological Survey.)*

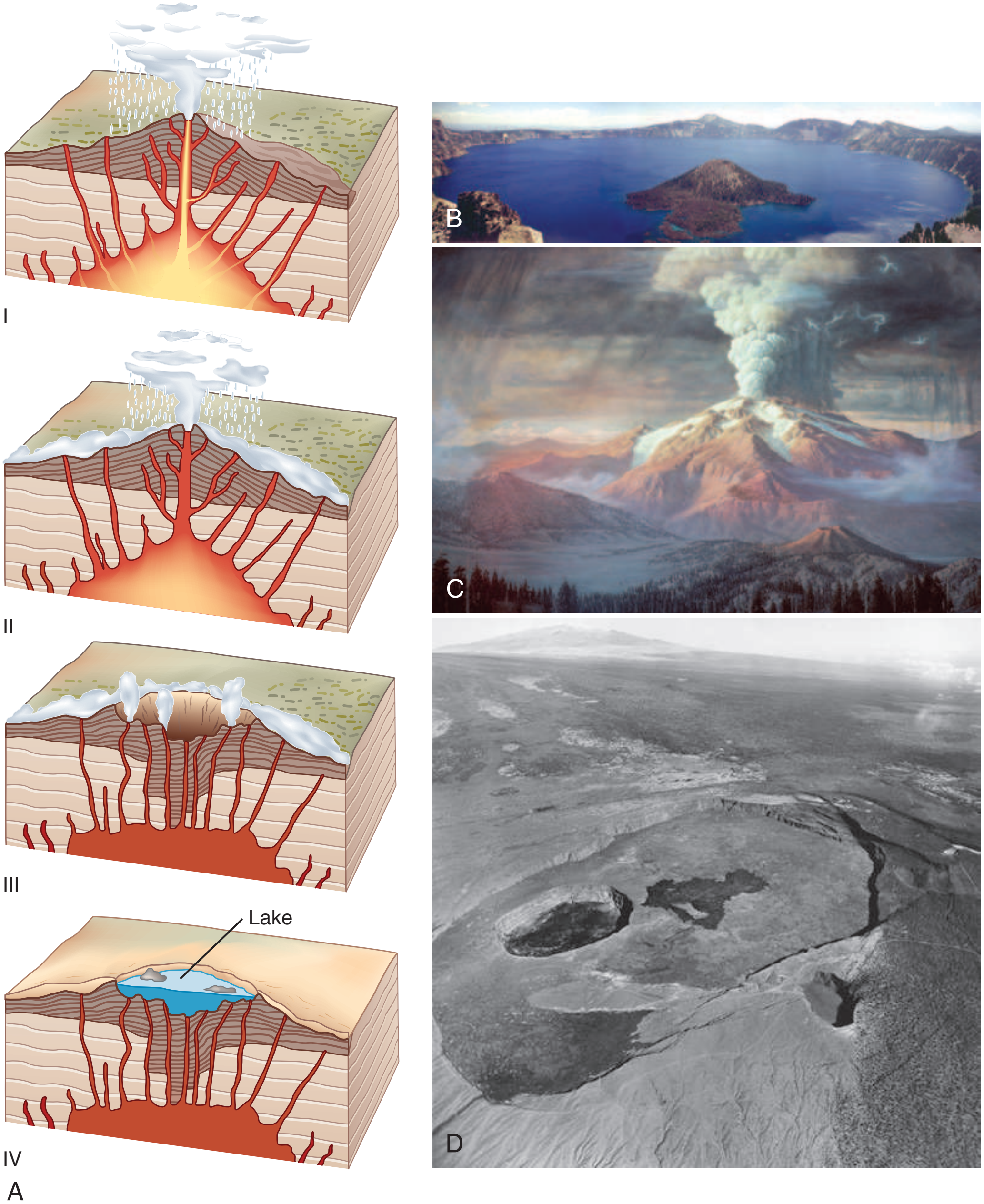


FIGURE 17-16 **A,** Cross section of formation of a caldera. **B,** Crater Lake, Oregon, was formed by the caldera-forming eruption of Mt Mazama 7700 years ago. **C,** When that mountain erupted cataclysmically, the summit collapsed, forming a caldera that eventually filled with water to form Crater Lake. **D,** Kilauea Caldera, Hawaii, in 1954 after an eruption within the caldera (dark area is the new lava). *(**B** courtesy Peter Dartnell, U.S. Geological Survey; **C** courtesy Crater Lake Natural History Association; **D** courtesy U.S. Geological Survey.)*

VOLCANO HAZARDS

Some volcanic eruptions cause injury, death, and destruction within minutes to hours. Others produce hazards that pose risks to human life, livestock, and the environment for months to years after the eruption. Explosive and nonexplosive volcanoes generate unique hazards, but explosive eruptions are usually associated with much larger numbers of deaths.

HAZARDS FROM EXPLOSIVE VOLCANOES

Volcanoes with explosive characteristics are extremely dangerous. They can cause thermal injury from hot gases and ash; mechanical injury from mudflows, debris avalanches, and falling tephra; chemical injury from toxic gases; and rarely, electrical injury from lightning or ionizing radiation injury from radon gas (Figure 17-22).[4] Most volcano-related deaths, injuries, and psychosocial effects occur because the volcano erupts violently and rapidly, leaving little or no time for people to escape or take shelter.[57] However, significant fatalities have been associated with mudflows and release of toxic gases during noneruption periods. Unfortunately, global distribution of explosive volcanoes, mostly along convergent plate boundaries, places them in densely populated areas.[7] Fortunately, explosive eruptions occur infrequently, and technologic advances have increased the ability of volcanologists to predict an eruption. Before the 1980 and 2004 eruptions of Mt St Helens, 1991 eruption of Mt Pinatubo, and 2010 eruption of Mt Merapi, high-risk zones around the volcanoes were evacuated because of timely warnings by scientists. These actions

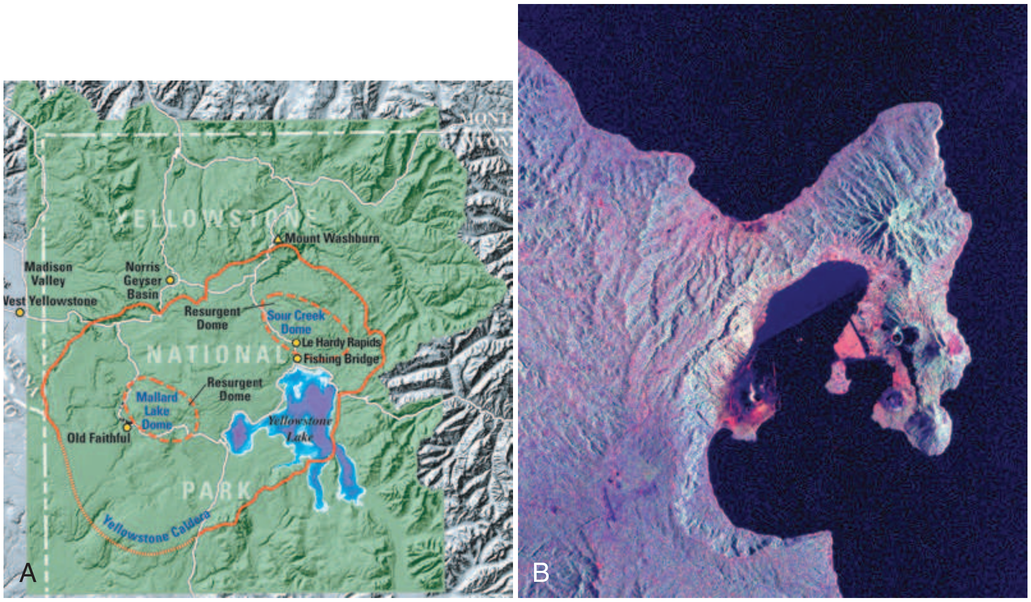


FIGURE 17-17 **A,** Map of Yellowstone National Park and the 650,000-year-old caldera *(outlined in red)* that is 45 km (28 miles) wide and 85 km (53 miles) long. **B,** View from space of Rabaul Caldera, Papua New Guinea. The caldera is 9 km (5.6 miles) wide by 14 km (8.7 miles) long and filled by the sea. *(**A** courtesy U.S. Geological Survey; **B** courtesy NASA.)*

greatly minimized the loss of life, especially in the case of Pinatubo, which was the largest eruption in the world in the 20th century.

Pyroclastic Flows and Surges

Typically, when an explosive volcano erupts, a volcanic cloud of gas, ash, and lava fragments rises vertically into the atmosphere. If this rising eruption cloud becomes denser than the surrounding air, it collapses and falls back toward the ground. Such gravitational collapse of the cloud leads to formation of a hot, high-speed avalanche of ash, volcanic gases, lava fragments, and heated air, called a pyroclastic flow.[65] Pyroclastic surges are similar to flows but are more dilute and less dense and can travel farther[4] (Figure 17-23).

