Scientific Ballooning

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Technology and Applications of Exploration Balloons Floating in the Stratosphere and the Atmospheres of Other Planets

Springer

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Cover photo: High-speed flight demonstration through free fall from a balloon at high altitude. This experiment was performed at ESRANGE, Kiruna, Sweden in 2003, conducted by the National Aeronautical Laboratory of Japan and the National Space Development Agency of Japan (now they are merged into Japan Aeronautical Exploration Agency). The balloon operations were carried out jointly by the CNES and the Sweden Space Cooperation (courtesy of the National Aerospace Laboratory of Japan).

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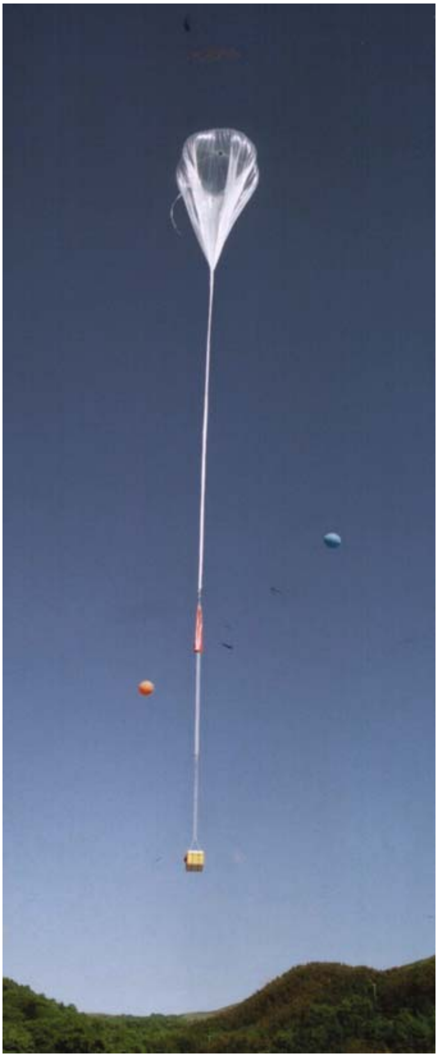
Frontispiece

Frontispiece 1 Balloon launch at the Sanriku Balloon Center, ISAS. (At the stage when gas is being injected into the balloon. The section protected by red film laid out on the ground also belongs to the main part of the balloon)



Frontispiece 2 Balloon commencing its ascent

Frontispiece 3 Balloon launch scene. (Location: Lynn Lake, Manitoba, Canada; Launch: NASA/NSBF) (courtesy of the High Energy Accelerator Research Organization, Japan)

Frontispiece 4 Balloon launch at Showa Station in Antarctica (1998). (courtesy of the Center for Atmospheric and Oceanic Studies, Tohoku University, Japan)

Frontispiece 5 Indoor inflation test of a super-pressure balloon based on a three-dimensional gore design

(a) Sanriku Balloon Center (courtesy of the ISAS)

(b) NSBF, USA (courtesy of NASA/NSBF)

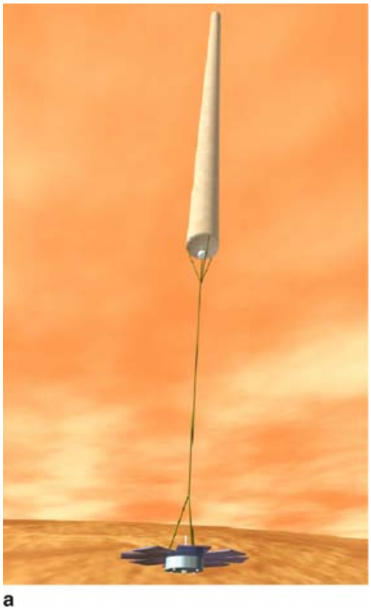
(c) Aire-sur-l'Adour base, France (courtesy of CNES)

(d) Kiruna, Sweden (courtesy of Esrange, SSC)

