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SCIENCE, TECHNOLOGY, AND WEAPONS
DEVELOPMENT IN HISTORY
ANNEX VOLUME II

HISTORICAL TRENDS RELATED TO
WEAPON LETHALITY
15 October 1964

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HISTORICAL EVALUATION AND RESEARCH ORGANIZATION
2233 WISCONSIN AVENUE, N.W.
WASHINGTON, D. C. 20007

HISTORICAL TRENDS RELATED TO WEAPON LETHALITY

Science, Technology, and Weapons

Development in History
(Annex II)

A Report prepared for the Advanced Tactics Project of the Combat Developments Command, Headquarters US Army, under Contract No. DA 30-069-AMC-647(X), dated August 28, 1964

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Historical Evaluation and Research Organization
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15 October 1964

SCIENCE, TECHNOLOGY, AND WEAPONS DEVELOPMENT IN HISTORY
(Annex II)

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Science, Technology, and Weapons Development
in History
(Annex II)

Metallurgy, Chemistry, Ballistics
(Part A)

by

Richard M. Leighton

THE ANCIENT WORLD

Two metals above all have served man in war, bronze and iron. Iron has been the basic material for weapons throughout most of recorded history, but bronze, with an earlier origin, has a record almost as long. Copper, its principal ingredient, was being mined in the Near East and elsewhere long before the dawn of history; copper implements dating back to about 6000 B.C. have been found in Switzerland and to 4500 B.C. in Mesopotamia. At first, it may be supposed, men merely collected the nuggets of pure metal they found lying about near the surface ore deposits. About the middle of the fourth millennium, with the accidental discovery that a very hot fire would somehow produce similar nuggets from certain brightly colored stones used for making pottery glazes--malachite, turquoise, lapis lazuli--the science of metallurgy was born.

Pure copper was easy to heat and highly malleable, but so soft that stone weapons proved more dependable in battle. Bronze, the hard alloy of copper and tin, exists in nature, as does the copper and zinc alloy, brass. It is thus impossible to say when bronze first came to be made artificially. Bronze implements were used, at all events, as early as 3000 B.C. in Crete, in Egypt in 2800 B.C., and in the second city of Troy in 2000 B.C. Bronze was hard, tough, and durable, and made excellent pointed and edged weapons. In time the ancient smiths learned, by

painful trial and error, to hammer the formed weapon while cold and then temper it by gradual heating and cooling, producing an extremely hard surface, almost like steel, that was yet not brittle.

The Discovery of Iron

As early as 2500 B.C., meanwhile, it had been discovered that an even harder metal could be produced from a common reddish brown ore, far more abundant than copper. To do this it was necessary to heat the ore to much higher temperatures than copper. Ancient furnaces could not, indeed, reduce iron ore to molten metal, easily separated from the charcoal and impurities of the ore, but only to a spongy mass of hot slag and cinders. Many centuries passed before it was learned that repeated hammering of this "bloom" would break out the impurities and blend the particles of pure iron. The pure wrought iron was itself not as hard as bronze, though it was more tough and malleable, and its melting point was too high (1535 degrees C. as compared with 1083 degrees for copper) for the crude furnaces of the time. Cast iron had to await the improved furnaces and bellows of the Middle Ages. It was not until about 1400 B.C. that the Chalybes tribe in the Armenian mountains learned the process of cementation, by which wrought iron, alternately heated in a charcoal fire and hammered, develops a very hard surface, harder even than bronze. Cementation produced, in fact, the first steel, through absorption of charcoal particles in the surface of the metal. Wrought iron weapons so treated were, in reality, encased in steel. Over the centuries additional refinements were learned: slagging the iron ore (adding a flux of limestone or other ingredients) to increase liquefaction of the slag in the furnace; quenching the hot steel in water to make it even harder (unlike copper and bronze which became softer under this treatment; and annealing through carefully controlled reheating and cooling, to reduce brittleness. The development of these techniques extended into Roman times.

