STANDARDS OF

By R. E. Wilson

AS A RESULT of the increasing need for reliable temperature measurements at both very high and very low temperatures, the National Bureau of Standards is extending its temperature standardization and research program toward the extremes of the temperature scale. While the accurate measurement of temperature has long been of interest to the research scientist, its importance, particularly at the extreme ends of the scale, has greatly increased with the rapid technical developments of recent years. During this period, many improvements in industrial processes for the manufacture of products such as steel, glass, gasoline, and other important commodities have resulted from the increased precision that is being attained in the measurement and control of temperature. In aeronautics there are new temperature problems in connection with the use of jet propulsion and the operation of aircraft at high altitudes and in polar regions. To attain the desired performance in jet engines, fundamental research is required to develop methods of measuring temperatures of flames and to develop temperature-sensitive devices for indicating performance and controlling operation. For use at jet-engine temperatures as well as in arctic cold, mechanical parts must be specially designed using materials capable of withstanding these extremes in order to function satisfactorily. Likewise, as a result of the applications of atomic energy, it has become necessary to learn more about the heat-transfer properties of a variety of materials at increasingly high temperatures. For effective research in these fields, temperatures must be accurately measured, and the results of one laboratory must be comparable with those of another.

TO PROVIDE a fundamental basis for precise temperature measurements, a practical scale of temperature has been established which covers the range from the boiling point of oxygen to the highest temperatures of incandescent bodies and flames. This scale, known as the International Temperature Scale, was adopted in 1927 to provide a scale which would conform as closely as possible to a thermodynamic scale proposed in 1854 by Lord Kelvin. Temperatures on the thermodynamic (Kelvin) scale are identical with those appearing in the ideal gas law and other thermodynamic relations. By observing the change of pressure with temperature of a constant volume of gas, or the change in volume of a quantity of gas under constant pressure, and correcting for the imperfection of the gas, temperatures on the thermodynamic (Kelvin) scale can be determined. In practice, however, the complexity of an accurate gas thermometer and the difficulty of making highly precise measurements with it are severe limitations on its use.

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The experimental difficulties involved in making precise measurements of temperature on the thermodynamic scale and the importance of measuring temperature with high precision on the same scale in all countries ultimately led to the establishment of the International Temperature Scale of 1927. This scale, proposed by the national laboratories of the United States, Great Britain, and Germany, and adopted by 31 nations, was designed to conform as nearly as possible to the thermodynamic scale as it was then known.

The International Temperature Scale of 1927 proved useful in providing a stable, uniform, and precise basis for obtaining temperatures. However, in the 20 years following its adoption, the increasing precision attained in temperature measurements made it apparent that some revision was desirable in order to make the scale more self-consistent and to improve its agreement with the thermodynamic scale. After many discussions with scientists and laboratories in this country and abroad, the Bureau prepared a draft that formed the basis of the document finally adopted at Paris by the Ninth General Conference on Weights and Measures as "The International Temperature Scale of 1948".[1,2] On January 1, 1949, the Bureau began using the definitions of the 1948 scale, both in its own research program and in calibrating instruments for other scientific and industrial purposes.

The six fixed points of the 1927 scale were the boiling point of oxygen (−182.97°C), the freezing and boiling points of water, the boiling point of sulfur (+444.60°C), the melting point of silver (+960.5°C), and the melting point of gold (+1,063°C). From −190° to +660°C,

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the measurement of temperature was based on the indications of a standard platinum resistance thermometer used in accordance with specified formulas; from +660°C to the gold point, the platinum versus platinum-10% rhodium thermocouple was standard; and above 1063°C, the optical pyrometer was used.

The same fixed points, with one slight modification, are specified in the 1948 scale, and the instruments and interpolation equations for obtaining temperatures between fixed points are essentially the same as those previously used. Only two revisions in the definition of the scale resulted in appreciable changes in the numerical values assigned to measured temperatures. One of these was the change in the value for the silver point from 960.5° to 960.8°C, which made numerical values of temperatures measured with the standard thermocouple in the range between 630° and 1,063°C somewhat higher, the maximum difference being 0.4 degree [3] near 800°C. The other change was the adoption of a new value (1.438 cm-deg) for the constant c_2 in the radiation formula used to calculate temperatures above the gold point as observed with an optical pyrometer. Also, in the new scale, Planck's radiation formula is specified instead of Wien's for calculating these temperatures.