There is little chance for survival in the direct path of a pyroclastic flow or surge traveling at 300 km/hr (186 miles/hr) or even greater, with temperatures of 600° to 900° C (1112° to 1652° F).[66] Everything living is carbonized by the extreme temperatures and swept away by the hurricane force of gas, ash, and rock sweeping downhill. Most human victims die as a result of asphyxiation (from breathing overwhelming amounts of ash or from oxygen deprivation), exposure to the intense heat, or burial under volcanic debris. Moreover, fatal traumatic injuries can result from associated devastating winds that can flatten trees and throw rocks. Survivors might have severe and extensive burns to their skin and respiratory tracts, or blunt trauma injuries.[60] Although the main impact only lasts a few minutes, pyroclastic deposits can remain extremely hot for weeks and pose a lingering danger.[4] Subsequent fires could cause further injury and death.

Some of the most famous volcanic disasters have involved pyroclastic flows and surges. The AD 79 eruption of Vesuvius sent pyroclastic flows down the volcano flanks, killing thousands in nearby towns. The 1980 eruption of Mt St Helens created a pyroclastic surge cloud that enveloped more than 100 people as it moved at locally supersonic speeds. The 57 people closest to the crater died. Many were buried by volcanic debris, and others died from exposure to intense heat or from asphyxia. One man was killed by a falling tree and another by a rock that flew through his car windshield. Two men died in the hospital from lung injury (acute respiratory distress syndrome) caused by inhaling fine ash.[4] Two others, near the edge of the pyroclastic surge, survived with minimal injury. More people would have died, but the area surrounding Mt St Helens had been evacuated after swarms of earthquakes and changes in the shape of the mountain signaled an impending eruption. Two weeks after the eruption, ash deposits on the volcano were still 300° to 400° C (572° to 752° F).[81] Gophers were the only animals to survive, because they were below ground.

The most devastating eruption of the 20th century occurred on May 8, 1902, when Montagne Pelée, on the Caribbean island of Martinique, sent pyroclastic flows moving greater than 100 km/

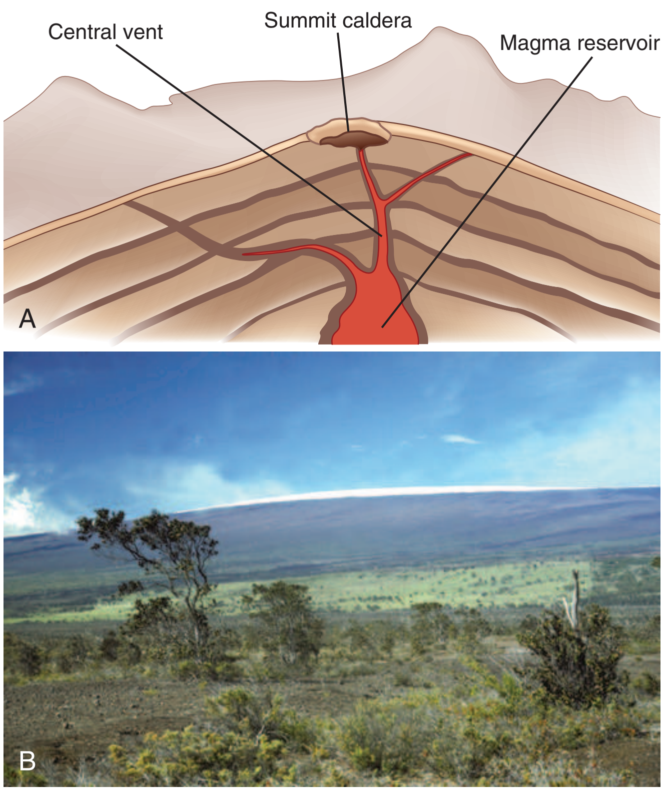


FIGURE 17-18 **A,** Cross section of a shield volcano. **B,** Snow-capped Mauna Loa as seen from the Hawaiian Volcano Observatory on the Big Island of Hawaii. *(**B** courtesy Robert I. Tilling, U.S. Geological Survey.)*

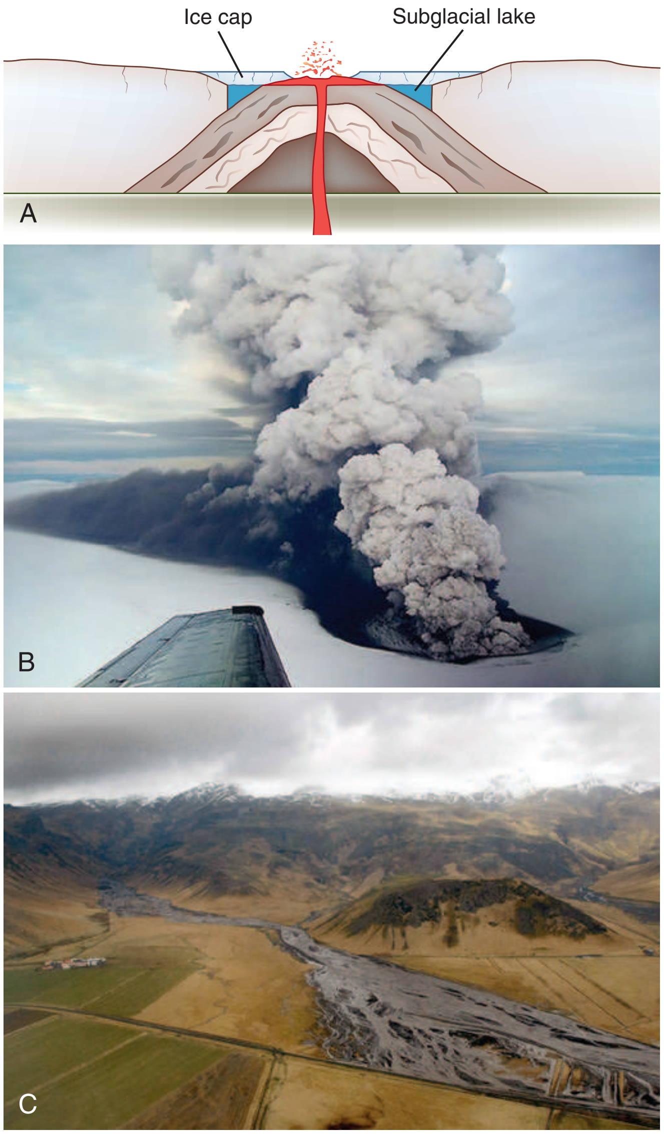


FIGURE 17-19 **A,** Cross section of a subglacial volcano. **B,** Subglacial volcano Grímsvötn in Iceland lies largely beneath the vast Vatnajökull icecap. The caldera lake is covered by a 200-m (656-foot)–thick ice shelf. A volcanic plume rises, during the November 2004 eruption, from the exposed southern rim of the 6- by 8-km (3.7- by 5-mile) caldera. **C,** Aerial view of jökulhlaups from the 2010-to-present eruption at Eyjafjallajökull, Iceland (see text). *(B courtesy Freysteinn Sigmundsson, Nordic Volcanological Center.)*

hr (62 miles/hr) down the mountainside. Within minutes, the city of Saint-Pierre, 6 km (3.7 miles) away, was annihilated and 29,000 people were killed. Only two survived in the town. At sea, ships were capsized and demasted, and people were burned by hot-air fall.[66] Since then, Montagne Pelée has been relatively quiet. Saint-Pierre has been rebuilt, but the population now is only 5000, much below the 1902 level (Figure 17-24).

Mitigation. Mitigation of future disasters from pyroclastic flows depends on evacuation before an impending eruption. Failure for any reason to evacuate in time will result in many deaths. Unfortunately, many countries with human settlements close to active volcanoes do not have the resources to monitor volcanic activity closely, as the United States did for Mt St Helens. In Latin America and the Caribbean alone, almost 60% of all deaths from volcanic eruptions are caused by pyroclastic flows.[60] Survival is possible without evacuation far from the volcano if there is adequate shelter to protect against high temperatures, asphyxiating gases, falling trees, and projectiles. Once persons are sheltered, windows, doors, and dampers should be closed. Skin should be completely covered, the head swathed in cloth, and to prevent severe lung damage, the breath should be held during the seconds to minutes when the hot cloud passes. Emergency medical personnel should be prepared to treat burns and blunt trauma injuries.

Lahars (Volcanic Mudflows)

Lahars, the Indonesian term for volcanic mudflows, can accompany most active, explosive volcanoes (particularly those with snow or ice cover). Historically, lahars have been almost as devastating as pyroclastic flows.[60] Mudflows occur when hot or cold volcanic debris mixes with water. Because the mixture has a high proportion of sediment, lahars behave like liquid cement and may cover 20 times the area of equivalent rock avalanches.[40] The mass of rock, mud, ash, and water sweeps down valleys, and when it reaches lowland plains, slows down and spreads out to cover hundreds of square kilometers. Lahars destroy buildings, bridges, and other structures and leave thick deposits behind (Figure 17-25). Most fatalities occur when victims are caught in the flow and are killed by trauma resulting from this destruction, flying debris, or burial.[4] More deaths occur later from famine and disease as people are displaced from their homes and local water sources become contaminated.