Bronze, Iron, and Warfare

The impact of bronze and iron weapons on ancient warfare was truly revolutionary. In the case of bronze, the immediate consequences are less visible because they occurred at the very dawn of history and over an immense span of time. It can hardly be doubted, however, that bronze weapons figured importantly in

the rise of the urban civilizations of the ancient Near East. For iron; the record is clearer. The beginning of the Iron Age is usually dated at about 1200 B.C., when the collapse of the Hittite Empire led to the dispersion throughout the eastern Mediterranean world of the skilled iron smiths who, for some two centuries, had clung to their trade secrets and confined the new technology to a small geographical area. These Chalybes craftsmen, subjects of the Hittites, held the key to the immense military potential of iron, which, unlike bronze, could be produced in sufficient abundance to arm the common soldier, not just a military elite. The Hittites themselves had so little mastered the new war material that in 1288 B.C., when they met the Egyptians under Rameses II on the field of Kadesh in the great test of strength between the two empires, the battle was a draw. The records give no indication, indeed, that iron weapons were used on either side. It would appear that, despite its potentiality, the new metal was still costly and rare. Hittite kings at this time, we are told, often had to wait while a new steel weapon was being forged for them.

After 1200 B.C., however, the use of iron weapons spread rapidly through the Near East and even farther eastward and westward, transforming the whole nature of war. In the iron-girt armies of Assyria the ancient world felt a brutal and crushing force never before experienced. Yet the older materials were not altogether displaced. Iron weaponry was limited to what could be hammered out on the smith's anvil. The sword was the chief symbol of the Iron Age on the battlefield. Iron spearheads and axe-heads were difficult to make, particularly in quantity, since sockets could hardly be fashioned with a hammer. Small plates could be forged, but plate armor and helmets needed skill and long hours of labor. Thus, the Assyrian warrior, the first to inherit the new technology, carried a long iron cutting sword and armor of iron scales sewed to a leather base; his other weaponry seems to have been fashioned from the older materials. The Greek hoplite wielded an iron-tipped spear and a short iron sword, but his armor, shield, and helmet were of bronze. The Roman legionary soldier benefited by technological advances which gave him iron weapons of quality superior to those of his predecessors and most of his barbarian opponents. His prime weapons were the short steel thrusting sword and the throwing pilum whose soft iron head, half its length, was designed to break off after striking its target, and he wore a cuirass of overlapping jointed iron plates. The iron entrenching tools he carried on his back were hardly less potent than his weapons in spreading the dominion of Rome over the civilized world. Iron also contributed to siegecraft in the last millenium of the pre-Christian era, notably in the heavy iron head of the battering ram.

Roman Advances in Metallurgy

In the period of the Roman Empire certain technological developments affecting the quality and availability of metal weapons should be noted. Both the scale and the techniques of mining underwent a marked growth, and the miner began to be recognized as a skilled craftsman, as free native labor tended to replace slaves and criminals. Mine drainage was improved by application of the Archimedean screw and the scoop-wheel; at one of the Rio Tinto copper mines water was raised nearly 100 feet by eight successive pairs of scoop-wheels powered by treadmills. Mining was extended to the far corners of the Empire, especially Britain (lead, copper, iron, and tin) and Spain (copper, iron, and tin). In the 3rd Century A.D. the Spanish tin mines were closed, and most sources of stream-tin were exhausted; the veins of Cornwall accordingly took on a new importance. One of the byproducts was pewter, an alloy of tin and lead, which became a popular household material. Brass manufacture also attained a considerable scale. It was produced by cementation, in which calamine (zinc carbonate), copper, and charcoal were roasted together; pure zinc was still unknown, and brass remained very expensive, more valuable in certain areas than silver.

Iron metallurgy under the Empire at first centered in Noricum (modern Styria and Carinthia in Austria), where it had been established as early as the 10th Century B.C. Later it moved to Spain, where the so-called Catalan furnace was developed, in which two pairs of bellows were used alternately to maintain a constant blast. The higher temperatures thus made possible, combined with the good quality ore, produced a malleable iron directly, though not yet molten metal. In Noricum some of the ores were of such quality as to produce steel directly, but cementation continued to be the only widespread method for producing this metal. Weapons and tools of very fine steel were made from what the Romans called "Seric" iron, imported from southern India; this was a high-carbon steel ("wootz"), produced by heating iron with charcoal in crucibles, made into small cakes, and extremely expensive.