TABLE 1. Fixed points [a] of the International Temperature Scale of 1948

Fixed point	Temperature
	°C
Oxygen point	−182.970
Temperature of equilibrium between liquid oxygen and its vapor	
Ice point (fundamental fixed point)	0
Temperature of equilibrium between ice and air-saturated water	
Steam point (fundamental fixed point)	100
Temperature of equilibrium between liquid water and its vapor	
Sulfur point	444.600
Temperature of equilibrium between liquid sulfur and its vapor	
Silver point	960.8
Temperature of equilibrium between solid and liquid silver	
Gold point	1,063.0
Temperature of equilibrium between solid and liquid gold	

[a] Under the standard pressure of 1,013,250 dynes/cm^2.

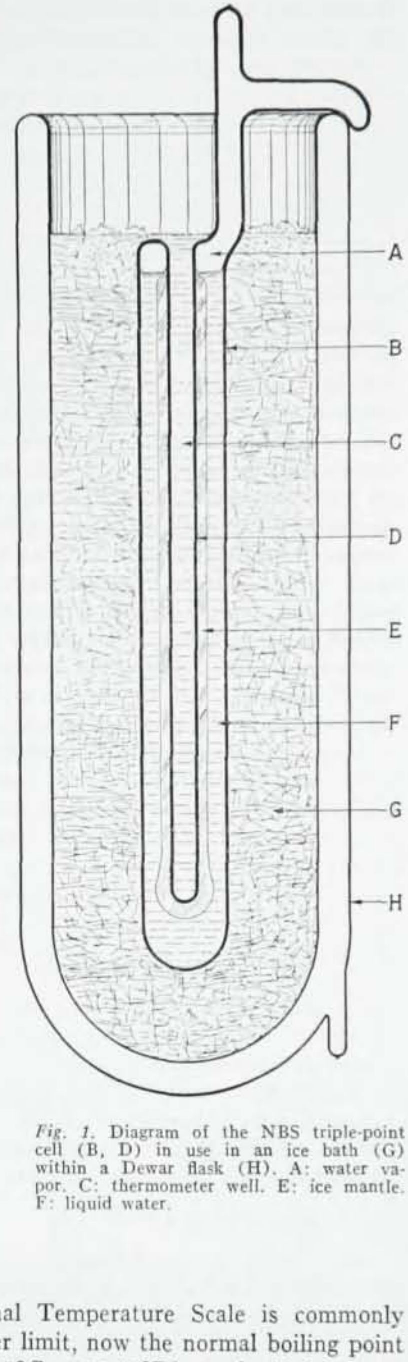

Fig. 1. Diagram of the NBS triple-point cell (B, D) in use in an ice bath (G) within a Dewar flask (H). A: water vapor. C: thermometer well. E: ice mantle. F: liquid water.

The International Temperature Scale is commonly used from its lower limit, now the normal boiling point of oxygen (−182.97°C or 90.19°K), to the highest temperatures measured. For temperatures below the oxygen point down to about 10°K, the Bureau maintains an auxiliary scale based on the resistance of capsule-type platinum resistance thermometers, some of which were calibrated using a helium gas thermometer.[4] At the time it was established, this scale was made to agree with the thermodynamic scale as closely as it was known. Capsule-type resistance thermometers are calibrated on this scale by NBS for laboratories in the United States and in foreign countries.

IN CONNECTION with maintenance of the International Temperature Scale, the Bureau calibrates the three standard instruments—platinum resistance thermometers, platinum-platinum rhodium thermocouples, and optical pyrometers—and certifies them for other laboratories. These laboratories then use the calibrated instruments as working standards for the calibration of other temperature-measuring instruments. In addition to the working standards, other thermocouples as well as liquid-in-glass thermometers and ribbon-filament lamps are certified by NBS. Standard resistance thermometers and thermocouples are used to determine the temperature of the testing baths and furnaces. Some types of liquid-in-glass thermometers are also calibrated against standard resistance thermometers and are then used as working standards to calibrate other liquid-in-glass thermometers. Approximately 2500 temperature-measuring instruments—optical pyrometers, ribbon-filament lamps, resistance thermometers, thermocouples, and liquid-in-glass thermometers—are certified each year for federal agencies, state and municipal governments, industrial laboratories, and manufacturers. About 48,000 clinical thermometers, a sampling of a much larger number, are also tested each year for the Veterans' Administration, the U. S. Public Health Service, and the U. S. Department of Agriculture to insure compliance with specifications. As a result of this standardizing service, practically all measurements of temperatures above the oxygen point in this country are based upon the International Temperature Scale as established and maintained by NBS.