Lahars are especially dangerous because they come unheralded. They can form during or after an eruption, or they may be completely unrelated to eruptive activity.[4] Water is the key ingredient. Lahars need at least 10% water by weight to become mobile.[66] During an eruption, hot pyroclastic material can melt glacial ice or snow, producing water that mixes with ash on the volcano's flank. The water may come from a crater lake drained during an eruption or from the volcano's own subsurface geothermal system. A subglacial eruption can form a subglacial lake that subsequently breaks out to the surface and mixes with glacial debris. Heavy rainfall occurring during an eruption can initiate lahar formation. Shortly after an eruption, when new volcanic material is on the volcano's flank and there is no ground cover, rainfall can mix with the ash to create a lahar. Even long after an eruption, under circumstances such as a sustained intense

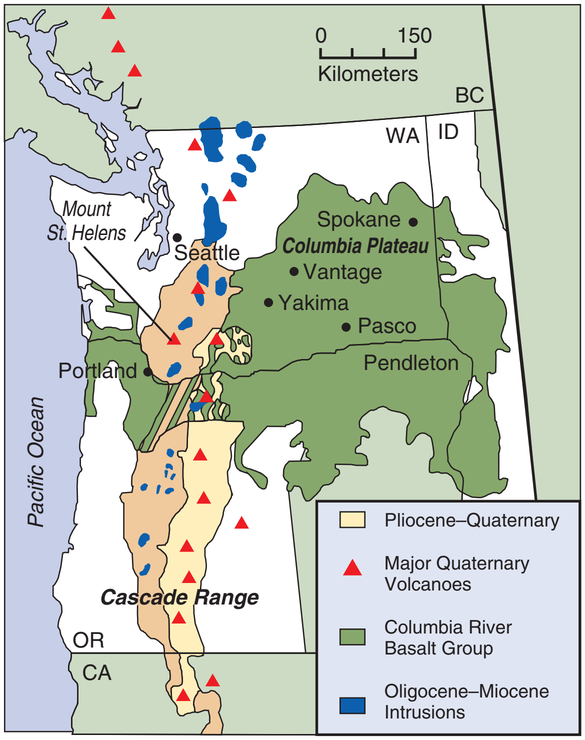


FIGURE 17-20 The Columbia River Flood-Basalt Plateau *(green)* covers approximately 163,000 km^2 (63,000 square miles) of the Pacific Northwest. In some areas, it is up to 1800 m (5900 feet) thick. *(Courtesy U.S. Geological Survey.)*

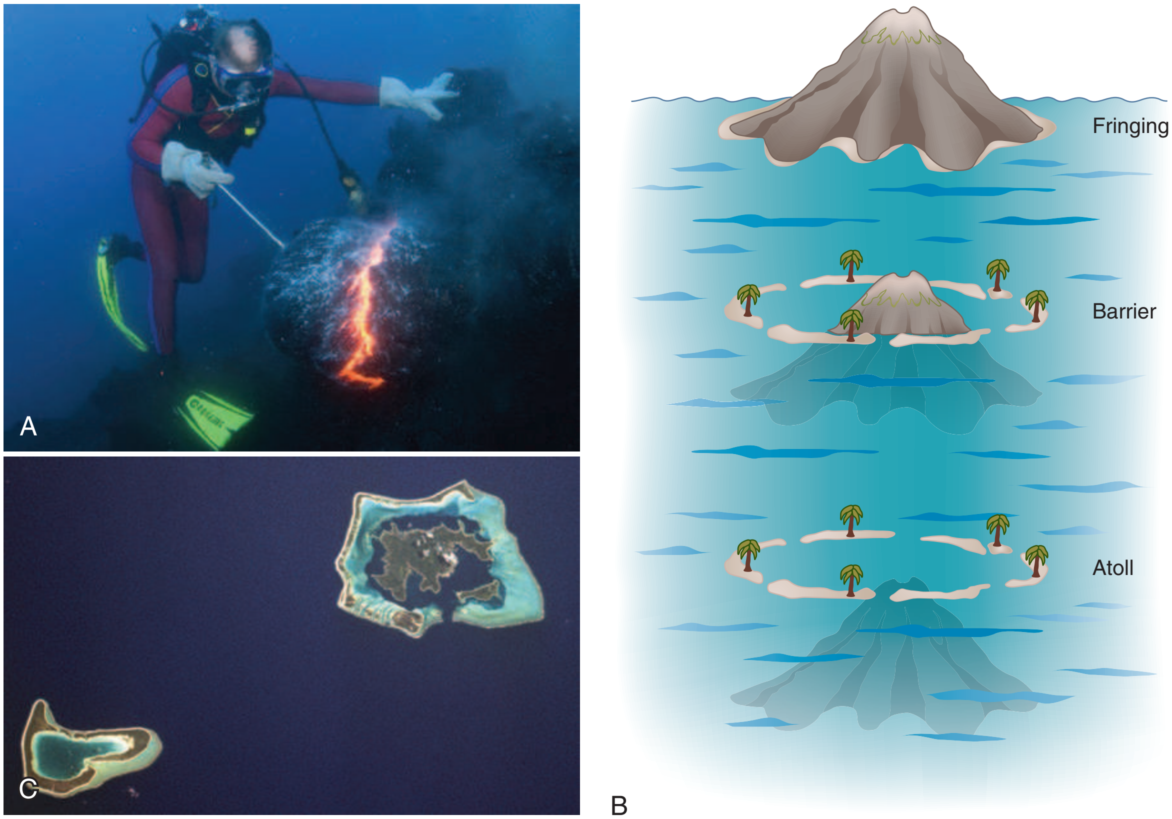


FIGURE 17-21 **A,** Scuba divers filming undersea volcanic activity offshore of Kilauea Volcano. **B,** Formation of an atoll. **C,** Bora Bora *(top right)*, Society Islands, French Polynesia. The island of Bora Bora includes remnants of an extinct volcano surrounded by a barrier coral reef. Tupai Atoll *(bottom left)* is all that remains of a sunken volcano. *(**A** from Doug Perrine / SeaPics.com; **C** courtesy NASA, photo STS068-258-042.)*

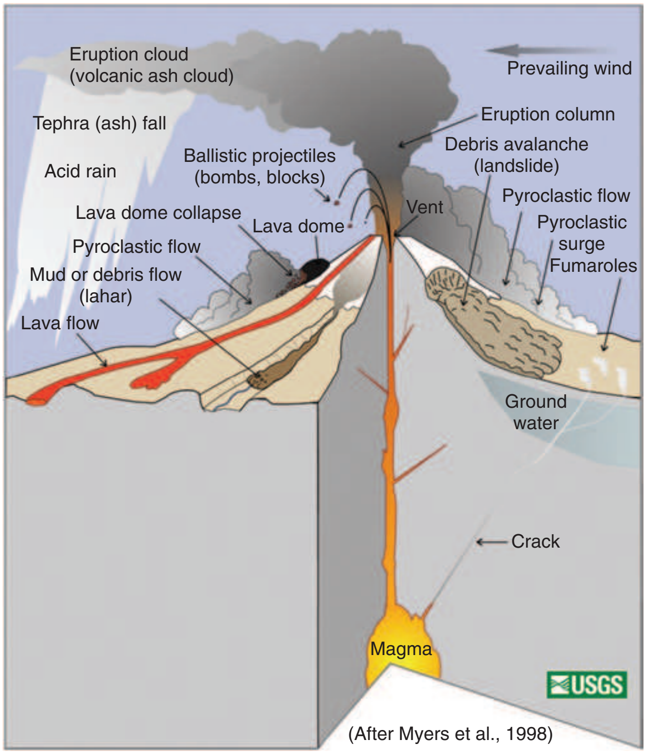


FIGURE 17-22 Common volcanic hazards. *(Modified from Bobbie Meyers, U.S. Geological Survey.)*

rainfall, water may mix with ash, and a lahar (now called a *secondary* lahar) can start to flow. Posteruption secondary lahars caused more fatalities than occurred during the catastrophic eruption of Mt Pinatubo, in the Philippines, on June 15, 1991.

Lahars can flow far from the site of the eruption. It is not necessarily the largest mudflows that produce the highest fatality rate; other factors include the victims' proximity to the hazard and the efficacy of a warning system. The greatest volcano tragedy of recent times began late at night on November 13, 1985, with a small eruption of the Colombian volcano Nevado del Ruiz. Small pyroclastic flows melted the snow cap and glacial ice on the mountain at 1656 m (5433 feet). The water mixed with

FIGURE 17-23 Pyroclastic flow sweeping rapidly downslope from Unzen Volcano, Japan, in 1991. *(Courtesy Shigeru Suto, Geological Survey of Japan.)*

FIGURE 17-24 **A,** City of Saint-Pierre, Martinique, with Montagne Pelée in the background, before the 1902 eruption. **B,** City of Saint-Pierre showing destruction from pyroclastic flows from Montagne Pelée, May 8, 1902. **C,** Seven months later, another, smaller pyroclastic flow sweeps down the flank of Montagne Pelée on December 16, 1902. *(**A** from an anonymous source; **B** and **C** courtesy Academy of Sciences, France.)*

FIGURE 17-25 Structure buried by mudflows (lahars) along the Sacobia-Bamban River during eruption of Mt Pinatubo. *(Courtesy R.S. Punongbayan, Philippine Institute of Volcanology and Seismology.)*

volcanic ash, forming lahars that swept down the steep valleys and destroyed the town of Armero 50 km (31 miles) away, killing 23,000 inhabitants (Figure 17-26). Around midnight, the first lahar struck the town, which was completely unaware of the danger, and covered it with 3 to 4 m (10 to 13 feet) of mud, burying three-quarters of the population.[4] Causes of death included suffocation from mud aspiration, trauma, hypovolemic shock, and later, gangrene. Of the 834 survivors, 578 (69.3%) had lacerations, 343 (41.1%) had penetrating injuries, 312 (37.4%) had fractures, and 272 (32.6%) had eye injuries; many had multiple injuries.[87] Armero had been rebuilt on the site of previous settlements destroyed by similar lahars in 1595 and 1845. Local officials were warned of the risk by an on-site scientific team, but failed to act.

