Chapter 1: INTRODUCTION

Richard G. Gann, Ph.D.
National Institute of Standards and Technology

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1.1 BACKGROUND

In its decade of research (1997-2006), the United States Department of Defense's Next Generation Fire Suppression Technology Program (NGP) revitalized the field of fire suppression science. The NGP arose as a result of a discovery that garnered the Nobel Prize for two accomplished chemists and legislation that turned science into public policy. This book tells the story of how the NGP came about, what research was performed, how it modernized the thinking in the field, and the technical findings that emerged related to fire suppression in aircraft.

1.2 THE EVOLUTION OF FIRE SUPPRESSION

The ability to control fire is universally and exclusively human. The history of that controlled use is also the history of civilization.[1] While individuals likely recognized the first principles of fire control, it was the rise of organized societies that led to structured activities and, later, products to mitigate the unwanted outcomes of fires. Now, the application of chemicals, manually and by mechanical devices, to control fires has become a mainstay of modern society. In particular, the development of the use of fire suppressant chemicals has a rich history.[2]

There is geologic evidence of fires as far back as there is evidence of vegetation on this planet, about 350 million years ago. The fires were started by frequent natural events, lightning strikes and volcanoes, and this was still the case when the first hominids appeared, some 3 million to 5 million years ago.

In the earliest years, small nomadic groups of these pre-humans observed the nature of fire. While they could see its destructive power, they soon recognized its benefits as well. They saw that animals ran from it, and thus it became a tool for trapping food. They found that animals and nuts that had been exposed to the flames were easier to eat. They enjoyed the radiant warmth from the fire on cold nights. They no doubt observed that rain made the fires stop, and some might have even noticed that there were few fires following a rainstorm. By about 400,000 years ago, the sparse nomadic clusters of homo erectus had learned how to "capture" fire and use it for their own purposes, both domestic and martial. Since the initial source of this benefactor occurred only episodically, they spent considerable effort to keep the fire from going out. A few burns and the occasional loss of a temporary dwelling was a small price to pay for its continuous availability.

The number of humans and their standards of living accelerated about 20,000 to 30,000 years ago, toward the end of the last glacial age. Over the next 10,000 years, the ability to use fire for clearing land for agriculture and capturing livestock engendered the rise of towns. Further amenities became available as fire was used to bake clay pots (about 20,000 years ago) and later (about 7000 years ago) to work with metal. It would be time for the appearance of codes to preserve these more permanent communities.

The first written records, about 5,000 years ago in Mesopotamia, made little mention of fire.[1] It is thus presumed that there was little concern for its use or misuse. Perhaps this was because all members of a family were well versed in the art of using fire, preserving it, and regenerating it when needed. It is noteworthy that there were two types of words for fire: one for intentional fires, another for dangerous ones. However, the hazard of a house fire was not regarded as paramount. Buildings were small and generally constructed of stone or mud brick, since these materials were readily available. With the small number of people and the ready availability of land, the dwellings were not tightly spaced. If a fire started, the interior wood framing (if any), the thatched roof, and the contents were lost, since there was little water available to quench the flames. Attempts to protect neighboring houses depended on wet cloths and a limited number of buckets of water. People had long since learned the use of firebreaks for clearing land intentionally, and these were used to contain fire spread in the residential clusters. The Code of Hammurabi (about 1780 BC), a collection of rules for everyday life that also reflected the serious crimes of the era, had no mention of fire prevention or arson. However, theft of goods during a fire was punishable by death in that fire. The first mention of an arson penalty (full reparation) appears in the laws of the Hittites, some 100 years to 600 years later, but there was still no text on controlling fires. In short, destruction by fire was not the most severe threat facing these early communities, and their only weapon against it, water, was not plentiful on short notice.

The citizens of Rome appear to have had the first formal building code for fire safety, and the Roman penchant for engineering provided a supply of water to attack fires.[1] The code required that houses could not be built too high, separations of at least 2½ feet, and means of escape. Tenants were often required to have a bucket of water in their flats, and intentional fires within those flats were often forbidden. Nonetheless, over 40 large conflagrations were recorded between 31 BC and 410 AD, including the famous fire in 64 AD during which the emperor Nero supposedly fiddled while one third of the city was destroyed. The city of Rome also had an official fire brigade and, because it was unable to cope with its charge, several private brigades arose as well. These featured intensive patrols to catch fires early and bucket brigades with access to the city's superb aqueduct system. Of course, virtually none of this existed in the Empire outside of the capital city.

Pre-industrial Europe continued to have numerous major urban conflagrations even past the Middle Ages (e.g., London, 1212; Venice, 1514; London, again, 1666; Rennes, 1720).[1] Most urban construction was now of wood and clay, which were cheaper than stone and brick. This was the era when the latter began to connote wealth, in large part due to the ability of the rich to afford fire safety. Buckets of water were still the only major means for stopping fire spread. In urban areas, legal measures were often instituted to bolster this limited capability. In the event of a fire, people were to leave the building and sound the alarm immediately; there were severe fines for removing their possessions first.

In the rural areas, fire control reflected an earlier time. The crime of arson, resulting from a grudge or as a threat to extort money, was considered second only to murder in severity and was punished accordingly.

An enabling breakthrough in fire suppression came in the late 17th century, with the invention by Jan van der Heyden of Holland of the rollable fire hose. In 1725, Richard Newsham of London patented an improved pump design that could take advantage of van der Heyden's hoses. Soon a variety of hand pumps were devised to move water (still the suppressant of choice) efficiently from a city reservoir to the fire. During the Industrial Revolution in the mid-nineteenth century, these pumps became combustion-powered.

Nonetheless, for the remainder of that century, large city fires continued to be a problem (e.g., Hamburg, 1842; Newcastle, 1854; Chicago, 1871; Boston, 1872). Life loss was significant, as city population densities rose and the buildings became taller, wider, and more densely situated. The San Francisco fire of 1906 was the "last" of the major urban conflagrations. This diminution is attributed to the rise of brick, concrete and steel for urban construction, the spreading of residences (e.g., detached houses with yards), and general adoption of improved fire fighting technology and procedures. Water continued to be the only suppressant.

The scientific and technologic revelations of the 18th and 19th centuries led to new capabilities for the control of fires. In particular, James Watt's invention of the steam engine in 1769 led to two major innovations. In 1812, William Congreve received a patent for a steam-driven, perforated pipe water distribution system. In the middle of the century, the fusible link and self-opening valve were added, making the system fully automatic. In 1852, Moses Latta produced the first steam-powered, self-propelled fire engine, and the first commercially successful ones followed in 1867. Now there were ways to bring water, still the predominant suppressant, to the fire. It thus became possible to react in time to save a complex commercial or residential structure and many of the people within. The installation of the first automatic sprinklers in the U.S. and England in the late 19th century began bringing the water directly into the building.[3] This provided faster response and further containment of the fire damage. What remained was the development of technology to assure the safety of the contents.