Calibration of a standard platinum resistance thermometer throughout its range is carried out by measuring the resistance of the thermometer at the oxygen point, the ice point, the steam point, and the sulfur point. From these data, constants are calculated for the interpolation equation which gives the resistance of the thermometer at any given temperature in terms of that temperature and the resistance at 0°C. The International Temperature Scale specifies that the platinum in the standard resistance thermometer must be annealed and must have a purity such that the ratio $\frac{R_{100}}{R_0}$ is greater than 1.3910.

The standard thermocouple, which must contain platinum of high purity and must satisfy certain specific requirements concerning the electromotive force it develops, is calibrated by measuring its electromotive force when one junction is maintained successively at a temperature between 630.3°C and 630.7°C (as determined by a standard resistance thermometer), at the silver point, and at the gold point. The reference junction of the thermocouple is held at 0°C. These three values of the electromotive force permit the calculation of the three constants in a quadratic equation which relates electromotive force to the corresponding temperature.

Optical pyrometers are used to measure the temperature of incandescent bodies by visual comparison of a portion of the radiation from the hot body with that emanating from an incandescent lamp filament. Calibration of such an instrument involves a determination of the pyrometer lamp current which corresponds to a particular temperature. This is done at NBS by comparison of the pyrometer under study with a previously calibrated standard pyrometer, both instruments being sighted upon a ribbon-filament lamp which serves as a source of constant temperature.

The current-temperature relation for the standard pyrometer is determined with the aid of Planck's law of radiation. In this process the pyrometer lamp current corresponding to the gold point (1,063°C) is first determined by matching the brightness of a portion of the lamp filament with that of a black body of thoria, beryllia, or carbon immersed in freezing gold. The calibration is extended above the gold point by using a ribbon-filament lamp and sector disks. The temperature of the ribbon-filament lamp is first adjusted until its brightness, when viewed through a given rotating sector disk, is equal to that of a black body at the gold point. From the known transmission of the sector disk, the brightness temperature of the lamp itself, without the disk, is calculated by means of Planck's law. The sector disk is then removed, and the pyrometer lamp current is increased to obtain a brightness match between the pyrometer lamp and the ribbon-filament lamp. When this match is obtained, the pyrometer current corresponds to the calculated temperature. In order to be able to calibrate commercial pyrometers below the gold point, the calibration of the standard pyrometer is extended to lower temperature by inserting, in turn, various rotating sector disks between the pyrometer and

Fig. 2. Liquid-in-glass thermometers are shown being tested at the National Bureau of Standards by comparison with one of the Bureau's standard platinum resistance thermometers. For the temperature range from 0° to 100°C, the thermometers are immersed in a mechanically stirred water bath. The power input to the heater is controlled by the variable transformer at the left of the bath. The thermometers under test are read with a telescope, and the corresponding reading for the platinum-resistance thermometer is obtained with a Mueller thermometer bridge.

the gold-point black body and observing the pyrometer lamp current required to match the resulting reduced brightness. The corresponding temperatures below the gold point are then calculated from the transmissions of the various sectors and Planck's law of radiation. By use of sector disks with different angular openings, the pyrometer lamp currents for various temperatures on either side of the gold point are determined, and a complete calibration is obtained by interpolation.

THE MOST COMMONLY USED fixed point in thermometry is the ice point, which is defined as the temperature of equilibrium at a pressure of one atmosphere between ice and air-saturated water. In practice, this definition is difficult to realize exactly because all impurities except air (the composition of which is not specified) must be absent and because complete saturation by air is difficult to attain. Fortunately, the effects of these factors are small except in measurements demanding the highest precision. When the ice point was first defined, the ice bath, made of finely divided pure ice and distilled water exposed to the atmosphere, was assumed to be sufficiently accurate to fix the ice-point temperature within 0.001 degree C. Later, however, when an accuracy of 0.0001 degree C was desired, a more reproducible standard became necessary, and an investigation was begun of the triple point of water, defined as the temperature at which ice, liquid water, and water vapor are in equilibrium. As a result of this work, a special apparatus known as a triple-point cell [5] was designed for determination of the triple point, and the triple point is now used by the Bureau instead of the ice point for high-precision measurements.