Another devastating lahar occurred in 1953 when Ruapehu volcano in New Zealand claimed 151 lives after an ash and ice dam retaining its crater lake collapsed. The resultant lahar swept away the Tangiwai railway bridge just minutes before the arrival

FIGURE 17-26 Armero, Colombia, after devastating lahars from Nevado del Ruiz swept down the steep-sided valley *(top center)* on November 13, 1985. *(Courtesy Richard Janda, U.S. Geological Survey.)*

of the Wellington-Auckland express, and five train cars plunged into the river.[66,83]

Mitigation. For communities at risk for being struck by a lahar, evacuation is as important as when the threat is a pyroclastic flow. Early-warning systems include using trip wires stretched across lahar channels, seismic instrumentation (e.g., acoustic flow monitors), video cameras, automated rain gauges, and human observers. Also, lahars might be partly diverted or contained by creating channels, and they might be held back by dams and retention basins.[66] To reduce the water source, reservoirs or crater lakes can be lowered in level. Survival is possible without complete evacuation if the population at risk can be quickly moved to higher ground. Caution should be taken when crossing bridges. Emergency medical personnel in high-risk areas need to be prepared to treat blunt and penetrating trauma (crush injuries, lacerations, fractures, eye injuries), hypovolemic shock, and wounds with gangrene complications. Access to victims buried in the thick, cement-like mud can be difficult and prolonged.

Tsunamis

Tsunami, the Japanese term for harbor wave, is a seismic sea wave triggered by an earthquake or by volcanic activity. Specific triggers include major earthquakes along subduction zones, submarine landslides, underwater explosions, eruptions of island volcanoes, and avalanches on the flanks of a volcano.[40] Waves can move at speeds of more than 800 km/hr (497 miles/hr) and travel hundreds or even thousands of kilometers away from the source. In deep water, a tsunami is generally less than 1 m (3.3 feet) high and of no threat, but as the wave approaches the shore, its speed falls and height increases until it becomes a steep-breaking wave or an enormous surging wall of water.

Although relatively infrequent, tsunamis pose a severe risk that cannot be ignored, as was illustrated by the 2004 Indian Ocean Banda Aceh undersea earthquake, magnitude 9.0, which generated a tsunami that devastated the shores of Indonesia, Sri Lanka, India, Thailand, and other countries, with waves of up to 15 m (49 feet) high, killing approximately 228,000 people, although it is difficult to know the exact figure (Figure 17-27).

FIGURE 17-27 Hundreds of dead bodies and debris are piled along the coast, a dramatic demonstration of devastation caused by tsunamis affecting the Indian Ocean basin, this one triggered by the Banda Aceh earthquake, December 26, 2004. *(Photographer unknown.)*

FIGURE 17-28 Early in the morning on April 1, 1946, an earthquake (magnitude 7.1) in the Aleutian Islands off Alaska sent large, destructive waves toward the Hawaiian Islands. Five hours later, the waves struck the Big Island, killing 159 people, including many curious schoolchildren who ventured into the exposed reef area, not knowing the receding water was a sign of an approaching tsunami. Pictured are people fleeing the approaching tsunami (seen in background) in Hilo, Hawaii. *(Courtesy the Pacific Tsunami Museum Archives; photo by Cecilio Licos.)*

Tsunamis caused by volcanic activity have directly killed more than 42,500 people, which is as many as have been killed by lahars. Tsunamis, as with lahars, can come unheralded to settlements close to the source but can also affect distant coastal regions. Fortunately, many of these distant communities can now receive forewarning from the Pacific Tsunami Warning System and the newly established Indian Ocean Tsunami Warning System. Death and destruction occur when a tsunami slams ashore and destroys low-lying coastal communities (Figure 17-28).

Fatalities associated with volcanogenic tsunamis include those triggered by Mt Unzen, Japan, in 1792 and Krakatau, Indonesia, in 1883. Mt Unzen, on the Japanese island of Kyushu, is an island-arc volcano created above a subduction zone. In 1792, part of the volcano collapsed, probably as a result of seismic activity. The subsequent debris avalanche swept 6 km (3.7 miles) down the volcano to devastate the city of Shimabara, killing more than 9500 people. Most of the debris then emptied into the sea and triggered a tsunami that struck much of the seacoast of Ariake, killing another 5000 people in villages and on farms, even those as high as 30 m (98 feet) above sea level, along nearly 100 km (62 miles) of coastline.[65] The famous eruption of Krakatau in 1883, involving volcano collapse and sending pyroclastic flows into the sea, set off a series of tsunamis that washed away 165 coastal villages on Java and Sumatra, killing 36,000 people.[40,66]

Mitigation. Volcanic islands at risk for being hit by a tsunami include the islands of Hawaii, the Marquesas, the Canaries, Tristan da Cunha, and Réunion.[66] Other low-lying coastal regions are at risk. Key to mitigation is a worldwide tsunami warning system similar to the Pacific Tsunami Warning System, which was created in 1965 to warn of impending tsunamis in the Pacific Basin. In Hawaii, the warning system consists of sirens throughout the islands. Lobbies of coastal high-rise buildings are designed to allow water to pass through them without causing structural damage.[66] In addition, tsunami-warning-system buoys are scattered throughout the Pacific Ocean, and many coastal communities are educated to flee to high ground in case of earthquake or volcanic eruption (Figure 17-29). As a result of the 2004 Indian Ocean Banda Aceh undersea earthquake and tsunami, three more tsunami warning systems have been proposed. The Indian Ocean Tsunami Warning System became active in June 2006, whereas the other two—the Caribbean Sea and Adjacent Regions Tsunami Warning System and the Northeastern Atlantic, the Mediterranean and Connected Seas Tsunami Warning System—have been established but are still in the planning stages and not yet fully operational. The United Nations Intergovernmental Oceanographic Commission, through

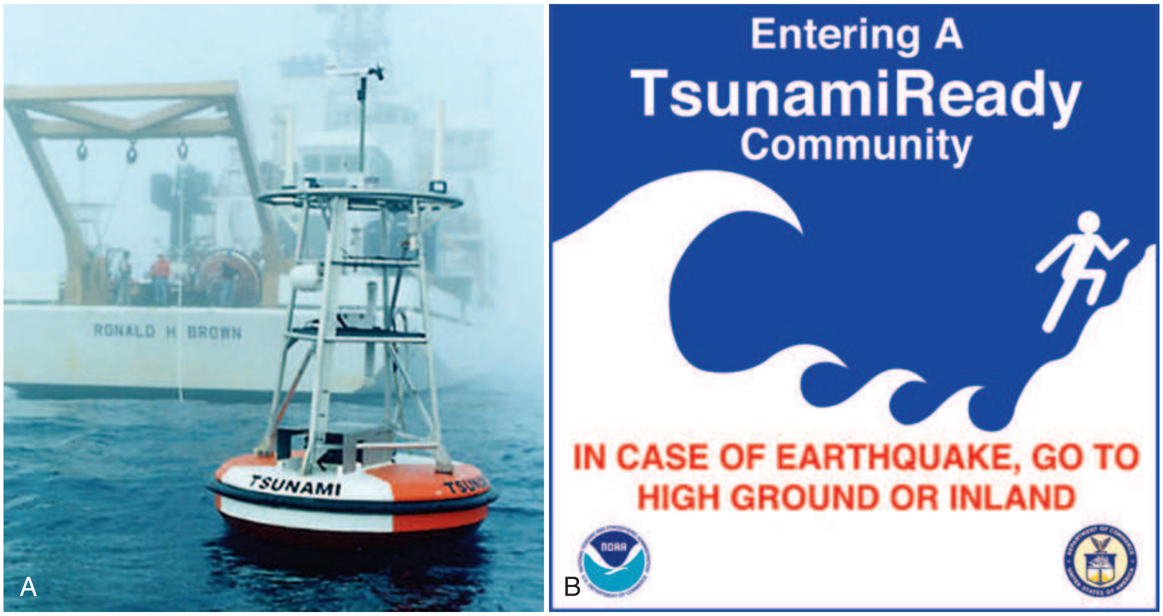


FIGURE 17-29 A, Tsunami buoy contains pressure sensors for determining a wave's size by gauging the weight of the water column passing over it. **B,** "TsunamiReady" sign. *(Courtesy National Oceanic and Atmospheric Administration.)*

the International Tsunami Information Center, coordinates the four systems.

Evacuation to higher ground is essential to reduce morbidity and mortality associated with tsunamis, and effective evacuation depends on public education of the officials and inhabitants of coastal communities. Emergency medical personnel need to be prepared to treat drowning victims, the effects of trauma, and disease epidemics.

Debris Avalanches

Volcanoes, especially steep-sided composite volcanoes, can be the site of catastrophic debris avalanches at any time.[65] In 1792 at Mt Unzen, mentioned previously, it was a debris avalanche that swept down the side of the volcano, killing thousands before emptying into the sea and setting off a devastating tsunami. Also in Japan, in 1888 an avalanche from the north flank of Bandai volcano sent 1.5 km^3 (0.36 cubic mile) of debris down the mountainside, killing 400 people below.[65,66] A debris avalanche also contributed to the eruption of Mt St Helens in 1980. Triggered by an earthquake, a debris avalanche on the north flank of the mountain removed rock overlying a shallow magma chamber. Pent-up volatile gases in the magma, no longer contained by the overlying pressure of the rock, quickly expanded, causing explosive fragmentation of the magma and the first eruption.