1.3 THE RISE OF THE HALONS

Just after the turn of the 20th century, another scientific advance stimulated just this capability. The prior years had produced breakthroughs in the understanding of the electrical behavior of solutions. Now, a process for the electrolysis of salt water enabled a large supply of inexpensive chlorine. This was used to make carbon tetrachloride (CCl_4), which soon came into use as a fire suppressant.

CCl_4 was the first clean agent; that is, unlike water, it caused no damage to a building or its contents and left no residue itself. It was also the first halon, halon 104 (see below). Like water, it was what is now called a streaming agent, i.e., it was squirted at the fire or was thrown at the fire in frangible containers, called grenades. However, concerns soon arose about its toxic effects on firefighters and others at the fire scene. The chemical had briefly seen use as an anesthetic, a practice that stopped when it was found that the difference between the amount which produced unconsciousness and that which produced death was small.[4] There was also an awareness of interaction with the large amounts of alcohol that firefighters consumed often before, during, and after their efforts at the fire scene. Nonetheless, the use of carbon tetrachloride continued through World War II, in which it was used extensively.[5]

By this time, the chemical similarities of the elements within a column in the periodic table were well known, and soon the neighboring halogen, bromine, was also considered as a possible component of fire suppressant compounds. Methyl bromide (halon 1001) appeared in the 1930s in the U.S., but did not find much acceptance, since it was found to be more toxic than CCl_4. The Germans developed and used chlorobromomethane (halon 1011) as their clean suppressant of choice during World War II. It was more efficient than halon 104, and after the war it found broad use elsewhere.[5]

Recognition of the need to consider agent toxicity was another milestone in the evolution of fire suppression technology. The drawbacks of water had been operational in nature, e.g., mechanical hurdles to overcome in its bulk transport to the fire, damage to building contents. Now the suppressant itself would need to be examined for its possible effects on fire fighters and building occupants. Clearly, the value system of this era appreciated the benefits of these new halogenated agents in protecting property and people. Some selection from among the effective halocarbons was in order, and toxicity was the new criterion on the list.

In 1948, the U.S. Army commissioned the Purdue Research Foundation to search for a suppressant of high fire suppression efficiency but low toxicity.[6] The Army coined the term "halon," short for halogenated hydrocarbon, and devised the naming system that shows the numbers of the types of atoms in the molecule in the order: carbon, fluorine, chlorine, bromine, iodine (terminal zeroes dropped). During the 1960s and 1970s, two of the compounds tested emerged as commercial successes. Halon 1301 (CF_3Br) found widespread use as a total flooding agent; i.e., it dispersed throughout a space, quenching flames regardless of location. (To a lesser extent, halon 2402 ($C_2F_4Br_2$) was used in this capacity, mainly in the Soviet Union and Italy.) Halon 1211 (CF_2ClBr) became the predominant streaming agent.

As the use of these chemicals increased, there were additional research, testing, and assessments performed, for example:

- In the 1960s and 1970s, extensive engineering studies developed information needed to design systems for implementation of the halons.[5]
- In 1966, the National Fire Protection Association established the Halogenated Fire Extinguishing Agent Systems Committee. In 1973, NFPA issued Standard 12A for halon 1301 systems and Standard 12B for halon 1211 systems. Much of the data to support these standards came from research and testing conducted at industrial laboratories, such as Factory Mutual, ICI, and DuPont.[5,7]
- In the 1970s, research at the U.S. Bureau of Mines[8] was directed at obtaining a better understanding of the mechanisms of halon 1301 that could guide its use as a suppressant for methane explosions in mines. At the U.S. Naval Research Laboratory[9], related fundamental research on halon 1301 was sponsored by the Naval Air Systems Command as part of a search for a more efficient extinguishing agent for in-flight fires.
- In 1972, the U.S. National Academy of Sciences held a Symposium to examine the state of knowledge on the toxicity and engineering applications of the halons.[10] The purpose was to provide "an up-to-date basis for intelligent selection of which, if any, of the halogenated agents should be used in a given set of circumstances." A summary of that symposium indicated that the halons were effective fire extinguishment agents, with the degree of

effectiveness depending greatly on the application. There was an awareness of toxicological risks from exposure to both the halons themselves and their decomposition products that were formed during the application of the chemical to the fire.

- In 1975, a symposium was held to examine the basic processes occurring in flames inhibited by the halons, leading to the inference of the mechanisms of flame suppression.[11]

Halon 1301 had turned out to be very efficient at quenching fires, as shown in Table 1–1. Because of the small amount needed, because it did no harm if deployed accidentally, and because it could put fires out before any significant damage occurred, halon 1301 systems were increasingly installed to protect contents of special value and spaces in which storage weight and volume were at a premium. By the 1980s, most computer rooms, nearly all commercial and military aircraft, and numerous museums were protected by these halon systems. As a footnote, their acceptance signaled the end of the use of CCl_4 as a fire suppressant, a prophetic result, as it was later determined that carbon tetrachloride was a carcinogen.

Table 1–1. Flame Suppression by Halon 1301 and Other Chemicals (volume %).

Flame/Fire	Halon 1301	HFC-227 ea	Carbon Dioxide
Small diffusion flame	3.1[12]	6.6 [12]	21 [13]
Pool Fire (10 s extinguishment)	4 [12]	8 [12]	--
Wood	3.0 [5]	5.8 [14]	--
Fiberglass/polyester resin	3.5 [5]	--	--

1.4 THE ATMOSPHERIC THREAT

In 1974, F. Sherwood Rowland and Mario Molina published a paper showing that certain chlorinated compounds (chlorofluorocarbons, or CFCs), while playing beneficial roles as, e.g., coolants and solvents, posed a threat to the global environment. These compounds had long lifetimes in the earth's lower atmosphere, or troposphere. Eventually, they would rise to the stratosphere, where they were readily photodissociated by short wavelength ultraviolet (UV) light. There, the chlorine atoms aggressively catalyzed the conversion of ozone, which absorbed solar UV light and protected the earth's flora and fauna from excessive UV radiation, to ordinary oxygen, which provided no such protection. Unchecked, this could result in major changes in life on the planet.[15] Subsequent atmospheric measurements and modeling showed that the threat was real. Rowland and Molina were awarded the Nobel Prize in Chemistry in 1995.