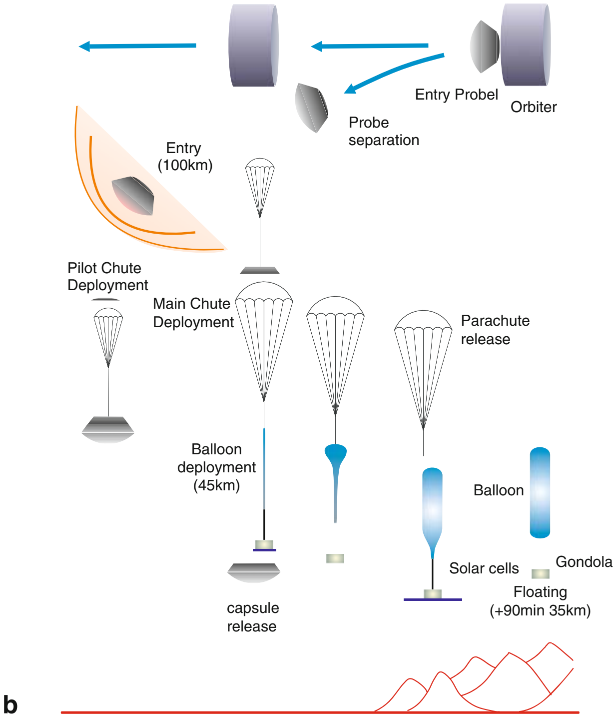
(e) Hyderabad, India (courtesy of TATA Institute of Fundamental Research) Frontispiece 6 Launch sites of various countries

Frontispiece 7 High-speed flight demonstration through free fall from a balloon at high altitude. (courtesy of the National Aerospace Laboratory of Japan)

Frontispiece 8 Scene of the flight of a rawinsonde at the Aerological Observatory (Tsukuba, Japan). (Direction finding equipment has been installed in the dome on the roof of the government building, and this automatically tracks the rawinsonde and receives its signals)



(a) Artist's illustration



(b) Entry and inflation sequence
Frontispiece 9 Low-altitude, cylindrical Venus balloon

Foreword

The balloons that are the subject of this book are balloons that transport payloads ranging from several hundred kilograms up to several tons into the earth's stratosphere. Specifically, they are stratospheric balloons that are used for scientific observations and for the development of space technology and balloons that are used for aerological observations. These balloons attain flight altitudes that are more than three times those of passenger planes. The density of the atmosphere at these altitudes is less than 1% that at the earth's surface. In addition, as part of planetary exploration, this book includes planetary balloons sent to float over other planets that have atmospheres, such as Mars and Venus. The general term used to describe these sorts of activities is *scientific ballooning*.

Although the flights of stratospheric balloons used for various scientific observations and technological experiments do not take place in the void of space, stratospheric balloons may be placed in the same fields as rockets and satellites, namely space science and technology. This, of course, goes without saying for planetary balloons that are transported into outer space on space vehicles. Organizations that conduct research and development and that launch and perform operations with this type of scientific ballooning are usually associated with each country's meteorological organizations and space research and development organizations.

Stratospheric balloons are giant pressurized membrane structures that float in the thin atmosphere of the stratosphere. Their volumes range from a few tens of thousands of cubic meters up to several hundred thousand cubic meters. Their flight characteristics are governed by complex relationships of fluid dynamics and thermodynamics. For planetary balloons, various atmospheric conditions that differ from those on the ground also come into effect. Consequently, performing systematic engineering design and analysis is a prerequisite for constructing and launching balloons. Aerological knowledge of the atmosphere is indispensable for conducting a flight. Such a foundation also ensures safety and reliability during flights. The aim of this book is to systematically describe the engineering aspects associated with scientific ballooning.

As for the structure of this book, Chap. 1 chronicles the adventure-story-like early stages of manned scientific ballooning. It also summarizes developments that gave rise to modern scientific ballooning since the 1940s, which is a technological line of demarcation, and describes the characteristics of these developments. Chapter 2 presents the geometric design problems of balloons, ballooning methods, and flight dynamics during flight, which are the common fundamentals for stratospheric ballooning and planetary ballooning. To provide details concerning balloons that fly in the stratosphere, Chap. 3 first gives an overview of the composition and movement of the earth's atmosphere where balloons fly and then describes how balloons are launched and how their flights are controlled. In addition, the materials used for balloon membranes and their manufacturing processes are described. Chapter 4 presents the atmospheric characteristics of each planet in regard to planetary ballooning. Actual examples of balloons that have flown in Venus' atmosphere are then introduced, and the possibilities of various ballooning techniques and scientific observations are mentioned. Chapter 5 describes future aspects of scientific ballooning.

In the writing of this book, Dr. Yajima and Dr. Izutsu were responsible for the engineering aspects of stratospheric ballooning as a whole, Dr. Imamura covered the earth's atmosphere, and Mr. Abe covered aerological observations that make use of rubber balloons. In addition, Dr. Izutsu wrote about the overall engineering aspects and individual balloon technologies in regard to planetary balloons, and Dr. Imamura covered planetary atmospheres and scientific observations. Finally, Dr. Yajima handled the overall coordination.