Mitigation. Mitigating danger from debris avalanches includes mapping the zones of potential slope collapse and avoiding travel to and high-density development within those areas. Fatalities and injuries are associated with blunt trauma and burial beneath rock debris. A victim caught in a rock fall should immediately seek some sort of shelter and roll into a ball to protect the head. Health care professionals need to be prepared for victims of blunt trauma.

Tephra

Tephra is the general term for fragmented rock of any size (volcanic blocks, glass shards, pumice, ash) ejected into the air by volcanic explosions. Tephra can range in size from large ballistic ejecta (>1 m [3.3 feet]) to ash (<2 mm). The largest tephra fall back to the ground at high speeds in the immediate vicinity of the volcano. Smaller fragments stay airborne longer, and the smallest are carried away by prevailing winds before ultimately being deposited, even at distances of many hundreds of kilometers from the volcano.

Ballistic Ejecta. An erupting volcano can eject huge ballistic fragments at high velocities (Figure 17-30). These can travel kilometers away from the volcanic vent and can cause significant damage (skull injuries, lacerations, blunt trauma of the chest and abdomen) to humans on impact.[4,66] The zone of damage from volcanic ballistics is generally limited to about 5 km (3 miles)—the maximum recorded range—so this is rarely a major human health hazard.[4] However, in Italy in 1944, three men were killed at Terzigno by falling volcanic rocks from Mt Vesuvius 5 km (3 miles) away. In 1924, an explosive eruption at Kilauea knocked a photographer down with flying stones and severed his leg. He died later that day, probably from toxic gas exposure.[10] Fire is a more common hazard, because hot flying ejecta can set fire to wooden structures, forests, or grassland.

Volcanic Ash. Smaller-sized tephra, especially ash, pose a much greater danger than do blocks and bombs. Drifting volcanic ash can be deposited hundreds to thousands of kilometers downwind from a volcano. Heavy accumulations of ashfall can collapse roofs, interfere with driving, clog machinery, and damage vegetation (Figure 17-31).

A layer of ash only 10 cm (4 inches) thick is enough to collapse a flat roof, especially if it is wet with rainfall.[60,66] Approximately 10,000 fatalities have been directly associated with ashfall, and the majority of these are from collapsed roofs. In 1991, Mt Pinatubo in the Philippines erupted during an untimely typhoon. Subsequent ash mixed with rain collapsed roofs and killed at least 300 people.[66]

Decreased visibility from airborne ash and slippery ash-coated roads pose danger to drivers of motor vehicles. During and after an eruption, the incidence rises of motor vehicle crashes and associated injuries. Moderate amounts of ashfall can also directly damage motors and other machinery, because fine ash clogs engine filters and lubrication systems.[66] Damaged machinery is rarely a risk to human health, except in the case of jet engines.

Volcanic ash clouds contain a combination of fine rock and glass particles. If a jet aircraft flies into a volcanic ash cloud, even thousands of kilometers away from the eruption site, the ash can damage engines, avionics, and airframes. Ash particles can block fuel nozzles, air filters, and external navigational equipment. Abrasion damage can severely scratch cockpit windows, landing lights, and turbine blades. Volcanic glass sucked into the engine will melt in the heat, accumulate, and solidify into a glassy layer that chokes fuel nozzles, coats turbine engines, and interferes

FIGURE 17-30 A, Spectacular explosive spray of ballistic ejecta when hot lava from Kilauea Volcano entered the ocean in 2008 in Hawaii; observers *(left corner)* give scale. B, Large ballistic block thrown up onto the shore from a previous lava entry into the ocean in the 1980s. *(**A** courtesy Michael Poland, U.S. Geological Survey; **B** courtesy Christina Heliker, U.S. Geological Survey.)*

with sensors, leading to reduced engine performance and ultimately total engine failure. High levels of static electricity in volcanic material can also interfere with radio communication. Comprehensive summaries of the damage and impacts of volcanic ash on aircraft operating and support systems have been described.[14,53]

Since the mid-1950s, more than 80 commercial aircraft have accidentally flown into eruption clouds, and seven of these encounters caused in-flight loss of jet engine power.[28,55] In 1982, two jetliners flew into the eruption cloud from Galunggung volcano on Java. The first, a British Airways jumbo jet carrying 240 people, lost all four engines and plummeted 7500 m (24,600 feet) in 16 minutes before cold air chilled and shattered the volcanic glass and the engines could be restarted. The jet made an emergency landing at Jakarta airport with three functioning engines and flying blind because the windshield was opaque from ash abrasion. A few weeks later, a Singapore Airline jumbo jet flew into a volcanic ash cloud from the same volcano, lost three engines and dropped 2400 m (7874 feet) before one engine restarted, and the aircraft was able to make an emergency landing (Figure 17-32).[10] Fortunately, to date no lives have been lost from aircraft–volcanic ash encounters. However, in mid-April 2010, the high eruption cloud from the Eyjafjallajökull eruption (Figure 17-33A) and its easterly drift over northern Europe (Figure 17-33B) raised serious concerns of possible damaging encounters between commercial aircraft and volcanic ash. As a precautionary measure, aviation officials closed many airports and grounded flights in the United Kingdom, France, Germany, Norway, Sweden, Finland, and Spain; many Europe-bound flights from the United States were also cancelled. The many airport closures and flight cancellations (>107,000) resulted in the largest disruption in commercial aviation since that caused by the September 11, 2001, terrorist attacks on the United States. An ash cloud from the 2011 eruption of Grimsvötn caused a similar crisis for commercial aviation. This time, however, even though the Grimsvötn plume was very large, it lasted for a relatively short time. Equally important, the international civil aviation agencies had learned valuable lessons from the Eyjafjallajökull experience in how to better manage a volcanic ash crisis. These two factors combined to greatly reduce the impact of the Grimsvötn eruption on global air travel.[76]

Heavy ash can strip vegetation from plants and coat surviving leaves. Destroyed vegetation and crops result in starvation of animals and can ultimately lead to famine in areas dependent on agriculture for subsistence. Famine from ash-related destruction of crops was the number-one cause of fatalities associated with volcanic eruptions before the 20th century. With global communication and world relief organizations, famine is now less common.

Most volcanic ash poses little direct danger to humans. Eye irritation may cause conjunctivitis and corneal abrasion, especially in persons wearing contact lenses.[39,60] Nose and throat irritation are common in persons not wearing a mask. Inhalation of ash, typically thought to be a significant health hazard, is for the most part benign, except for people with preexisting lung disease and heavily exposed workers, such as gardeners, road workers, and police.[6,8,11,15,26,50,67,86] Most ash particles are too large to be respired, high dust concentrations are of brief duration, and ash is biologically inert.[60,83]

However, fine ash particles less than 10 μm in diameter can irritate the lungs. This is especially dangerous for people with asthma and chronic bronchitis and results in increased visits to emergency departments (EDs) for exacerbation of chronic lung disease.[54,68] For example, after Mt St Helens erupted in 1980,

FIGURE 17-31 **A,** Enormous ash cloud from the 1980 eruption of Mt St Helens passing over the small town of Ephrata, Washington, 233 km (145 miles) to the west. **B,** Ash-covered village of Parentas, Java, after one of the eruptions of Galunggung Volcano in 1982. **C,** In the city of Yakima, central Washington, ash made roads slippery and decreased visibility after the 1980 eruption of Mt St Helens. *(**A** courtesy Douglas Miller; **B** courtesy Maurice Kraft; **C** courtesy U.S. Geological Survey.)*

there was a fourfold increase in the number of asthma patients and a twofold increase in the number of bronchitis patients visiting EDs in two large hospitals.[6] However, except for a single recent study,[31] no other studies have suggested significant long-term consequences of regularly breathing ash, even in the densely populated regions around Mt Sakurajima in Kyushu, Japan, where eruptions occur hundreds of times each year.[86] Some studies have shown certain types of ash, especially ash with a high content of the mineral cristobalite, can cause lung inflammation, but there is no evidence of any fibrogenic lung changes.[36,44,69]

Mitigation. To prevent injury from large-size tephra, danger zones around the volcano should be mapped, and these zones should be closed when eruption is a possibility. If closure is not possible, concrete shelters can be built in danger zones for the public to access in case of sudden onset of tephra fall. Hard hats should be worn at all times, and anyone unprotected caught in the open should watch for falling fragments and try to dodge them.[4] Emergency medical personnel need to be prepared for blunt trauma to the head and torso, and for burn victims.

To minimize injury from ash, drive slowly, minimize engine use, and wear eye protection and a dust mask. All vehicles and machinery should be put inside a garage or barn. Animals and livestock should be brought into closed shelters. Consider evacuating children and high-risk individuals (e.g., with asthma or chronic bronchitis) until ash levels are lower. Although communities formerly were advised to keep flat roofs clear of ash buildup, this is not recommended now, because people have been injured or killed from falling off roofs while removing ash (Figure 17-34). Health care professionals should be ready for an increase in emergency visits from motor vehicle collisions, eye injuries, and respiratory problems.