The nations of the world moved toward an international agreement to protect the environment, the Montreal Protocol on Substances That Deplete the Ozone Layer.[16] As the agreement was being forged, it was realized that some brominated compounds were potentially even more dangerous than their chlorinated cousins,[17] and the halons (with the name mistakenly used to mean only brominated and chlorinated perhalocarbons) were named explicitly. Their production was curtailed sharply in amendments to the U.S. Clean Air Act of 1990. As of January 1, 1994, under the 1992 Copenhagen Amendments to the Montreal Protocol, halon 1301 was banned from production, except in certain developing countries and countries whose economies were in transition.

The dense and growing population had been informed of a threat on a global scale, and the nations of the world had clearly decided that fire safety must be weighed against other cultural values. For the fire safety community, this was a new paradigm. The prior bounds on saving lives, property and the community had generally been local: budgets limitations, interferences with other social amenities, etc. Now, the protection of the planet as a whole took priority over local safety, which presumably could be provided in some other manner.

Even as the search for alternative fire suppressants was underway, usage was declining markedly. Major releases of the halons were from firefighting training, fire extinguishment system testing, and leakage from the storage containers. By the early 1990s, alternatives for training and testing had been identified. There were also approaches to fire protection that did not rely on clean agents, e.g., a number of facilities converted to automatic sprinklers. In some cases, fire suppression became unnecessary. For instance, with small and inexpensive computers able to do much of the work previously done by large mainframe units, it was less costly to back up the computer than to provide fire protection.

Halon 1301's exceptional performance and success over the years had resulted in minimal research into alternatives for fire suppression. After a period of bewilderment, denial, and indecision following the 1987 Montreal Protocol, manufacturers and users of the halons began searching for safe replacements and alternatives. The early solutions were identified during the quest for replacement refrigerants, a far larger commercial market. Some of these, such as the hydrochlorofluorocarbons (HCFCs) were ozone depleters themselves and were soon generally disregarded as fire suppressants. An early brominated compound, CHF_2Br (halon 1201), was found to have a fire suppression efficiency comparable to halon 1301, but even though its ODP value was far lower than that of halon 1301, it was above that permitted by the U.S. Clean Air Act. For a variety of applications, chemical manufacturers began increased production of hydrofluorocarbons, or HFCs, which had no bromine or chlorine atoms and thus zero ozone depletion potential (ODP) values.[i,18] These were far less effective fire suppressants, but appeared to have no harmful atmospheric effects. Other commercial products included mixtures of inert gases, also less efficient suppressants, and blends of halocarbons.

The U.S. Department of Defense (DoD) had come to rely heavily on halon 1301 systems, in particular, for fire protection in its numerous ground, sea, and air systems, as shown in Table 1–2.[19]

These uses encompass a wide range of fire conditions. The locations vary in size, shape, function, and whether or not they are populated. The fuels are solids, vapors, and liquids; the latter burning as pool fires or sprays. The required time for suppression ranges from hundredths of a second to tens of seconds. In some cases, the agent must be "clean" and in others, not. The hazards to be avoided include harm to people, thermal damage to equipment, post-fire corrosion, loss of visibility, and overpressure. Finding a "one-size-fits-all" fire suppression approach to replace halon 1301 was highly improbable.

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[i] The ozone depletion potential of a gas is defined as the change in total ozone per unit mass emission of the gas, relative to the change in total ozone per unit emission of CFC-11 ($CFCl_3$).

Table 1–2. Use of Halon 1301 in Fielded Weapons Systems.

	Army	Navy	Air Force
Ground Armored Vehicles	Crew compartments Engine compartments	Crew compartments Engine compartments	
Shipboard	Maritime craft	Propulsion machinery Flammable liquid storerooms Fuel pump rooms Emergency generator rooms	
Aircraft	Engine nacelles APU compartments	Engine nacelles Dry bays Fuel tanks Crew compartments	Engine nacelles Dry bays Fuel tanks Weapon bays Cargo bays
Facilities	Communications shelters	General facilities	General facilities
Hand-held Extinguishers	Air/ground/maritime		Multiple uses

The U.S. Department of Defense was, and continues to be, committed to reducing its dependence on halon 1301 and made great strides in this direction by eliminating non-essential uses, totally revamping its fire suppression system testing, certification, and recycling procedures, and replacing halon systems with alternative technologies where possible. Nonetheless, there remained some applications where no substitute chemical or system was judged satisfactory, and several others where the identified alternatives were saddled with serious deficiencies. One of these applications was for military aircraft, which were particularly vulnerable to fire during combat and also needed in-flight fire protection during routine missions, a need shared by the commercial fleet. Further research would be needed to identify effective alternate fire suppression technologies.

The DoD delineated its policy on halon replacement research early in 1989.[20] The Directive stated that:

- DoD Components "... shall conduct R&D to identify or develop alternate processes, chemicals, or techniques for functions currently being met by CFCs and halons;"
- The Director, Defense Research and Engineering (DDR&E) "... shall coordinate R&D programs, as appropriate, on alternative chemicals or technologies for fire and explosion suppression and, if necessary, other CFCs;" and
- The Military Departments and Defense Agencies "... shall conduct R&D programs, as needed, to support mission requirements, with emphasis on substitutes for halons."

From 1993 to 1998, the DoD conducted a major program on ozone-depleting substances (ODSs), the Technology Development Program (TDP). It focused on the identification of near-term, environmentally friendly, and user-safe alternative fluids, developed by industry, that were either readily available or could enter commercial production in the near future. The TDP research was successful in identifying replacements for the non-firefighting ODSs.

However, despite the examination of a wide range of chemicals in the laboratory and at real scale, none of the available alternatives offered all the needed properties of halon 1301. The best available replacement chemicals were two HFCs: C_2F_5H (HFC-125) onboard aircraft and C_3F_7H (HFC-227ea) for shipboard use.[21] These were substantially less efficient fire suppressants and thus required two to three times the mass and storage volume relative to halon 1301. This would severely compromise their implementation, given the tight weight and space limitations. In addition, their use would result in a post-deployment atmosphere containing appreciable concentrations of acid gases, that was not suitable for human occupancy, and that could chemically attack metals, synthetic materials, and electronics. Nonetheless, some engineering was conducted to adapt the use of these chemicals for some platforms. One alternative approach that showed some promise was the use of solid propellant fire extinguishers. Similar to the units developed for automobile airbags, these systems rapidly generated large quantities of inert gases. They were considered for use in aircraft dry bays, where people would not be exposed to the resulting sub-habitable oxygen levels.