Uses of Chemistry in Ancient War

In any strict sense of the word, chemistry was unknown to warfare in the ancient world. Ancient smiths had no notion of the chemical processes involved in the reduction of ore to metal

or in the casting and forging of metals. Ancient metallurgy was a craft, not a body of scientific knowledge. The ancients similarly employed chemical processes, without understanding them, in what a later age would call chemical warfare. The Assyrians appear to have developed a special form of liquid fire, and simple incendiaries were fairly common in much earlier periods of warfare. The Greeks used a gas attack with sulphur fumes at the siege of Delium in 424 B.C. Finally, perhaps the most famous chemical warfare device in all military history, Greek fire, was introduced in 673 A.D. by a Syrian architect, Callinicus of Heliopolis, in the service of the Byzantine Emperor Constantine Pogonatus during the siege of Constantinople by the Saracens. The exact formula for Greek fire is not known today, though it was used for centuries by the Byzantines and later the Moslems; it was evidently a mixture of sulphur, pitch, niter, petroleum, and quicklime and could be propelled through tubes to considerable distances by a method which also remains unknown. More conventionally, it was also tossed in containers by ordinary siege engines.

THE MEDIEVAL INTERLUDE (400-1550 A.D.)

In the thousand years following the disintegration of central political authority in the west in the 5th Century A.D. there were significant advances in the scale and techniques of mining--depth of shafts, ventilation, drainage, use of powered machinery for hoisting ore to the surface, etc. In metal working, there were no really spectacular developments, though, contrary to widespread belief, the period was not one of retrogression. The art of the armorer became highly perfected in western Europe, producing finely wrought and decorated daggers, swords, scabbards, and armor that could hold their own with the best products of the Renaissance. This aesthetic craftsmanship was later carried over in the design and decoration of artillery pieces. A new development, crucial to the technology of war, was chain mail, which was for several centuries part of the standard defensive armament of the medieval man-at-arms; in the 14th Century chain mail began to yield to plate armor, in response first to the challenge of the crossbow and longbow, and later to the new hand firearms. Plate armor continued to be used into the 17th Century, and during its heyday in the 15th and 16th Centuries it absorbed the energies of a large class of artisans. Despite the heavy pressures for improvement, both in quality and in efficiency of manufacture, the armor of the late Middle Ages and early Renaissance became able to turn an

arrow only at the cost of becoming more elaborate, heavy, cumbersome, and expensive. The bullet could not be countered.

Some qualitative improvement in materials can be noted. The colonization and intensive settlement of many areas of Europe, both inside and outside the frontiers of the old Empire, led to the exploitation of new sources of superior ore. The old steel-yielding iron ores of Styria and Carinthia were vigorously exploited with the new mining techniques; so also were the copper deposits of Saxony and Sweden, the lead of central Europe and England, the tin of Cornwall, and eventually zinc. From the Arabs (who in turn had learned it from the Hindus) Europe learned the technique of making crucible steel, though the transmission of this and other learning from the Moslem world was hampered and delayed by the antiscientific bent of the medieval Church and medieval philosophy. Eventually the armorers of northern Italy and the Rhineland produced swords of a steel that rivalled in quality the celebrated "damascened" blades of Damascus and Toledo. About 1370 the medieval armorer added another weapon to the existing arsenal--the steel crossbow, a very powerful as well as a durable weapon of improved design which had to be bent by a mechanical device.

Cast Iron

The most significant single technological advance affecting warfare in the late Middle Ages was the technique of casting iron. There are evidences that ancient smiths had on rare occasions accidentally developed furnace temperatures high enough to produce molten iron, but, being unable to handle it, they had discarded it. Throughout the Middle Ages the older techniques of smelting iron continued to be used. Both the Catalan furnace, with its continuous blast, and the Stuckofen, of Roman origin, a tall (ten feet or higher) furnace, in which the ore was continuously reduced by charcoal, were widespread in central Europe. A new feature was the application of water power to the forging process, through water-driven hammers, and also, by the 14th Century, to the crushing of the ore. Similarly, water power was used, from about 1300 on, to operate larger and more powerful bellows; in that century, the heart-shaped bellows was invented, producing a more concentrated blast. These techniques, in combination, made possible the high temperatures needed to cause absorption of the carbon into the iron, and liquefaction, so that the molten iron (an alloy of iron and carbon) could be released from the bottom of the furnace through clay-sealed holes to flow into previously prepared molds of sand and clay. Beginning in the 14th Century the