To mitigate the dangers associated with aircraft possibly encountering volcanic ash clouds, air traffic is routed away from eruption clouds based on the analyses of a global system of Volcanic Ash Advisory Centers. Working with volcanic observatories, these centers disseminate information on atmospheric volcanic ash clouds that may endanger aircraft. In addition, if aircraft accidentally fly into an ash cloud, pilots are now trained in what to do at the first sign of engine failure. Pilots will turn around the plane to fly out of the eruption cloud and try to cool the engines by idling. With engine cooling, the glassy coating will break off, thus preventing total engine failure.

FIGURE 17-32 **A,** Eruption cloud from Rabaul Volcano, New Britain Island, Papua New Guinea, September 1994. Note the difference in appearance between the eruption cloud and ordinary meteorologic clouds. **B,** Aircraft damage after flying into an eruption cloud from Redoubt Volcano in Alaska, December 1989. *(**A** courtesy NASA, photo STS064-116-47; **B** courtesy Joyce Warren.)*

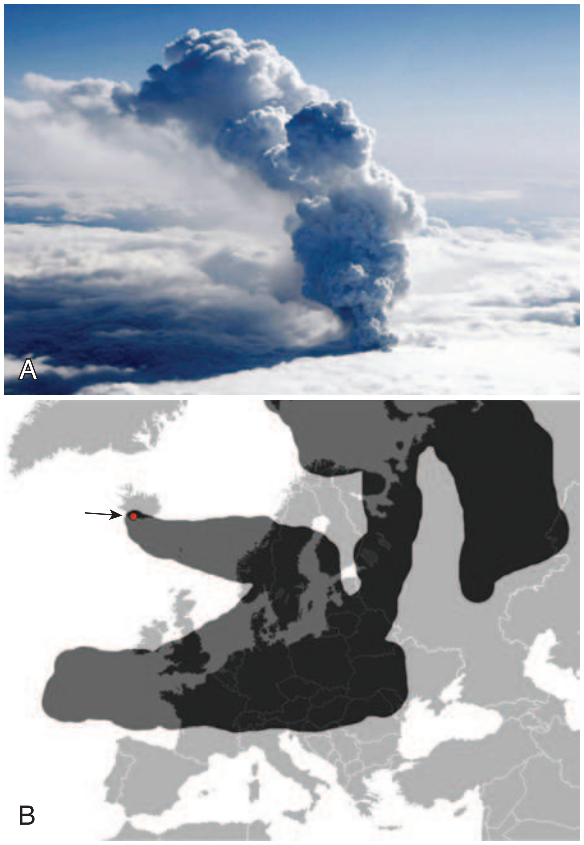


FIGURE 17-33 **A,** High-rising eruption cloud from the explosive phase of the ongoing eruption of the subglacial volcano Eyjafjallajökull in Iceland. **B**, The airspace of northern Europe affected by the drifting eruption ash cloud from Eyjafjallajökull Volcano (arrow, red dot). *(Courtesy UK Met Office.)*

FIGURE 17-34 Ash removal in Moses Lake, eastern Washington, after 1980 eruption of Mt St Helens. Keeping roofs clear of ash is not advised because of the risk of falling. *(Photographer unknown.)*

Volcanic Gases

Gases dissolved in magma can separate explosively or passively from the molten rock and can be discharged into the atmosphere. During an explosive eruption, 10 million to 1 billion tons of volcanic gases can be released into the atmosphere over a few hours to a few days. During noneruptive periods, gas can also escape continuously from fissures, geysers, and other sites of volcanic activity. The most abundant gas released from magma is water (H_2O) vapor. Second is CO_2, closely followed by SO_2. Carbon monoxide, hydrochloric acid, hydrogen, and hydrogen sulfide (H_2S) are other common gases released in appreciable quantities.[65] CO_2 and H_2S are by far the most dangerous. Because both are denser than air, they collect in low-lying areas and cause harm if inhaled by unsuspecting individuals.[60] CO_2 is an asphyxiant, and at concentrations higher than 20%, even a few breaths can very quickly lead to unconsciousness and death from acute hypoxia, severe acidosis, and respiratory paralysis. H_2S, the colorless gas that smells like rotten eggs, is so toxic that a high-level exposure can kill a human after a single breath.[66] H_2S, similar to cyanide, arrests cellular respiration and thus aerobic metabolism.

There are numerous accounts of fatalities associated with CO_2 emissions from volcanic activity. Perhaps the most lethal tragedy occurred in 1986 at Lake Nyos, Cameroon, when dangerous amounts of dissolved CO_2, once trapped in the lower levels of this volcanic crater lake, suddenly rose to the surface and were abruptly released, like champagne suddenly uncorked.[33] The gas rose 80 m (262 feet) before the CO_2 settled to the ground and rolled down valleys and into villages up to 20 km (12 miles) away, instantly suffocating 1746 people and 3000 livestock. Survivors suffered transiently from burns, headache, nausea, vomiting, cough, dyspnea, hemoptysis, and chest pain (Figure 17-35).[1] Only 2 years earlier, at nearby Lake Monoun, a similar but smaller cloud of CO_2 welled up from the lake, flowed downhill, and killed 39 people.[33] In Indonesia in 1979, a release of CO_2-rich volcanic gas from Sinila Crater (Dieng Plateau) killed 142 local inhabitants as they evacuated the area via a low-lying valley.[45] Less dramatically, CO_2 leaking from underground volcanic systems in Italy has been linked to the deaths of animals and two children. In the Mammoth Lakes region in eastern central California, accumulation of volcanic CO_2 trapped under snow may have contributed to the death of a cross-country skier as well as three ski patrol members.[12,32]

There are a few reports of H_2S-associated fatalities. Six downhill skiers on Kusatsu-Shirane volcano in Japan died in 1971, and four hikers who wandered into the lowest part of the summit crater on Adatara volcano in Japan died in 1997. Neither volcano

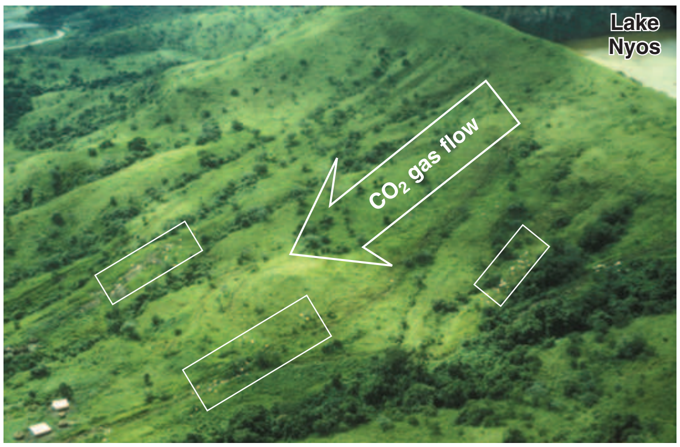


FIGURE 17-35 Village of Fulani downslope from Lake Nyos in Cameroon, Africa, where 25 people died from CO_2 poisoning in 1986. Clusters of white dots (*in rectangles*) on slope are dead cattle, also killed by the CO_2. *(Courtesy John P. Lockwood, U.S. Geological Survey.)*

was erupting at the time.[35,66] Chronic low-level H_2S exposure may also have deleterious health effects. In Rotorua, New Zealand, where 30% of the city's population lives downwind of an actively degassing geothermal field, preliminary findings indicated a spatial relationship between exposure and an increase in respiratory symptoms, especially in individuals with chronic obstructive pulmonary disease.[23]

An irritant to mucous membranes, SO_2 can induce respiratory distress and can adversely affect pulse rate and blood pressure, but it has never been proved to directly cause death.[2,46-48,66] However, in Japan, SO_2 emissions from Mt Oyama on the island of Miyake forced evacuation of Miyake's 3900 residents to the mainland from September 2000 to February 2005.[17] Since the return of residents to Miyake, despite ongoing SO_2 emissions, research has showed a relationship between SO_2 concentrations and acute respiratory symptoms such as cough, sore throat, and shortness of breath.[37] Similarly, there are no fatalities associated with hydrogen fluoride (HF), but indirectly, HF was responsible for the death of 10,000 Icelanders in 1783. HF from the prolonged Laki fissure eruption poisoned much of the pastureland and crops, causing the death of half the livestock and crop failure, which ultimately led to famine and death.[64-66]

Mitigation. Mitigating the danger associated with toxic volcanic gases depends on the type of gas and how it is released. Since the Lake Nyos disaster, scientists have placed 12 pipes into the lake at different depths to allow CO_2 to escape continuously rather than accumulating to dangerously high levels. Danger zones can be mapped and warnings signs posted. Equipment can be stationed to monitor gas emissions. Recreationists should be educated to avoid certain activities at times of gas release or buildup under snow. Low-lying areas where poisonous gases can collect should be avoided. Emergency medical personnel should remove victims from the source of toxic gases, place them on high-flow oxygen, and treat other injuries accordingly.

HAZARDS FROM NONEXPLOSIVE VOLCANOES

In general, nonexplosive volcanoes pose little direct danger to humans. Few fatalities are associated with them because lava usually flows slowly enough for people to avoid it.[4,5] Generally, those who have died either lingered to watch the lava or returned to their homes too early. On the other hand, rivers of lava can cause significant property damage as they set fire to, knock down, or bury buildings and roads. On rare occasions, flows of low-viscosity lava have been witnessed to travel down steep slopes at speeds as high as 100 km/hr (62 miles/hr).