At the then-current state of the technology, the DoD was faced with three options, each with significant and undesirable trade-off considerations. The use of dissimilar fluids required costly re-engineering of both the fire suppression system and the host weapon system. The vintaging of fielded weapon systems required indefinite dependence on a substance that was no longer in production and which was subject to future environmental regulations. The abandonment of fire protection altogether was not feasible, since personnel safety and weapon systems survivability are high DoD priorities. Recognition of these limitations led to a decision to formulate a successive research program focused on improved options for fire suppression in fielded weapons systems.

However, even before replacements for the CFCs and halons could be implemented, an additional threat to the global environment was identified. Since the middle of the 20th century, there had been concern that anthropogenic carbon dioxide was increasing in the lower atmosphere. Its increasing absorption of infrared radiation from the planet surface and re-radiation back to that surface would lead to warming of the earth. The term "greenhouse gas" was created, and it was soon realized that most of the replacements for clean fire suppressants fell into this category.[22] This added yet another constraint to the search for the successors to the halons.

As an interim measure, the DoD (among other organizations and governments in about 20 countries[23]) had created "banks" of halons 1301 and 1211 as a means of continuing protection during the search for alternatives. In 2000, the systems and banks were estimated to contain about 90 million pounds of halon 1301 and about 300 million pounds of halon 1211. It was estimated that the emission rate from fixed systems was about 2 % of the banks' capacity per year, and the rate from portable extinguishers was about 4 % of the banks' capacity per year.[24] It is these banks from which supplies are still drawn as the halons are deployed in theaters of conflict.

The security of such banks, however, is not assured. The few essential uses for ODSs allowed by international agreement were conditional on continued efforts to find environmentally benign alternatives. Furthermore, in 1994, the United Nations Environmental Program (UNEP) announced that just after the turn of the century, the mass of chlorine and bromine (and the accompanying ozone depletion) in the stratosphere would have peaked and would begin to diminish.[25] Their report also identified four principal actions that would speed this decrease. The second most effective of these was the non-release of all halons currently in existing equipment. This was a clear signal to the fire protection community that the world was watching the effort to identify and implement alternatives to the halons and that an accelerated phase-out was a clear possibility. In related activity, research was underway to develop processes for the economical conversion of the halogenated hydrocarbons into other useful chemicals.

At the time of publication of this book, the global average ozone depletion has stabilized. The ozone layer is now expected to begin to recover in the coming decades.[24]

1.5 HISTORY OF THE NGP

To ensure the safety and mission capability of U.S. forces and to preclude any long-term halon *use restriction* impacts, a new DoD technology program was formulated.[26] The Next Generation Fire Suppression Technology Strategy Program (NGP) had as its goal:

> "to develop and demonstrate, by 2004, retrofitable, economically feasible, environmentally acceptable, and user-safe processes, techniques, and fluids that meet the operational requirements currently satisfied by halon 1301 systems in existing weapons systems."

The emphasis was on *retrofit*, i.e., developing technologies that could readily be installed on existing weapons systems.[ii] This led to an oversimplification of the task, by some observers, as a search for a "drop-in" replacement chemical. In fact, the NGP included examination of technologies that could improve the performance of a chemical whose inherent fire suppression efficiency was only mediocre relative to that of halon 1301, approaches that used granular materials, rather than compressed fluids, and even technologies that used no active suppressant at all. The Program would be complete when the generic know-how existed to design cost-effective alternates to halon 1301 systems.

The concept of the NGP was created by Dr. Donald Dix and Mr. Paul Piscopo of the Office of the Secretary of Defense. Planning began in 1994, and the Program was initiated in fiscal year 1997. Oversight and guidance of the Program was provided by a DoD Halon Alternatives Research and Development Steering Group (HASG). The HASG was chaired, in turn, by Dr. Dix and Mr. Piscopo. The membership consisted of representatives from the DoD agencies with responsibility for fire suppression research and development, testing, and implementation of new technology. The U. S. Environmental Protection Agency (EPA), which approved suppressants based on their environmental impact and safety during exposure, provided a liaison to monitor DoD development of alternatives to halon 1301.

The principal sponsor of the NGP was the DoD Strategic Environmental Research and Development Program (SERDP), directed initially by Dr. John Harrison and subsequently by Mr. Bradley Smith. The SERDP Pollution Prevention (later Weapons Systems and Platforms) Program Managers were Dr. Carl Adema, Dr. Robert Holst, and Mr. Charles Pellerin. The NGP was Project WP-1059.

The author of this chapter had the privilege of serving as the Technical Program Manager for the duration of the NGP. Providing additional scientific and pragmatic expertise was a Technical Coordinating Committee, whose membership evolved over the life of the Program: Mr. Lawrence Ash and then Mr. Donald Bein of the Naval Air Systems Command, Dr. Michael Bennett of the Air Force Research

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[ii] Although not explicit in the goal statement, the presumption was that the new science and improved approaches to fire suppression would also be adaptable to the design of future weapons systems. The economics of adapting the new knowledge would likely be more restrictive for an existing aircraft, ship, or ground vehicle; and it was recognized that some expensive-to-retrofit technologies might not be pursued within the NGP, although they might be more viable economically for new weapons systems.

Laboratory and then Mr. Martin Lentz of the Air Force's 46th Test Wing, Dr. William Grosshandler of the National Institute of Standards and Technology, Dr. Andrzej Miziolek of the Army Research Laboratory, and Dr. Ronald Sheinson of the Naval Research Laboratory. Administrative support for the NGP was provided by Gamboa International Corporation.

The NGP was a closely integrated research program whose potential for success was maximized by bringing together the nation's best scientists and researchers in fire suppression and associated technologies, with extensive interactions between the technical disciplines and the project principal investigators. The research was organized into six technical thrusts:

1. Risk Assessment and Selection Methodology: development of a process for program managers to choose among alternative technologies for each application.
2. Fire Suppression Principles: establishment of the mechanisms of flame extinguishment, leading to new approaches for fire control.
3. Technology Testing Methodologies: development of test methods and instrumentation to obtain data on the effectiveness, toxicity, environmental impact, and materials compatibility of new suppressants and their principal degradation products during fire extinguishment.
4. New Suppression Concepts: definition of new ideas in processes, techniques, and fluids for fire suppression based on chemical and physical principles.
5. Emerging Technology Advancement: acceleration to maturity a variety of processes, techniques, and fluids that are currently under development.
6. Suppression Optimization: development of the knowledge to obtain the highest efficiency of each candidate technology.