The triple-point cell consists of a cylindrical glass container having a coaxial re-entrant well for a thermometer. Very pure air-free water is sealed in the cell, partially filling it. The NBS technique in preparing a cell for use is to freeze a mantle of ice along the thermometer well. This method further purifies the ice adjacent to the thermometer well. A thin layer of ice is then melted to provide the interface between pure water and pure ice, both of which are in contact with the vapor phase. Experiments [6] carried out in 1942 showed that the triple point is very close to 0.0100°C (0.00997°C) and that its value as obtained with the triple-point cell is reproducible to within approximately 0.0001 degree C.

Next in importance to the ice point (or triple point) is the steam point, defined as the temperature of equilibrium between liquid water and its vapor under the standard pressure of 1,013,250 dynes per square centimeter (one atmosphere). While the steam point may be determined in a boiling-point apparatus left open to the atmosphere, corrections for atmospheric pressure, which is constantly changing, must be made; and precision is difficult to obtain in this way. A controlled pressure system, employing a precision monometer, has been developed and has been used for the calibration of standard platinum resistance thermometers. The ultimate use of this system will be the measurement of the pressure in a gas thermometer. A closed boiler, into which six thermometer wells extend, is connected to the precision manometer by a tube filled with helium. The manometer, located in a temperature-controlled cellar, consists of a mercury column with a mercury cell at each end mounted on Hoke gage blocks.

3. The National Bureau of Standards ates optical pyrometers by compari- with a standard pyrometer (right). instruments are sighted on a ribbon- ent lamp (back-ground), which serves constant-temperature source.

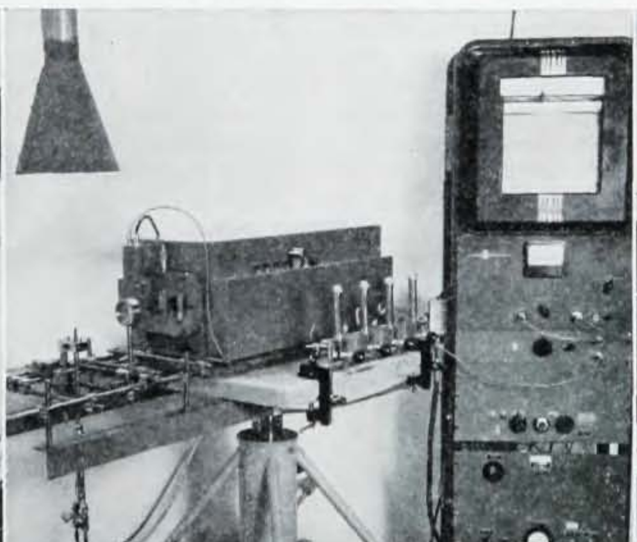

Fig. 4. Photoelectric recording spectrometer, loaned to NBS by Leeds and Northrup Co., is used to study intensities of ultraviolet spectral lines emitted from or absorbed by different regions of flames under various flame conditions. This is one phase of research on factors which complicate the interpretation of spectral intensities in terms of flame temperature.

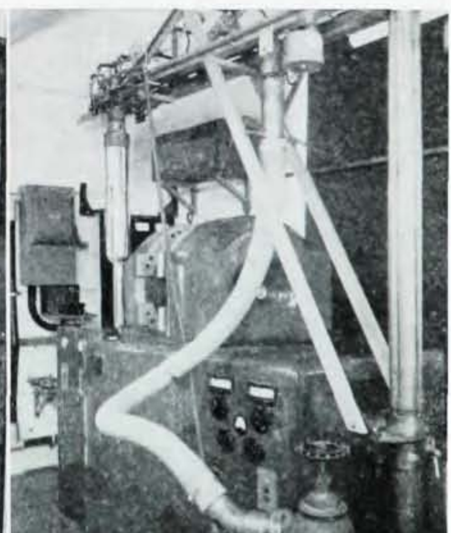

Fig. 5. Adiabatic demagnetization apparatus showing electromagnet and cryostat; latter is suspended from end of rotatable arm which also carries the high vacuum system and rough-vacuum line to the liquid helium.