Stratospheric ballooning in its modern-day form was active in both observation and experimentation in the infancy of space exploration. This activity continues even today, so that its current significance has in no way diminished. One example is the planetary balloon that has already floated over Venus. Nevertheless, we know of no publication that systematically describes the technology associated with scientific ballooning. The authors hope that this book will deepen interest and understanding in this field and that it will contribute even slightly to the further development of scientific ballooning.

We are deeply grateful to the editing committee for accepting this book as one of the volumes of the "Space Engineering Series" and for the helpful suggestions we received regarding its content. We thank Professor Takao Nakagawa of the Institute of Space and Astronautical Science for his valuable advice regarding the effects of the atmosphere remaining above balloons during space observations in the stratosphere. In addition, we express our heartfelt thanks to the many people who cooperated during the course of writing this book. We also thank the people at Corona Publishing for their kind assistance from the planning stage through to publication.

December 2003 *The Authors*

Preface to the English Edition

This book was first published in Japanese in March 2003 as one of the volumes of the “Space Engineering Series” by Corona Publishing, a publisher of science and technology books in Japan. Up to this point, there has been no book published that systematically covers the technology pertaining to scientific ballooning in the same way that this book does. Moreover, the content of the book is intended to cover scientific ballooning being carried out throughout the world, not just within Japan. As a result, many friends have recommended that we publish the book in English and broaden our target readership. Fortunately, we were able to obtain a Grant-in-Aid for Publication of Scientific Research Results from the Japan Society for the Promotion of Science (JSPS), and this has enabled the publication of this book in English to become a reality. The authors hope that this book will contribute to the future development of scientific ballooning worldwide.

We thank Forte, Inc. for its cooperation in translating this book into English. We express our gratitude to Corona Publishing for graciously agreeing to publish this book in English and accommodating our requests in various ways. We are deeply grateful to the JSPS for their support in its publication.

Nobuyuki Yajima (on behalf of all the authors)

Please note that the names of some space organizations have changed recently (see later). In this book, however, the names of organizations and facilities used are those that were correct at the time of the writing the Japanese language edition of this book.

1. In 2003, the Institute of Space and Astronautical Science (ISAS) and the National Aerospace Laboratory were integrated into the Japan Aerospace Exploration Agency (JAXA) and became the Institute of Space and Aeronautical Science (ISAS) and the Institute of Aerospace Technology (IAT) of JAXA, respectively.
2. In 2005, Sulphur Springs Balloon Plant of Raven Industries, Inc., the balloon manufacturing plant of US, changed to the Sulphur Springs Aerospace Balloon Engineering and Manufacturing Facility of Aerostar International (the parent company of Raven Industries).

3. In 2006, the National Scientific Balloon Facility (NSBF) of NASA was renamed as the Columbia Scientific Balloon Facility (CSBF) in remembrance of the Space Shuttle Columbia disaster.

Preface to Series

A long time has elapsed since the phrase "space age" was first coined. Commencing with the rockets of Tsiolkovsky and Goddard, over 40 years have passed since the launch of the first artificial satellite Sputnik. These days, approximately 100 large rockets for artificial satellites are launched a year, and 1,600 satellites orbit Earth for various missions.

Although the first practical use made of the means of transport (rockets) was space research, space industries subsequently arose, such as satellite communications and remote sensing. Initially, the situation was such that transporting even minimal equipment into space was just barely possible, but now artificial satellites are constantly increasing in size, or alternatively, smaller equipment is being launched at more frequent intervals. In addition, long-duration manned missions have become possible with the Space Shuttle and space stations. Moreover, construction of a space station founded on international cooperation continues. In addition, space tourism and the development of resources on other celestial bodies continue to be discussed as real possibilities. To make these concepts a reality, new reusable space transport vehicles will be necessary, and in addition, the laws and insurance pertaining to space will need to be improved. The realm of space-related activities has suddenly expanded. Perhaps the true space age is only just beginning.

To make such space activities possible, space systems have to be created. Space systems may be described as "systems within systems," and high levels of complexity and optimization are rigorously pursued. In fact, systems consist of many basic technologies, and the teams that implement them are formed by bringing together graduates of aerospace engineering, electrical engineering, materials engineering, and other such fields. Particularly for mission planners and satellite designers, it is no exaggeration to say that it is essential to have insight into all of these basic technologies. Moreover, the technological fields associated with space activities may be categorized into fundamental technology areas (such as rockets, artificial satellites, space stations, and space measurement and navigation) and areas of practical application (such as satellite communications, remote sensing, and uses of zero-gravity). To make use of these space systems, a broad range of knowledge and technologies is required.