While the early NGP research was underway, the military services were pursuing solutions, based on TDP technology, for some of the DoD platforms. The Army had identified fire suppression technologies for both current and planned ground vehicles that needed only engineering for implementation. The Navy had no plans to retrofit current ships and had initiated a research program on water mist technology for forward fit.

However, the aircraft safety and survivability engineering teams from all three Military Services had fire suppression needs for engine nacelles and dry bays that were not being addressed by Science and Technology (S&T) efforts outside the NGP. Thus, in 1999, the goal for the NGP was refined:

> "to develop and demonstrate technology for economically feasible, environmentally acceptable and user-safe processes, techniques, and fluids that meet the operational requirements currently satisfied by halon 1301 systems in aircraft." [27]

In this revised statement, there was recognition that the NGP, as the only DoD S&T program in this field, should develop the technology base for both existing and planned aircraft. The deliverables, in addition to a well-documented science basis, were to be:

1. Identification of the best chemicals to consider as alternatives to halon 1301 for extinguishing in-flight fires in engine nacelles and dry bays;

2. Guidance for engineering the fire suppression system to obtain the most efficient use of the suppressant chemicals;
3. Development of practicable non-fluid-based suppression technologies; and
4. Creation of means for deciding among candidate solutions for a given application.

The documentation was to include not only those tests, models, and computations that led to improved firefighting capability, but also those that were not promising. This documentation would then serve as a resource for those who entered the field in future times.

Realization of the difficulty in searching for an effective fire suppressant system comes from viewing an aircraft engine nacelle (Figure 1–1).[iii] A dry bay is no less complex.

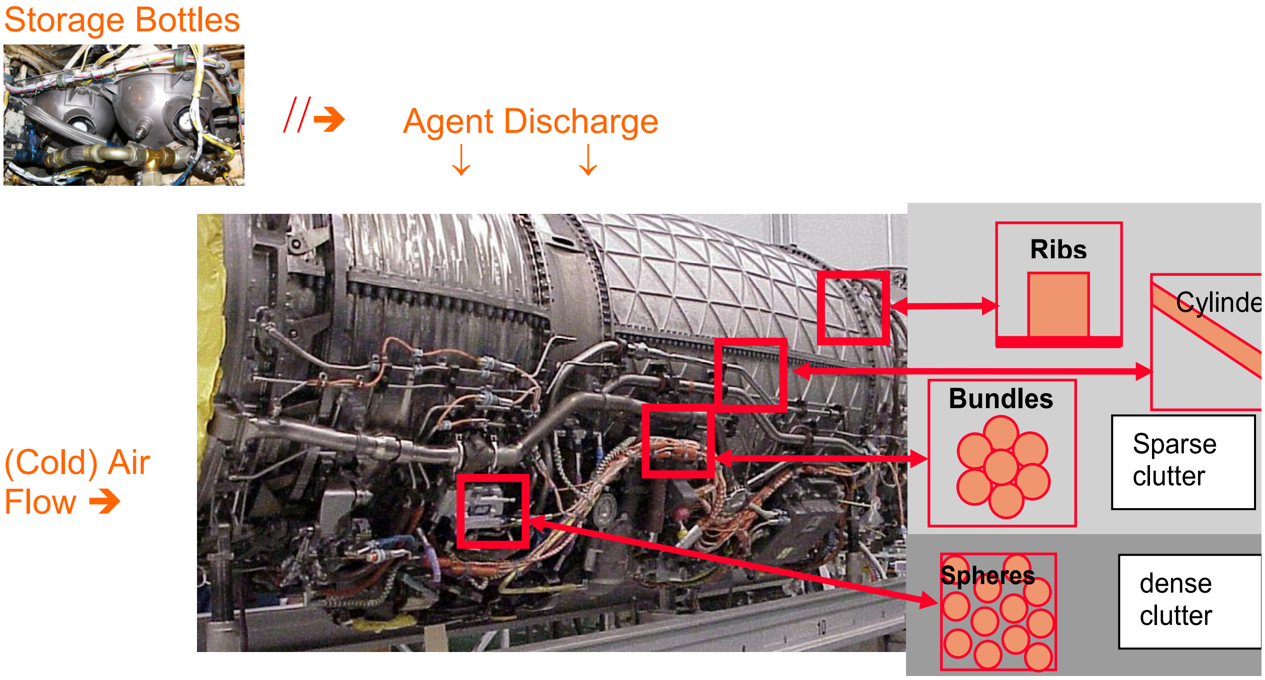

Figure 1–1. Interior of an Aircraft Engine Nacelle.

The suppressant is injected, at a small number of points, into this annular space between the pictured engine exterior and the outer, cylindrical housing (not shown in the figure). The agent must fill the annulus, reach all the nooks and crannies, and put out the flames from a fire in any location, all before the cold air flow flushes the chemical from the nacelle.

Scientists and engineers were thus looking for compounds that had:

- High fire suppression efficiency
- Effective quenching of flame re-ignition
- Low ozone depletion potential (ODP)

[iii] An engine nacelle is the housing of an aircraft jet engine. The exterior is aerodynamically smooth, while the interior has ribbing that provides the structural strength for the nacelle.

- Low global warming potential (GWP)[iv]
- Short atmospheric lifetime[v]
- Low suppressant residue
- Low electrical conductivity
- Low corrosivity to metals
- High compatibility with polymeric materials
- Stability under long-term storage
- Low toxicity of the chemical and its combustion and decomposition products
- High speed of dispersion

The research on advanced fire suppression processes, technologies, and fluids encompassed 42 interrelated projects. Many of these were outlined in the original NGP Strategy Document and were structured by successful proposals in an open competition. These were complemented by solicitations for proposals of new ideas. The remaining projects were commissioned by the Technical Coordinating Committee, with approval of the HASG and the sponsor, based on the outcome of the prior projects and newly acquired understanding of the additional research needed to meet the NGP goal.

Figures 1−2 through 1−5 depict the relationships between the projects and their relationships to the NGP deliverables. Cyan boxes are projects that were performed, red boxes indicate projects that were planned but not performed, the yellow box represents work in progress elsewhere at the time of this book, and orange boxes depict the deliverables. An asterisk (*) notes projects that appear more than once.

As the research progressed, the findings were published in archival journals, issued as DoD reports, and presented at technical meetings. Prominent among these meetings were the annual Halon Options Technical Working Conferences (HOTWC), founded by Dr. Robert Tapscott of the New Mexico Engineering Research Institute. Attendance at these meetings included domestic and international representatives of weapons platforms manufacturers, the military services' safety and survivability teams, civilian customer for fire suppression systems, fire suppression systems manufacturers, and members of the national and international fire research and engineering communities. Eventually, when this key meeting lost its original host, the NGP assumed the responsibility for the organization and conduct of the meetings and for the publication of the cumulative papers.[28]

[iv] The global warming potential of a gas is defined as the change in irradiance at the tropopause (the boundary between the stratosphere and the troposphere) per mass of the gas emitted relative to the change in irradiance per mass of carbon dioxide.