Adjusting the difference in the heights of the two columns of gage blocks establishes the desired pressure, which is transmitted by means of helium to the closed boiler. In order to determine the heights of the mercury surfaces in the mercury cells, the electrostatic capacity between the mercury surfaces and insulated metal plates above them is made a part of a beat-frequency oscillator circuit. After the manometer is adjusted, a change in pressure is detected by a change in the beat frequency. The pressure can be returned to its original value by the manual adjustment of a small piston in the helium system. With this equipment, a change in pressure equivalent to 0.00001 degree C at the steam point can be detected, and determinations of the steam point made during one day agree within 0.0002 degree C.

Until recently, standard platinum resistance thermometers were calibrated singly at the sulfur point using apparatus open to atmospheric pressure. However, the use of pressure control has now been extended to measurements of the sulfur point. Previously, variations in atmospheric pressure had been both troublesome and a source of uncertainty in the measurements, and most of the determinations were being made at night because pressure variations are smaller during that period. The new method uses a closed all-aluminum boiler having wells for 10 thermometers and connected to the precision manometer. This apparatus will make possible a study of the sulfur point as a precise fixed point for thermometry.

For use in thermodynamic calculations, temperatures expressed on the thermodynamic scale are frequently required. Since the actual measurements may be made on the International Temperature Scale, it is essential that the differences between the two scales be known. To aid in this work, a "noise thermometer" developed at the University of Chicago [7] has been set up at NBS to measure thermodynamic temperatures. The mean-square voltage due to thermal fluctuations in electron density in a resistor—usually referred to as thermal noise—is a function of the thermodynamic temperature of the resistor. By comparing the noise voltages across two resistors at different temperatures, it is possible to determine the ratio of the temperatures of the resistors. The first measurements will be made of the temperature of the gold point, which is important both for the thermocouple and optical-pyrometer ranges of the International Temperature Scale.

In connection with the maintenance of the temperature scale, future plans call for the construction of comparator furnaces to study the performance of standard platinum resistance thermometers and thermocouples between calibration points. As the International Temperature Scale is based on a relatively small number of fixed points, it is necessary to investigate the standard temperature-measuring instruments between these points and to evaluate the precision with which they can be relied upon over the intervening ranges. In this way the Bureau hopes to determine how nearly calibrated instruments of a given type indicate the same temperature at any temperature within their range.

CLOSELY RELATED TO THE WORK on the temperature scale is the development of improved temperature-measuring instruments. Thus, in connection with the maintenance and improvement of the International Temperature Scale in the temperature range from 630.5° to 1,063°C, investigations [8] have been made to determine the effect of annealing on the electromotive force of thermocouple platinum. This study included a determination of the effects of different annealing temperatures, cooling rates, and atmospheres in which the samples were cooled. It was concluded that annealing could be carried out in vacuum, air or helium without introducing effects traceable to solution of the gases. Quenching affected the electrical properties in a way similar to mechanical strain. This effect may result from strain introduced by nonuniform contraction on cooling, or it may result from a "freezing" of a high-temperature distribution of lattice defects. The kinetics of annealing was interpreted in terms of a thermally-activated process.

A search is now under way for a better material to substitute for the alumel wire of a chromel-alumel thermocouple. When used under conditions encountered in exhaust gases in aircraft engines, the alumel becomes brittle due to intergranular corrosion by sulfur compounds and fails after a relatively short period of operation. Available substitutes of alumel which appear likely to withstand the vibration and corrosive atmosphere are being investigated to determine their performance under these extreme conditions.

Investigative work is also carried on in connection with the testing of clinical thermometers. Recently, in order to develop an improved specification for clinical thermometers, a study [9] was made of the change with time in the calibration of a group of thermometers which had been given a special stabilizing heat treatment by the manufacturer. Previous specifications had required that clinical thermometers be aged by three months' storage before calibration so that the volumes of the bulbs would have time to become constant. The results of the Bureau's study showed that the "artificial aging", which requires less than a week, is fully equivalent to the earlier method.