This "Space Engineering Series" consists of separate specialized volumes, and covers these broad-ranging basic technologies. Furthermore, these volumes are written by specialists who are active at the forefront of their fields. In Japan, many instruction manuals and individual books on technology have so far been written, but there has been no plan for providing an overall description of space technology from these technological and theoretical viewpoints. For that matter, there is almost no precedent to be found anywhere in the world.

Our hope is that those who intend to construct rockets or artificial satellites and launch them into space, those who intend to use satellites for communications, remote sensing, or other applications, those who wish to study space itself, and those who desire to travel into space will consult each volume from their own viewpoint. In addition, we hope that these volumes will prove useful to specialist technologists, system designers, and students who are enthusiastic about these fields.

July 2000

Tadashi Takano
Editing Committee Chairman

Contents

Chapter 1
Introduction

Abstract This chapter begins by chronicling the adventure-story-like early stages of manned scientific ballooning. It then summarizes the developments that led to the rise of modern scientific ballooning since the 1940s, which represents a technological demarcation line. This chapter also introduces the various worldwide organizations that conduct scientific ballooning in their respective countries. A brief summary of scientific ballooning is then given through introductory descriptions of the following chapters.

1.1 History of Ballooning

Humankind first escaped from the ground and became able to fly freely to high altitudes in the atmosphere by using balloons. In the following pages, we will summarize the history of ballooning from its advent to its current status, focusing on the use of balloons for scientific applications. For the overall history of balloons, we refer the reader to the literature [1–3], although some references are a bit dated.

1.1.1 Advent of Balloons

The large, unmanned, hot-air balloon that the Montgolfier brothers (J. M. and J. E. Montgolfier) successfully tested in public in Annonay in the south of France on 5 June 1783 is regarded as humankind's first balloon. From the facts that its volume was 700 m^3 and that it attained an altitude of approximately 2,000 m, we can gauge that it was a large-scale balloon (Fig. 1.1) [4].

The brothers were born into a household of paper wholesalers, and it is reported that they were highly interested in science and read many science-related books. Because they had this foundation, after conceiving of the hot-air balloon,

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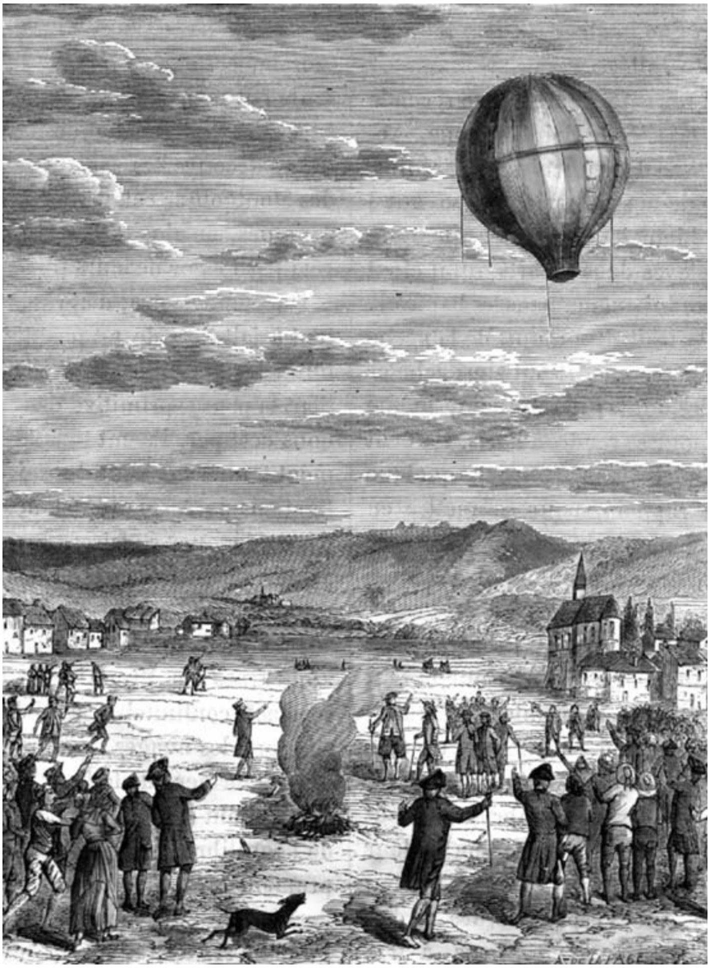