Lava Flows

Fatalities associated with lava flows account for only about 0.3% of total deaths from volcanic activity. The most deadly lava flow took place at Mt Nyiragongo, Congo.[4] Nyiragongo is among the few volcanoes with an active lava lake inside its summit crater, and during an eruption in 1977, this lake suddenly drained through fissures in the crater wall. A very fluid lava flow, estimated to be traveling at 100 km/hr (62 mph), swiftly engulfed small towns, killing hundreds of people.[4,58,65,66] In 1947, a scientist filming a lava flow at Mt Hekla in Iceland was killed by a glowing lava block rolling downslope.[10] Other hazards include methane-fueled explosions when lava overruns vegetation, and explosions or scalding steam when lava flows over ice or snow or into water (Figure 17-36).[66]

Mitigation. Because lava flows rarely pose a significant health hazard during volcanic activity, they are not a high priority for health planning.[60] However, to limit property damage, lava flow diversion is a possibility. In 1973, after 6000 years of inactivity, Eldfell volcano on the island of Heimaey in Iceland reawakened and lava poured out, threatening the most important port of the Icelandic fishing industry. To stop or divert the lava flow, cold seawater was sprayed onto the advancing lava front, and after 2 weeks of nonstop work, the port was saved.[65,66] Other attempts at diversion, including building rock and dirt barriers, and aerial bombings,[79] have not been successful. Health care professionals should be prepared to treat burns from contact with lava or scalding steam.

FIGURE 17-36 A rapidly advancing lava flow from Puu Oo vent, Kilauea Volcano, Hawaii, engulfs vehicles. *(Courtesy Robert W. Decker, U.S. Geological Survey.)*

Jökulhlaups

A jökulhlaup is a large outburst flood associated with eruption of a subglacial volcano. The heat from the volcano melts overlying ice, forming a subglacial lake. As the lake rises, the overlying glacier is lifted and begins to melt, forming a subglacial river. If this river bursts to the surface, disastrous flooding can occur. When this happened in 1996 from a subglacial eruption at Grímsvötn in Iceland, water escaped from a 3.5-km (2.2-mile) crevice at a maximum rate of 45,000 m^3/sec (12 million gal/sec) to form, temporarily, the second-largest river on Earth.[66] Miles of road and bridges were destroyed. A smaller jökulhlaup emerged in November 2004 from volcanic activity at Grímsvötn, with a peak discharge of up to 4000 m^3/sec (1 million gal/sec), but this time no roads or bridges were destroyed.[75] In 2010, jökulhlaups of the Eyjafjallajökull eruption (see Figure 17-19C) caused substantial destruction of roads and infrastructure locally, but fortunately no deaths or injuries.

POSTERUPTION HAZARDS

Major eruptions can be hazardous long after the eruption is over. Large quantities of gas released into the atmosphere can cause air pollution, produce acid rain, and deplete ozone, possibly affecting global climate for a few years.[4] Water supplies can be contaminated and crops destroyed, leading to disease epidemics and famine.[3] Moreover, overcrowding and poor sanitation conditions, commonly associated with temporary evacuation camps, pose health hazards and sometimes lead to disease epidemics. After the eruption of Mt Pinatubo in June 1991, a measles outbreak, diarrhea, and respiratory infections resulted in the death of hundreds of children from an isolated tribe forced to live in evacuation centers.[25] Ongoing smaller eruptions, such as the continuing (since 1983) nonexplosive activity at Kilauea Volcano, can also cause problems related to sustained volcanic gas emissions[80] (Figure 17-37). In Italy, Mt Etna is the largest continuous source of volcanic SO_2 globally, and Stromboli is probably the second largest in Europe.[22]

During the 8 months that the Laki fissure in Iceland was erupting in 1783, at least 122 million metric tons (MT) of SO_2, 7 MT

FIGURE 17-37 The ongoing eruption of Kilauea's east rift zone (which began in 1983) has put a huge amount of natural pollutants, including sulfur oxides, into the air. Introduced vegetation, such as Kona coffee plants, can be scorched, and downwind of Kilauea, only native species tolerant of the natural acid rain survive. The two images compare atmospheric clarity between a volcanic-smog (vog)–free day (**A**) and a heavy-vog day (**B**). *(Courtesy Jeff Sutton, U.S. Geological Survey.)*

of hydrogen chloride, and 15 MT of HF were released into the atmosphere.[84] HF poisoned most of Icelandic sheep and destroyed crops, contributing to the death of nearly a quarter of Iceland's entire population from famine.[64] In addition, the Laki eruptions were probably responsible for the death of more than 10,000 people in England during summer 1783 and winter 1784. Noting that the mortality rate was 16.7% above normal for this time period, experts in the United Kingdom suggest that a cloud of volcanic gases and particles swept south from Laki into England and was responsible for the very hot 1783 summer and subsequent severe winter.[64,84] Climatic data, burial records, and written accounts describe a summertime "volcanic haze" or "dry fog" that shrouded the moon and sun, reduced visibility, withered vegetation, and caused health problems.[22,64] As with smog, the dry fog caused headache and eye irritation, exacerbated lung disease, and irritated mucous membranes. Wintertime deaths were associated with unusually cold temperatures. Benjamin Franklin, U.S. ambassador to France in Paris at the time, was the first to link the effect of Laki's eruption on climate and presented a scientific paper on the topic.

Eruption clouds that penetrate the upper atmosphere can spread volcanic particles and gases across an entire hemisphere.[66] During the 3 months it can take fine ash particles to settle out, solar heating is reduced and the lower atmosphere is cooled. The 1991 eruption of Mt Pinatubo in the Philippines created a large volcanic cloud that drifted around the world and caused a temporary average global temperature drop of 0.5°C (0.9°F).[40] The largest eruption in recorded history in 1815 at Tambora, Indonesia, reduced the average global temperature by 3°C (5.4°F) for several years.[40] This eruption directly or indirectly caused the death of an estimated 60,000 people in Indonesia and was responsible for a typhus epidemic in Great Britain, cholera in India, and mass migration from northern Europe and Russia. It ruined farms in New England and spurred westward migration.[66] The greatest eruption since humans evolved was that of Toba in Indonesia, about 74,000 years ago. The global temperature dropped 5°C (9°F) for many years, causing a global environmental catastrophe. It may have resulted in an estimated decrease in the population of *Homo sapiens* from over 100,000 to less than 2000.[66]

Some volcanic soils may also pose a health risk. Nonfilarial elephantiasis, otherwise known as podoconiosis or mossy foot, appears to be caused by chronic exposure of unprotected feet to irritant alkalic red-clay soils rich in volcanic particles. Microscopic particles absorbed through abrasions in the feet penetrate the lymphatic system, causing inflammation, lymphatic fibrosis, and ultimately blockage. As the lymphatics are obstructed, the lower extremities swell, resulting in elephantiasis. Podoconiosis is predominantly found in high-altitude areas (>1250 m [4101 feet]) of tropical Africa, Central America, and North India.[18-20,56,82,85] Fluoride leached from volcanic rocks into drinking water can also cause disease. In eastern Turkey near Tendurek Volcano, mottled enamel from high levels of fluoride, called endemic dental fluorosis, has been observed in humans and livestock since the 1950s.[59]

Several studies have suggested people living near volcanoes may be at increased risk for developing thyroid cancer.[9,21,27,42,61,62] Epidemiologic surveys conducted in Italy, Iceland, Hawaii, and the Philippines report increased incidence of thyroid cancer in volcanic areas. However, the specific carcinogenic agent has yet to be identified; suspects include toxic air pollutants, a pollutant in volcanic soil or volcanic aquifers, and volcanogenic radiation.

RISK REDUCTION FROM VOLCANIC HAZARDS

Humans are vulnerable to severe, unpreventable volcanic eruptions. Risk reduction starts with comprehending the seriousness of volcanic hazards and being prepared for the associated dangers. Almost 99% of fatalities associated with volcanic eruptions are from pyroclastic flows and lahars, yet one-tenth of the world's population lives in cities and homes near volcanoes, sometimes on the volcano slopes or on the remains of a previous pyroclastic flow, lahar, or debris avalanche.[60,66] Fortunately, most volcanic eruptions are preceded by premonitory events, such as earthquakes and other measurable phenomena, far enough in advance to enable scientists and emergency workers to plan for disaster. However, a few of the most severe eruptions have occurred with little or no warning, and most of the world's dangerous volcanoes are in densely populated countries that lack the resources or political interest to monitor them.[5,79]

Nevertheless, emergency planning for an eruption, including creation of hazard-zone maps and hazard evaluation, should be routine for all populated areas near volcanoes, regardless of their location or apparent state of activity.[5] Risk reduction includes volcano monitoring, eruption prediction, and effective coordination between volcanologists, scientists, health care professionals, and the community at risk. In addition, with tourism increasing to volcanic destinations, the tourist industry, practitioners of travel medicine, and adventure travelers need to educate themselves and others about the potential health hazards of volcanic environments.[29]

VOLCANO MONITORING

Scientists monitor volcanoes for seismic activity (earthquakes), changes in volcano shape (ground deformation), surface temperature, magma level, gas emissions, and other chemical and physical attributes (Figure 17-38).[57] Earthquakes and ground deformations are the most reliable diagnostic observations for helping scientists predict when a volcano might erupt or when