blast furnaces of the Rhineland were casting iron in a variety of shapes. Since iron was relatively cheap, the products of casting found a rapidly growing market. The casting of copper and bronze also expanded after the discovery, in the mid-15th Century, of a process for separating silver from common argentiferous copper ores through the use of lead.

The new techniques for making both wrought and cast metal found an important new application in the firearms that began to transform warfare in the 14th Century. Gunpowder, introduced in Europe during the 13th Century, was first used in metal firearms in the 14th Century. Large "bombards," both long and short barreled, were being built by the middle of the century. The short bombards were mortars, smaller at the breech than at the muzzle, and were cast from bronze and iron, possibly also copper and brass; cast-iron bombards are alleged to have been used at the siege of Terni in 1340. Longer artillery pieces were made in the same century of forged iron bars welded together and bound with hoops. Richard II had some constructed for the defense of the Tower of London. The famous Mons Meg gun, at Edinburgh, was made of several sections screwed together, the whole piece being strengthened by welded hoops.

Probably the most famous and formidable of the bombards were the monsters used by the Turks at the siege of Constantinople in 1453. Twelve of these, including one super-bombard called Basilica, were designed for the Sultan by a Hungarian engineer, Urban, who had defected from the Byzantine Emperor. Basilica was built of wrought iron bars and hoops; it measured 36 inches in bore diameter, its stone balls weighed 1,600 pounds, it ranged more than a mile, and 200 men and 60 oxen were required to move it. Its rate of fire was to be about seven shots a day, but after the first few shots it blew up. The smaller pieces in the Sultan's siege train proved more effective. Some of them were used 354 years later with good effect against an attacking British squadron.

The technique of casting large guns was adapted from that of bell founding, which dated from the 8th Century. This involved pouring the metal into a clay mold consisting of a core and an outside cope. The clay mold, reinforced by iron brass, was lowered into a pit; the furnace was tapped and the molten metal poured into the mold; after the metal had cooled, the mold had to be broken. Thus each gun was an individual product, like a piece of sculpture, which indeed it resembled also in its elaborate decoration. Not for 200 years was an effort made to cast cannon in series from a single mold. After the mold had been broken, the rough casting had to be bored out by a bit

mounted on a long shaft powered by a water wheel; since the shaft was supported on one end only, the boring was frequently inaccurate. It could not, in any case, remedy inaccuracies in the original mold. It was not until the 18th Century that the Dutch took the lead in boring out solid-cast barrels. Early in the evolution of firearms the effort was made, but soon abandoned, to produce workable breech-loading pieces. The technology of the times was incapable of producing the tight seal of the breech-block needed to contain the expanding gases of the charge. This problem would not be solved until the development of precision machining in the 19th Century.

Cannon by the Casting Process

It is uncertain when long cannon were first made by casting. Cast bronze guns came first, though cast iron pieces are recorded at Dijon before the middle of the 15th Century--evidently isolated and not very successful products of a technology still in its infancy. The new techniques were brought over to England by the early Tudors, along with skilled technicians, at the beginning of the next century, laying the basis for the Sussex iron industry which dominated European gun metallurgy until the rise of the Swedish iron industry in the 17th Century. The first iron gun made in a single casting in England was produced in 1543 on order for Henry VIII, by an imported French metallurgist using continental techniques already applied to casting bronze. The advantage of cast iron lay in its cheapness, not its superiority over other metals, for both brass and bronze, though expensive, were tougher and less prone to burst.