A significant advance in the measurement of extremely high temperatures in nonprotective atmospheres (to about 3800°F) was the development of an iridium vs iridium thermocouple.[10] Because of the high temperatures which prevail in the primary burning zones of turbojet and ramjet combustion chambers, conventional temperature-sensing instruments are not suitable for use in these applications, and the importance of this thermocouple has increased greatly. In preliminary studies, this thermocouple has been found to withstand both the thermal and mechanical stresses incident to combustion-chamber operation, and heat-resistant supporting tubes and insulators are being developed so that the device can be used in flight.

A reliable method for the measurement of the temperature of hot gases is needed in many industrial and scientific research investigations. A fundamental program for studying radiation methods is underway in the Bureau's high-temperature laboratory. The basic data required include a knowledge of the energy levels of the various molecules, free radicals, and atoms that occur in hot gases and flames, the transition probabilities, and the line widths. Three phases of the program are currently being investigated. These are (1) the study of the relative intensities of lines in the visible and ultraviolet spectra of simple flames, (2) the determination of transition probabilities and line widths under conditions of thermal equilibrium, and (3) the analysis of infrared spectra of flames and the investigation of methods of determining temperatures from them.

At low temperatures (below 90°K) NBS research on thermometry has two major objectives: first, the determination of thermodynamic temperatures by means of a gas thermometer and, second, the development of convenient, sensitive, and reproducible secondary thermometers which can be calibrated by means of the gas thermometer. Resistance thermometers constructed of the semiconducting elements, silicon and germanium, have proved to be extremely sensitive. While satisfactory reproducibility still remains a problem, results of initial tests have been quite promising.

Temperatures in the range from approximately 4° to 1°K are obtained by controlling the pressure on a bath of liquid helium, and the relation between the vapor pressure of helium and the temperature is used to determine temperatures. Below this range, another method of both attaining and measuring temperatures must be used (the lowest limit attained by reducing the pressure on the helium is approximately 0.7°K). The method of adiabatic demagnetization of paramagnetic salts proposed by Giauque and Debye in 1926 is used to achieve these low temperatures. During the past year, equipment has been constructed and installed at NBS which is designed to permit investigation of the properties of these paramagnetic salts which serve as low-temperature thermometers. No effort has been made to set a low-temperature record, but the paramagnetic salt has been used to cool liquid helium to 0.02°K in order to investigate its properties at these extremely low temperatures.

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Books

Electronic and Ionic Impact Phenomena. By H. S. W. Massey and E. H. S. Burhop. 669 pp. Oxford University Press, London, England, 1952.

At a time when interest in electronic and ionic phenomena in gases is on the increase, this compendious and authoritative volume is most welcome. Here at last is a review of the experimental results and an outline of the theoretical calculations in the field of electronic and ionic collisions done the past thirty-odd years, presented in readable form by two authorities in the subject.

The large amount of material is organized logically, starting with electronic impacts with atoms, the measurement of total cross sections, then the results for elastic and inelastic impacts; this quarter of the book terminating with an outline of the quantum theory of such collisions and a comparison between theory and measurements. After a similar discussion of electronic collisions with molecules there is a chapter on electron impacts with surfaces of solids and one on electronic collisions involving radiation, bremstrahlung, etc. Next comes a chapter on the collision between atoms and one on the passage of ionic or atomic beams through gases. Finally there are chapters on the impact of ions and atoms on surfaces and on recombinations.

The book appears quite complete in its coverage of these complex phenomena. The references to the original papers seem to be inclusive. There are several bibliographies on special subjects and an adequate author and subject index. The volume will be a necessity to anyone working in this field.

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Civil Defense in Modern War. By Augustin M. Prentiss. 429 pp. McGraw-Hill Book Company, Inc., New York, 1951. $6.00.

Civil defense, although long recognized as a necessity in countries which have undergone aerial attacks, was until very recently considered virtually an academic issue in the United States. The appalling vulnerability of our cities and industrial centers to modern bombing planes and guided missiles capable of delivering atomic bombs is painfully evident at the present time, however, and as a result progress is being made toward the establishment of an effective civil defense program. A great deal of information both on what is to be expected from modern weapons and on how to combat their effects is presented in *Civil Defense in Modern War*. In the words of General Prentiss, the purpose of the book