FIGURE 17-38 U.S. Geological Survey scientists sampling volcanic gases within the Mt St Helens crater. *(Courtesy Kathy Cashman, University of Oregon.)*

it is no longer likely to erupt.[52,78] The importance of monitoring cannot be overstated. During the last half of the 20th century, most eruptions from monitored volcanoes were anticipated weeks or months in advance. These include the eruptions of Mt St Helens in 1980 and 2004 and Mt Pinatubo in 1991 (see next). Often, the problem is not predicting when the volcano will erupt but convincing government officials to act on the warning. Before 1985, authorities in Armero, Colombia, were warned that lahars could devastate their town, but the warning was disregarded, and the eruption at Nevado del Ruiz and the subsequent lahars destroyed the town and killed more than 25,000 people.[66]

ERUPTION PREDICTION AND MT PINATUBO: EFFECTIVE VOLCANIC-EMERGENCY RESPONSE

In April 1991, the Philippine volcano Mt Pinatubo began to erupt, weakly, for the first time in recorded history. Ultimately, the activity escalated into the world's largest eruption in the preceding eight decades. However, only 300 people were killed, even though at least 600,000 people lived in cities, villages, and military bases around the volcano. The larger tragedy was prevented by effective cooperation between local authorities and scientists of the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and the U.S. Geological Survey (USGS).

Two months before the climactic eruption on June 15, PHIVOLCS consulted the USGS's Volcano Disaster Assistance Program (VDAP), a mobile volcano-response team (i.e., an eruption SWAT [special weapons and tactics] team) of experienced volcanologists and other scientists who rapidly respond to a developing volcanic crisis with state-of-the-art portable monitoring equipment (Figure 17-39). The request for assistance came after an increase in the number of earthquakes (up to 500 per day), explosions, and new cracks opening in the volcano. The VDAP team set up a base camp at Clark Air Force Base and began to monitor and interpret seismic activity, ground deformation, and gas emissions. They also gathered data about Pinatubo's previous eruptions to predict the types of hazards that could be expected and to create a map of the area, delineating zones at risk during an eruption. Finally, the PHIVOLCS-USGS team worked with local authorities to develop an evacuation plan and educate people. A 30-minute video, *Understanding Volcanic Hazards,* produced after the tragedy of Armero, Colombia, in 1985, was shown to local officials and populations to raise awareness of hazardous volcanic processes.

On June 7, a month and a half after the USGS team arrived, a warning was sent out about a possible major eruption within 24 hours. Villages and cities were evacuated. Five days later, the first in a series of powerful explosive eruptions began. An eruption cloud rose 19 km (12 miles) into the air, and small pyroclastic flows started down to the north and northwest. Additional eruptions took place over the next 2 days. On June 15, a cataclysmic eruption took place during a typhoon. The eruption cloud rose 12 km (7.5 miles) into the atmosphere and spread out like an umbrella more than 200 km (124 miles) in all directions. Wet ash covered a 4000-km^2 (1544-square-mile) area, burying crops and collapsing roofs, and many destructive lahars were generated.[16] Ash fell as far away as the Indian Ocean. The warning saved at least 5000 lives and prevented extensive property damage.

COORDINATION BETWEEN VOLCANOLOGISTS AND HEALTH CARE PROFESSIONALS

Coordination among geologists, other scientists, and health care professionals is essential to prepare communities for volcanic emergencies. Planning for future eruptions requires determining the history of a volcano's past eruptions and their impact, developing a hazard-zone map, anticipating when a volcano might erupt, and describing the types of hazards to be expected and their potential effects on health (Figure 17-40). Furthermore, health care professionals need to identify high-risk populations, prepare for disaster victims, and help volcanologists educate the community about potential health effects for each volcanic hazard.[57] Evacuation of communities, especially in low-lying areas and river valley regions, is of utmost importance. Goggles and masks should be distributed, especially to individuals who must work in dusty conditions.

FIGURE 17-39 Volcano Disaster Assistance Program "SWAT" team lands near Rabaul Volcano, Papua New Guinea, in 1994. *(Courtesy Elliot Endo, U.S. Geological Survey.)*

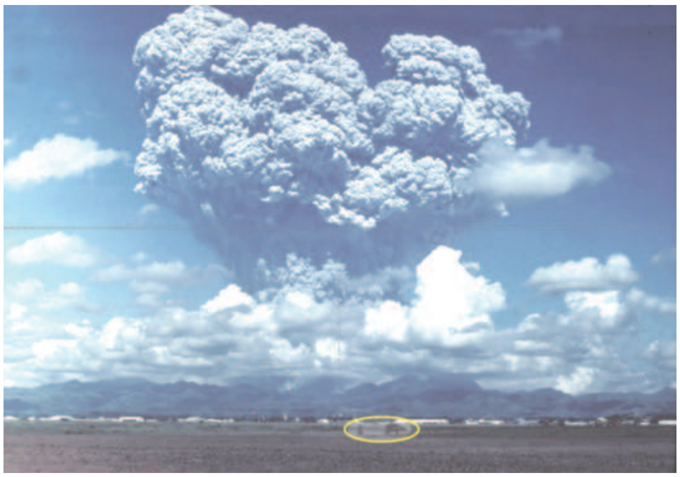


FIGURE 17-40 First of a series of powerful explosions beginning on June 12, 1991, Pinatubo Volcano, Philippines (see text); note within the yellow oval a farmer and buffalo plowing. *(Courtesy David Harlow, U.S. Geological Survey.)*

TABLE 17-5 Casualties Caused by Pyroclastic Flows in 20th-Century Explosive Eruptions

Eruption	Year	Deaths (*N*)	Ratio of Dead to Injured	Survivors after Treatment
Montagne Pelée, Martinique	1902	28,000	230 : 1	163 treated, 123 survived
La Soufrière, St Vincent	1902	1565	11 : 1	194 treated, 120 survived
Taal, Philippines	1911	1335	10 : 1	Not known
Lamington, Papua New Guinea	1958	2942	44 : 1	70 treated, 67 survived
Mt St Helens, United States	1980	58	16 : 1	130 airlifted, 9 treated, 7 survived
Unzen, Japan	1991	43	5 : 1	17 treated, 4 survived (minor burns)
Mt Merapi, Indonesia	1994	63	3 : 1	86 treated, 11 dead on arrival
Soufrière Hills, Montserrat	1997	19	4 : 1	7 treated, all survived

From Baxter PJ: Impact of eruptions on human health. In Sigurdsson H, Hougthon BF, McNutt SR, et al, editors: *Encyclopedia of volcanoes*, San Diego, 2000, Academic Press.

EMERGENCY MEDICAL RESPONSE

Emergency medical care plays a small role in severe volcanic eruptions. The number of injured who could benefit from treatment is much smaller than the number of victims killed within minutes of a catastrophic eruption (Table 17-5).[5] Therefore, prevention is of utmost importance, and evacuation is the key to decreasing morbidity and mortality.[5] Health care professionals should be prepared to treat a variety of medical problems in persons who survive (Box 17-2), and they must be aware that access to victims will be limited by high-level ash conditions, burial beneath volcanic debris, and ongoing hazards. Transient increases in ED visits and hospital admissions will require additional resources.[8]

GEOTOURISM

With the increased interest in visiting volcanic environments, the numbers of injuries and illnesses are increasing. Areas such as Hawaii Volcanoes National Park have experienced a high rate of injuries and illness because of inexperienced hikers entering high-risk environments and disregarding warning signs.[30] People working or traveling near an active volcano or volcanic environment should heed these safety recommendations:

- Read about the volcanic environment, including past eruptions and accidents.
- Know the current volcano warning level, and obey local authorities.
- Travel with a guide experienced in local conditions.
- Leave travel details with a responsible person.
- Wear a hard hat and carry a gas mask, if appropriate.
- Beware of the sources of danger on a volcano:
  Rock falls
  Avalanches
  Hazardous gases
- Look for warning signs of an eruption.
- Immediately leave the area if it becomes dangerous.
- Do not approach lava flowing through vegetation.

BOX 17-2 Summary of Health Effects from Volcanic Eruptions

Physical

Blunt trauma from pyroclastic material, lahars, debris avalanches, tsunamis, and tephra
Burns, wounds, and gangrene complications
Asphyxiation from lack of oxygen or inhaled ash
Acute irritation of the respiratory tract caused by ash
Exacerbation of prior respiratory disease caused by inhaled particles
Respiratory tract and lung burns caused by inhalation of hot steam
Conjunctivitis and corneal abrasions
Toxic effects of gases such as CO_2, H_2S, SO_2, HF, CO, and radon
Gastroenteritis
Skin irritation from acid water
Drowning in lahars or tsunamis

Psychological

Depression
Anxiety
Nightmares
Psychomotor disorders
Irritability
Insomnia
Confusion
Neurosis
Stress

Modified from Zeballos JL, Meli R, Vilchis A, et al: The effects of volcanoes on health: Preparedness in Mexico, *World Health Stat Q* 49:204, 1996.
CO_2, Carbon dioxide; *CO*, carbon monoxide; *HF*, hydrogen fluoride; *H_2S*, hydrogen sulfide; *SO_2*, sulfur dioxide.

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