[v] Faced with two chemically different effects of compounds on the environment, it was recognized that a broad approach to minimizing atmospheric perturbations was advisable. Atmospheric lifetime is an indicator of the potential for released chemicals to be degraded or removed from the environment before they could effect harm. It is the time, after its initial emission into the atmosphere, it takes for the compound to decay to 1/e (37 %) of its original concentration.

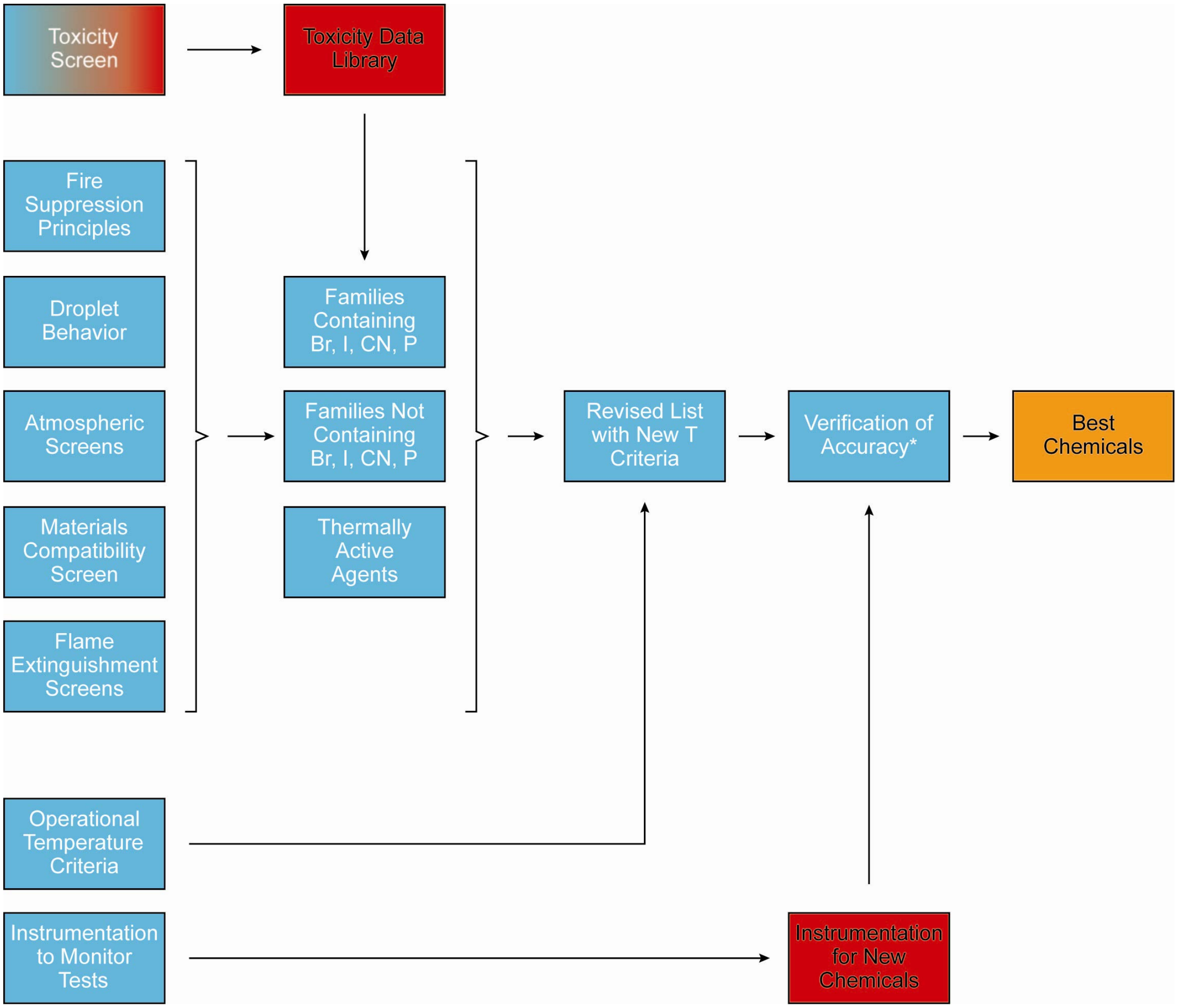

Figure 1–2. Projects Contributing to Deliverable 1: Best Alternative Suppressant Chemicals.