Over the ensuing two and a half centuries, indeed, bronze and brass would hold their own against cast iron in the manufacture of artillery except in heavy naval ordnance; bronze gun barrels, being relatively soft, had a tendency to deform under the repeated pounding of round shot bounding eccentrically through the tube, and thus proved unsuitable for the heavier types of guns. The chief limitation on the use of wrought iron for large artillery pieces was the size and power of the forging equipment required; here, again, the 19th Century would bring heavy steam hammers, rollers, and other machinery that would expand the uses of wrought iron. Meanwhile, bronze and brass remained the most dependable materials for field artillery, and cast iron, despite its nasty tendency to burst in action, remained the basic material of large naval ordnance.

THE AGE OF CHEAP IRON (1550-1850)

With the development in the mid-16th Century of techniques for casting heavy ordnance, the technological basis was laid for the manufacture of artillery during the next two and a half centuries. Wrought iron cannon would not return to warfare until the 19th Century. Meanwhile the use of metals steadily expanded, both in scale and variety, mainly in articles of peacetime application, and techniques of metalworking underwent many improvements. In all metals, including iron, the manufacture of weapons and munitions made up only a small part of the total demand. Copper, with its two derivatives, brass and bronze, found many new uses in this period, and became available in larger quantities through the process of separating silver from the common silver-bearing copper ores. One significant development merits particular notice, the invention, in the early 16th Century, of the reverberatory furnace for smelting copper and copper alloys, though not yet iron. In this type of furnace, the heat is reflected downward from a low roof, so that direct contact between fuel and metal can be avoided.

In this period the main thrust of development in metallurgy, responding to the basic demand for larger quantity at lower cost, was the effort to adapt coal, the most plentiful of fuels, to the manufacture of iron, the cheapest of the metals. By the 17th Century, the expanding consumption of charcoal was exhausting timber supplies in many iron-producing countries, including England, whose iron industry had dominated the field in the preceding century. In the 17th Century Sweden's new iron industry, nourished by still plentiful timberland, began to encroach on England's continental markets, and by the following century it had gained undisputed supremacy. At the same time, the expanding scale of warfare in the 17th Century, with its new emphasis on artillery, along with growing demand for articles of peacetime use resulting from expanding population and advancing technology, combined to increase the total demand for iron. Under the pressure of this demand, the late medieval Stuckofen had developed, by the end of the 17th Century, into blast furnaces 30 feet or more high, with water-powered bellows, which operated continuously for many weeks at a time. But while the new furnaces produced a better grade of cast iron than before, the high temperature they attained caused a fusion in the ore which left sulphur and phosphorus in the final product, making it too brittle to be worked into bar iron from which most articles were made. For this purpose the older techniques, using charcoal, still gave a superior product, and the bulk of the total demand was still for wrought iron.

The problem in using coal in the smelting or working of iron was that the sulphurous fumes given off by burning coal, especially the readily available soft coal in most European deposits, ruined the quality of the iron. A partial solution was found, in the 18th Century, through the use of coke, which had been developed in the preceding century by the brewers of Derbyshire for drying malt. Its application to the smelting of iron was developed in several stages by two generations of the Darby family of Coalbrookdale in Shropshire, largely during the first half of the 18th Century. The Darbys used carefully selected hard coal to make a coke hard enough to support the heavy load of ore in the furnace and permit free circulation of blast air.

High-Quality, Inexpensive Cast Iron

By this process, and using carefully selected ores of low phosphorus content, the Darbys were able to produce a high grade of cast iron which proved admirably adaptable to the manufacture of a wide variety of household and other consumer wares. Coke-smelted cast iron was also being used in England, before the end of the century, for large structural castings. Significant improvements in the process contributed to its wider use. Toward the end of the century, coke manufacture was improved by the introduction of closed ovens, resembling bee hives, instead of the open stacks copied from the traditional process of making charcoal. In 1760 Smeaton replaced the bellows of the blast furnace with two water-powered pistons of greatly increased capacity, and 16 years later Wilkinson applied the far greater power of the steam engine to strengthen the blast. Even though mainly confined to the production of cast iron, for the reasons given, the application of coke to iron smelting expanded rapidly. From only 17 in 1760, the number of coke furnaces in England rose to 31 in 1775 and 81 in 1790; the total production of iron in England, which had been only 20,000 tons in 1720, had risen by 1800 to 250,000 tons. On the continent, the widespread use of coke was delayed until well into the 19th Century.