Fig. 1.1 Public experimental flight of the world's first full-scale hot-air balloon by the Montgolfier brothers (5 June 1783) (courtesy of Saburo Ichiyoshi)

they systematically pursued their research and, commencing with small-scale models, they conducted trials involving successively larger balloons. It is interesting that this approach is consistent with that adopted by the Wright brothers, who 120 years later made the first successful airplane flight, and who conducted their work based on a scientific process; for example, they designed the wings by using wind-tunnel testing.

Following the success at Annonay, the Montgolfier brothers succeeded in front of a large number of spectators, which included Louis XVI, in Paris on September 19, and on November 21. In the first flight, small animals were placed on board, and they then accomplished a manned flight with two human passengers on board during the second flight. These steps closely resembled the process of development in preparing to send men into space 170 years later, when flights were first conducted with monkeys and dogs on board.

The principle of buoyancy itself was already understood in the pre-Christian era, and the phenomenon of the ascension of air heated by a fire has been observed constantly in everyday life ever since humankind first used fire in primitive times. From this commonplace phenomenon, however, it seems that the impressive advancement of European society at the time of the Industrial Revolution was required for people to conceive of a balloon that a human could ride and then to actually build and fly.

A gas balloon that employed hydrogen as the buoyancy medium was first flown successfully in Paris on 27 August 1783, by J. A. César Charles, a scientist at the French Academy of Sciences. This was a little less than three months after the Montgolfier brothers. A successful manned flight, similar to that of the hot-air balloon, was subsequently conducted on December 1 of that same year. (Fig. 1.2).

Hydrogen had previously been discovered in 1766 by H. Cavendish of Britain, and it was already known to be lighter than air. The Montgolfier brothers also considered using hydrogen gas in their balloons, but they abandoned this approach since manufacturing a balloon membrane to seal in the hydrogen was more difficult than manufacturing one for a hot-air balloon. Charles solved this problem by making the balloon fabric from silk and paper and then coating it with rubber.

In contrast to the Montgolfier balloon, the bottom of which was open, the balloon tested by Charles was a closed, sealed-gas balloon. Therefore, as the balloon gained altitude, the pressure across the membrane increased, so that eventually the balloon would burst. Hence, the first flight finished in a shorter time than anticipated. Consequently, an exhaust valve was installed for the manned flight to circumvent this rise in pressure. Charles's gas balloon included technology that has been passed down even to the balloons of today; specifically, it incorporated detailed measures for ensuring the air tightness of the membrane, guaranteeing its strength and controlling its pressure.

1.1.2 First Uses for Scientific Observation

Once the feasibility of flying balloons had been demonstrated, the activity quickly captured the public's imagination. Attention focused on amusements and adventures with manned balloons at exhibitions, and in addition, a great deal of interest and effort was devoted to long-distance flights, such as over transoceanic distances. Even in Japan, in 1890, a British aviator performed demonstrations on a large scale by parachuting from a balloon.

But then, there were some people who looked askance at these trends and thought that balloons could be used more effectively for scientific observation. First, they tried to discover how the atmosphere changes with altitude by flying as high as possible. On 24 August 1804, a mere 21 years after the first balloon flight, the French