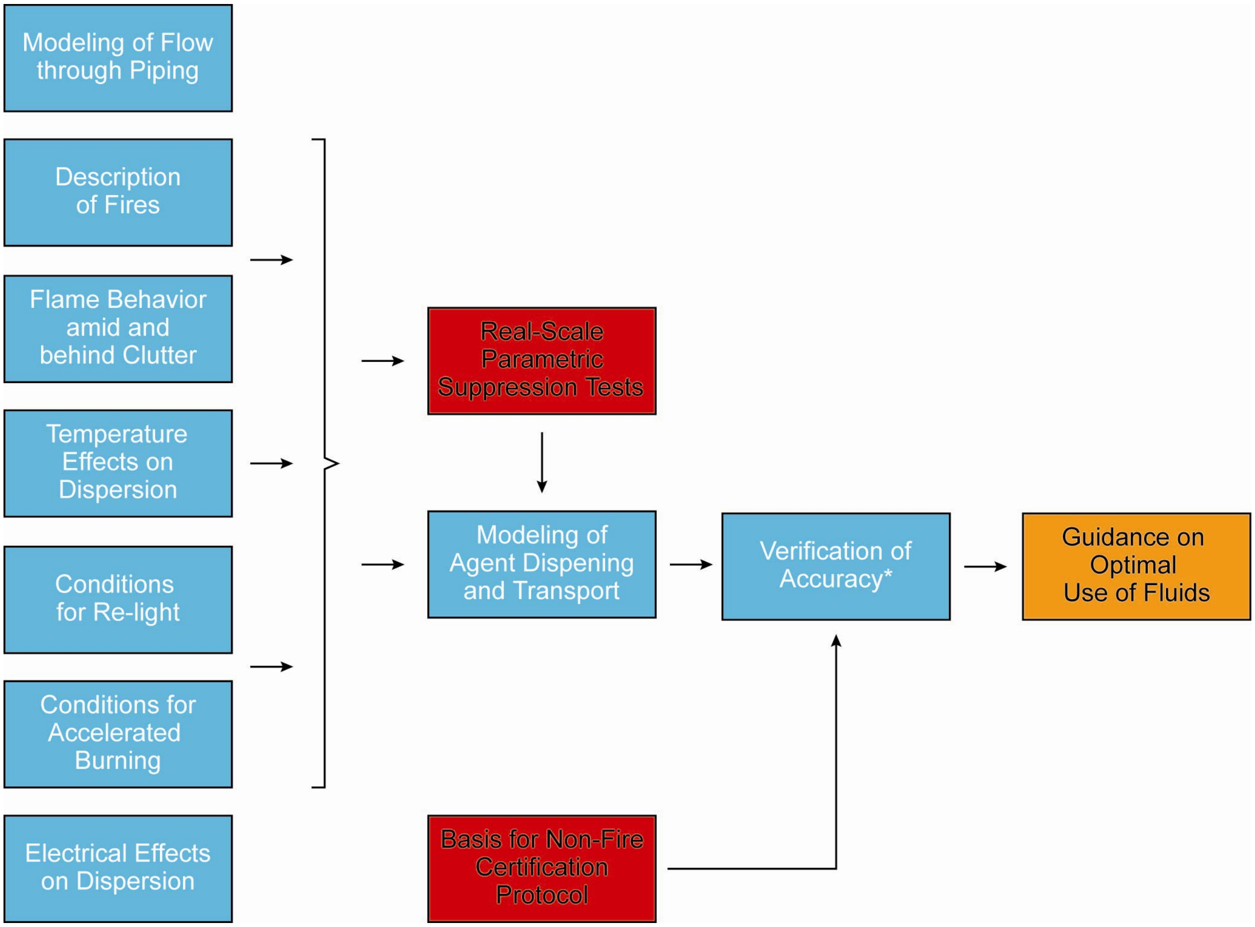

Figure 1–3. Projects Contributing to Deliverable 2: Guidelines for Optimal Application of Extinguishants.

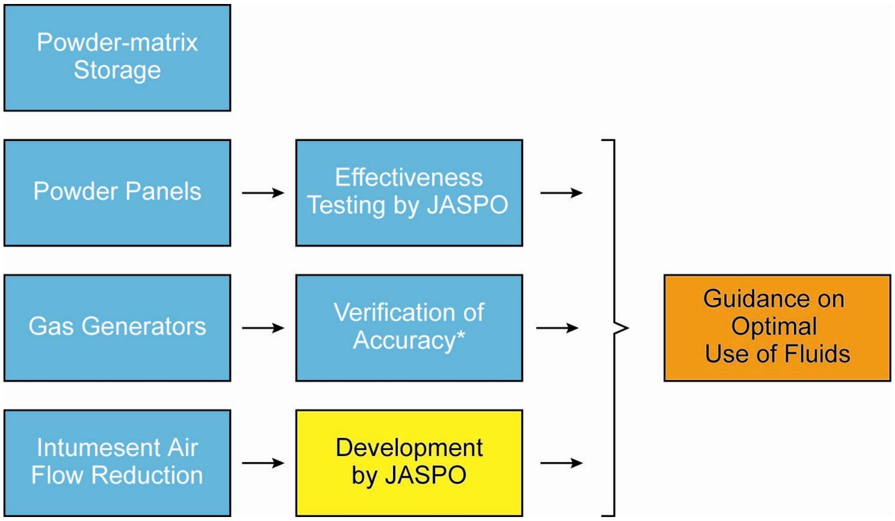

Figure 1–4. Projects Contributing to Deliverable 3: Alternative Extinguishment Technologies.

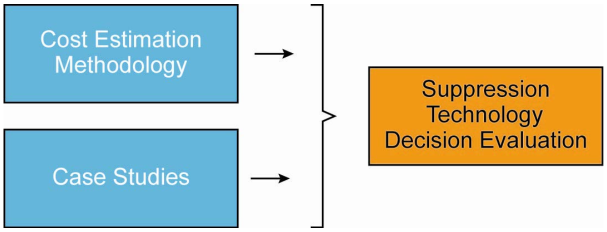

Figure 1–5. Projects Contributing to Deliverable 4: Technology Options Assessment Protocol.

1.6 THIS BOOK

There are multiple reasons behind the preparation of this book. First, as the search for alternative technologies began, reports of much of the prior work were not readily available. Some were out of print, some had only been issued for limited distribution, and other studies had not been fully documented. Second, building on increased knowledge of the fundamentals of fire, the NGP and contemporary studies re-defined the field. However, many of these reports were interim reports or were, for other reasons, not documented in the archival technical literature. Third, the large number of NGP reports makes it difficult to understand how the many projects combined to advance the science and engineering of fire suppression. Finally, it is the intent of the authors and sponsors to document this national research effort such that future researchers and engineers who work in this field (and we firmly believe this will arise again) will have an organized archive from which to begin their work. To this end, the authors of the chapters of this book have compiled, edited, and enhanced the contents of the numerous documents generated under the NGP. As appropriate, they have added information that puts this material in context.

The structure of this book is as follows. Chapter 2 presents an overview of how aircraft have been (and are) protected from the consequences of in-flight fires. Chapter 3 presents what NGP scientists have learned about the chemical suppression of flames. Chapter 4 discusses the properties of suppressant aerosols that contribute to (and detract from) efficient flame quenching. Chapter 5 summarizes the instrumentation the NGP developed for learning about and monitoring fire suppression processes, especially in real-scale tests. Chapter 6 describes the NGP approach to screening chemicals for their potential as alternatives to halon 1301. Chapter 7 describes the process and results of examining numerous chemicals. The amount of a chemical required to extinguish fires in full-scale engine nacelles and dry bays also depends on the geometry of the test fixture, the air flow field within the nacelle, the effectiveness of the mixing of the suppressant into this air flow, and the manner in which the flame is stabilized. These factors are separate from the properties of the suppressant itself. They are discussed in Chapter 8 for suppressants that are stored as compressed fluids and in Chapter 9 for agents that are powders or are delivered by chemically generated impulses. Chapter 10 presents a formalism for considering the life-cycle costs of alternative installed fire suppression systems, to be used in the implementation decision process by aircraft platform managers. Chapter 11 summarizes the key lessons learned during the conduct of the NGP and how they were verified with real-scale experiments. Readers might find the first part of this chapter useful to read first, providing an overview of the results of the technology presented in the rest of the volume. Chapter 12 establishes where the NGP has brought the field of fire suppression science and engineering and identifies the challenges that remain. Three appendices provide lists of the NGP projects and publications and acknowledge those who assisted with the preparation of this volume.