Effect of Better Metal on Ordnance Manufacture

Both in scale and quality, the manufacture of artillery in the 18th Century responded to these technical improvements.

A corollary adaptation in heavy castings was the remelting in the foundry of the iron obtained from coke furnaces, using reverberatory furnaces which kept the iron away from direct contact with the fuel. The improvement in quality thus achieved was evident in the guns used in the Royal Navy which, according to a French source, had not a single burst gun in 20 years. Another qualitative improvement in gun-founding was the introduction of boring of solid-cast barrels, in the Netherlands in 1747 and in England in 1775 with John Wilkinson's hollow boring bar. More generally, the great expansion in cast-iron output in the 17th and 18th Centuries had as one of its byproducts the marked increase in the use of artillery, with a steady increase in calibers in naval ordnance, which characterized the evolution of warfare in this period.

Growth of Wrought Iron Production

Even with the improvements in coke-smelted cast iron, it was still too brittle to be used to make wrought iron, the form in which iron was most in demand. By the latter part of the 18th Century, the rising cost of wrought iron, resulting from the continued depletion of timber resources, posed a serious problem. The eventual response to this need was the use of the so-called "puddling" process, in which the molten metal was agitated by a long steel bar in a reverberatory furnace fueled by coke; this had the effect of exposing all the metal, not merely that on the surface, to the air, thereby achieving a more complete decarburization which transformed it into malleable iron. The process was invented almost simultaneously in 1783 by Peter Onions, a Welsh ironworks foreman, and Henry Cort, owner of a forge and slitting mill near Portsmouth; history has given the credit mainly to the latter. Cort followed the puddling process by immediately rolling the hot lumps of wrought iron between heavy grooved rollers to squeeze out the dross and form the metal into bars; these had previously been produced, as a separate process, by first stamping the metal into plates which were divided into bars in a slitting mill, or by hammering them out individually. The rolling technique itself had been developed in Sweden by Christoph Polhem in 1745.

Wrought iron produced by the puddling process was still inferior to charcoal iron, but it was far cheaper. A further improvement came in 1829 with the introduction of preheated blast air, using the spent gases from the blast furnace itself; this innovation, by Neilson at the Clyde Ironworks in Glasgow,

made it possible to produce three times as much puddled iron with the same amount of fuel. Still another development was the "wet" puddling method by which the floor of the furnace was coated with small pieces of slag containing iron oxide, which combined with the carbon in the metal to produce carbon monoxide under the surface, resulting in an effervescent agitation which accelerated the decarburization. By 1850 England was producing 2½ million tons of iron annually, reflecting the expanded output of both cast and wrought iron.

THE AGE OF CHEAP STEEL (1850-)

Since ancient times there had been no fundamental change in the methods of making steel, which remained a product of small-scale individual craftsmanship. The primitive technique of cementation, by covering bar iron with fragments of charcoal and heating in a charcoal fire, was still practiced. A widespread technique was an adaptation of the ancient cementation method; it consisted of dipping blooms of wrought iron into molten iron of a high carbon content, and then forging it to the requisite hardness. Wrought iron bars could also be cemented by firing with charcoal for several days in a closed oven. Finally, using the technique of the ancient Hindus for making wootz steel, iron was heated with charcoal in crucibles. The basic material used in all these processes in England was Swedish bar iron of high quality and commensurate cost. As a result, steel cost five times as much to make as wrought iron, and as late as 1850 England produced only 40,000 tons of steel as against three million tons of wrought iron.

The first significant improvement in these processes was developed by Benjamin Huntsman about the middle of the 18th Century. He placed small crucibles of special clay inside a melting chamber fired by coke, and through intense heat and a special flux succeeded in producing a cast steel completely free from silica or slag at a slightly lower cost than that of other existing methods; the product unfortunately could not be welded, and its very hardness was disadvantageous for certain uses. Huntsman's technique became, nevertheless, the basis of the Sheffield steel industry and was widely copied in Europe. No other notable improvement occurred until the middle of the 19th Century, and the high cost of steel, together with the imperfections of the material itself, continued to deter its use in the manufacture of heavy ordnance.