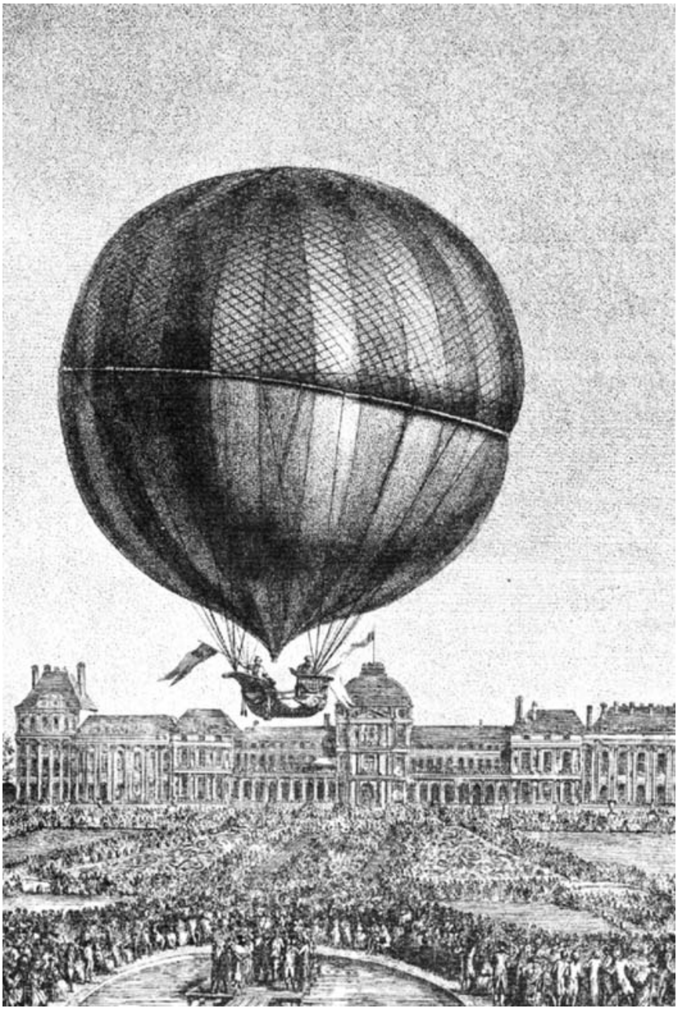

Fig. 1.2 First manned flight of Charles' hydrogen gas balloon (1 December 1783) (courtesy of Saburo Ichiyoshi)

scientist J. L. Gay-Lussac ascended to a height of nearly 8,000 m, with a barometer, a thermometer, and a hygrometer on board. In 1862, the British scientist J. Glaisher attained an altitude of 10 km.

These manned flights were done without any protection against the thin atmosphere at high altitudes. Since the balloons ascended higher than Mt. Everest in less than an hour, this was enough to cause loss of life, making these tests only a step away from being reckless adventures. These exploits also revealed the intensity of the desire that the people of that era had to explore the unknown. On the basis of these pioneering works, at the end of the nineteenth century, the usefulness of ballooning for scientific observation was accepted by academic institutions, for example, by the Society of Arts in the Royal Academy [5].

The experiment that is regarded as the first step toward full-fledged use of balloons in astrophysics is the observation of cosmic rays carried out by V. F. Hess of Austria in 1912. Hess ascended to 5,000 m, carrying a simple ion chamber, and measured how the number of cosmic rays varied with altitude. On the basis of these observations, the term *cosmic rays* was coined, testifying to the fact that these rays came from space. Hess was awarded the Nobel Prize in 1936 for this achievement. This test was also significant as it demonstrated that true space could be observed unimpeded by the atmosphere by ascending to high altitudes.

Reaching the stratosphere, which represented a milestone in scientific ballooning, was achieved in a flight by A. Piccard of Swizerland in 1931, in which he attained an altitude of 15.8 km. This manned flight was not as reckless as those of the pioneering days, since he employed a small spherical airtight cabin made of aluminum [6].

Another noteworthy development occurred in 1938, when R. H. Upson of the United States suggested a new balloon shape design that later came to be termed the *natural-shape balloon*. It was clear that by this stage, ballooning had already attained the status of modern scientific ballooning, which is described in the next section.

1.1.3 The Age of Modern Scientific Ballooning

The scientific ballooning of today is founded on new technologies, such as shape design concepts, configuration, balloon membrane materials and their adhesives, and the introduction of reinforcing methods that use high strength fibers. Balloons based on these new technologies are classified as modern scientific balloons.

The most significant technological advancement was the development of low-density polyethylene film in the early 1930s by the British chemical company, Imperial Chemical Industries (ICI). By using this film (which is thin, lightweight, tough, and has good elongation characteristics), substantial reductions in the balloon's own weight were achieved, and it became easy to reach altitudes of 30 km or higher. However, the temperature of the atmosphere when passing through the tropopause near an altitude of 12 km is -70°C. The development of a film that did not lose its flexibility even at such a low temperature was an important, early challenge [7].

In the 1940s, systematic research was conducted under the auspices of the U.S. Navy, the University of Minnesota, and other universities, and balloons were put to practical uses, such that they could almost be considered the prototypes of modern balloons. Not only were balloon films developed during this period, but also were the principal technologies of zero-pressure balloon systems that are equipped with a venting duct to prevent a pressure increase on the film and fiber reinforcement methods that use load tape. Progress in electronics, which was advancing concurrently, enabled the realization of wireless communications devices that could be mounted