1.7 REFERENCES

1. Goudsblom, J., *Fire and Civilization*, The Penguin Press, London, 1992.

2. Gann, R.G., "A Millennial View of Fire Suppression," 2001, in Gann, R.G., Burgess, S.R., Whisner, K.C., and Reneke, P.A., eds., Papers from 1991-2006 Halon Options Technical Working Conferences (HOTWC), CD-ROM, NIST SP 984-4, National Institute of Standards and Technology, Gaithersburg, MD, (2006).

3. Nash, P., and Young, R.A., *Automatic Sprinkler Systems for Fire Protection*, Victor Green Publications, Ltd., London, 1978. (2nd edition, Paramount Publishing, Ltd., Borehamwood, 1991.)

4. Auck, S.E., "Short History of Halogenated Fire Extinguishing Agents," in A*n Appraisal of Halogenated Fire Extinguishing Agents*," National Academy of Sciences, Washington, 1972.

5. Ford, C.L., "An Overview of Halon 1301 Systems," in Gann, R.G., ed., *Halogenated Fire Suppressants*, ACS Symposium Series 16, American Chemical Society, Washington, DC, 1975.

6. *Final Report on Fire Extinguishing Agents for the Period September 1, 1947 to June 30, 1950*, Purdue Research Foundation, Lafayette, IN, 1950.

7. Miller, M.J., "The Relevance of Fundamental Studies of Flame Inhibition to the Development of Standards for the Halogenated Extinguishing Agent Systems," in Gann, R.G., ed., *Halogenated Fire Suppressants*, ACS Symposium Series 16, American Chemical Society, Washington, DC, 1975.

8. Biordi, J.C., Lazzara, C.P., and Papp, J.F., "The Effect of CF_3Br on Radical Concentration Profiles in Methane Flames," in Gann, R.G., ed., *Halogenated Fire Suppressants*, ACS Symposium Series 16, American Chemical Society, Washington, DC, 1975.

9. Gann, R.G., "Initial Reactions in Flame Inhibition by Halogenated Hydrocarbons," in Gann, R.G., ed., *Halogenated Fire Suppressants*, ACS Symposium Series 16, American Chemical Society, Washington, DC, 1975.

10. *An Appraisal of Halogenated Fire Extinguishing Agents*, National Academy of Sciences, Washington, DC, 1972.

11. Gann, R.G., ed., *Halogenated Fire Suppressants*, ACS Symposium Series 16, American Chemical Society, Washington, DC, 1975.

12. Sheinson, R.S., Eaton, H.G., Black, B.H., Brown, R., Burchell, H., Maranghides, A., Mitchell, C., Salmon, G. and Smith, W.D., "Halon 1301 Replacement Total Flooding Fire Testing, Intermediate Scale," in Gann, R.G., Burgess, S.R., Whisner, K.C., and Reneke, P.A., eds., *Papers from 1991-2006 Halon Options Technical Working Conferences (HOTWC)*, CD-ROM, NIST SP 984-4, National Institute of Standards and Technology, Gaithersburg, MD, (2006).

13. Ewing, C.T., Hughes, J.T., and Carhart, H.W., "The Extinction of Hydrocarbon Flames Based on the Heat-absorption Processes Which Occur in Them," *Fire and Materials* **8**, 148-156 (1984).

14. Robin, M.L., Rowland, T.F., and Cisneros, M.D., Fire Suppression Testing: Extinguishment of Class A Fires With Clean Agents," in Gann, R.G., Burgess, S.R., Whisner, K.C., and Reneke, P.A., eds., *Papers from 1991-2006 Halon Options Technical Working Conferences (HOTWC)*, CD-ROM, NIST SP 984-4, National Institute of Standards and Technology, Gaithersburg, MD, (2006).

15. Molina, M.J., and Rowland, F.S., “Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom Catalyzed Destruction of Ozone,” *Nature* **249**, 810-812, 1974.

16. *The Montreal Protocol on Substances that Deplete the Ozone Layer as Adjusted and/or Amended in London 1990, Copenhagen 1992, Vienna 1995, Montreal 1997, Beijing 1999*, United Nations Environment Programme, http://hq.unep.org/ozone/Montreal-Protocol/Montreal-Protocol2000.shtml

17. Wofsy, S.C., McElroy, M.B., and Yung, Y.L., "The Chemistry of Atmospheric Bromine," *Geophysical Research Letters* **2**, 215-218 (1975).

18. Wuebbles, D.J., "Chlorocarbon Production Scenarios: Potential Impact on Stratospheric Ozone," *Journal of. Geophysical Research* **88**, 1433-1443 (1983).

19. *Technology Development Plan for Alternatives to Ozone-depleting Substances for Weapons Systems Use, Final Report*, Office of the Deputy Under Secretary of Defense (Science and Technology)/Weapons Systems, September 1998.

20. *Directive 6050.9, Subject: Chlorofluorocarbons (CFCs) and Halons*, Department of Defense, February 13, 1989.

21. *Technology Development Plan for Alternatives to Ozone-Depleting Substances for Weapons Systems Use, Final Report*, ODUSD (S&T) Weapons Systems, 1998.

22. Finlayson-Pitts, B.J., and Pitts, Jr., J.N., *Chemistry of the Upper and Lower Atmosphere*, Chapter 14, Academic Press, New York, 2000.

23. "Halon Banks," *FS World*, 63-65, Summer 2001, www.fs-world.com.

24. *Safeguarding the Ozone Layer and the Global Climate System*, Intergovernmental Panel on Climate Change and Technology and Economic Assessment Panel, United Nations Environmental Panel, New York, 2005.

25. *Scientific Assessment of Ozone Depletion: 1994, Executive Summary*, World Meteorological Organization, Geneva, 1994.

26. *Next-Generation Fire Suppression Technology: Strategy for a National Program*, Office of the Director, Defense Research and Engineering, 1996, available on the NGP web site: www.bfrl.nist.gov/866/NGP.

27. *Next Generation Fire Suppression Technology Program Strategy (Update)*, Office of the Deputy Undersecretary of Defense (Science and Technology), 2000, available on the NGP web site: www.bfrl.nist.gov/866/NGP.

28. Gann, R.G., Burgess, S.R., Whisner, K.C., and Reneke, P.A., eds., *Papers from 1991-2006 Halon Options Technical Working Conferences (HOTWC)*, CD-ROM, NIST SP 984-4, National Institute of Standards and Technology, Gaithersburg, MD, (2006).