The Krupp Works and Modern Cannon

The Krupps built their reputation during the first half of this century on the manufacture of fine cast steel, and by mid-century they were producing steel artillery pieces in very limited numbers. One of these of advanced design, shown at the Great Exhibition of 1851 in England, attracted much attention and proved a harbinger of future developments. Krupp steel had four times the tensile strength of cast iron and twice that of wrought iron. Yet artillerymen generally regarded steel as too brittle (several Krupp guns had burst since the first was built in 1847) and lacking in uniformity to supersede the more dependable wrought iron, cast iron, and bronze, particularly since this very period was witnessing a revolution in large gun design and manufacture, using these traditional metals.

Good, Cheap Steel

The manufacture of steel of fairly good quality in quantities and at cost comparable to the manufacture of cast and wrought iron was first made possible through the Bessemer process, actually discovered first by William Kelly, an American iron manufacturer in Kentucky. Kelly went bankrupt in 1857 and his claims were eventually transferred to Henry Bessemer, a young English engineer who had been experimenting along the same lines. Working under the patronage of Napoleon III of France, who had offered a prize for a cheap method of making armor for warships, Bessemer by 1856 developed a process of forcing a blast of air completely through a mass of molten iron, using the carbon in the metal itself as fuel. By stopping the blast at any desired point the amount of carbon remaining in the metal could be controlled, and either wrought iron or steel could be produced. The impurities oxidized by the air blast were slagged by adding iron ore. The process was rapid, making it possible to produce 20 tons of steel in 25 minutes from one loading of pig iron.

At about the same time, the Siemens brothers in England were developing a process of heat regeneration, using hot waste gases and--somewhat later--gases produced from low-grade coal, to preheat incoming fuel and air. The so-called Siemens-Martin "open hearth" process, developed a few years later, used a regenerative furnace to melt pig iron mixed with scrap iron or steel; the Siemens process used pig iron with iron ore. Both were superior to the Bessemer process in that the heat regeneration

developed a very high working temperature, the method permitted the use of scrap iron (in the case of the Siemens-Martin process) and low-grade coal, and, being relatively slow, it permitted strict control. One difficulty in the Bessemer was that, because of the acidic nature of the siliceous materials used in refractory lining of the converter, it was effective only when ores and pig iron of low phosphorus and sulphur content were used, and most ore deposits in northwestern Europe had a high phosphorus content. At first, the Siemens process involved the same problem. In 1875, S. G. Thomas and Percy Gilchrist overcame this defect by introducing limestone in the firebricks of the phosphates formed by the blast air in the converter and slagged the sulphurous compounds. In open-hearth furnaces the same results were attained by the use of high-grade siliceous bricks.

In England the Bessemer process, using the so-called "Bessemer" ores of Cumberland and other high-grade ores imported from Sweden and Spain, remained the basis of most British steel production until near the end of the century; in the United States the Bessemer method held on somewhat longer. Elsewhere the open-hearth processes largely superseded it. The basic product of all these processes was "mild" steel, harder than wrought iron but less so than the "blister" steel produced by the older processes. It provided the material for a wide variety of uses--rails, boiler plate, bars, structural steel (for ships, houses, and reinforced concrete), and sheet metal. Between 1856 and 1870 the price of steel dropped by 50% and its production increased sixfold. In 1863 the first steel ship and the first steel locomotive were manufactured. Some idea of the rise in total production is given by the increase in British output of steel from 220,000 tons in 1870 (practically all by the converter process) to 4.9 million tons in 1900 (of which 3.1 million was by the open-hearth process). American steel output in 1900 was ten million tons, that of Germany about eight million.

Alloy Steels for Shells and Armor

The most significant avenue of subsequent development in the metallurgy of steel was in alloy steels for special applications. Faraday had made chromium and nickel steel as early as 1819, but it was not until 1868 that Mushet began to manufacture high-carbon tungsten-manganese steel, from which highly durable tools could be fashioned without the quenching technique.

Chromium steel for armor-plate and shells was produced commercially in France in 1877. Sir Robert Hadfield of Sheffield discovered how to make manganese steel, by quenching, in 1882, and Le Creusot started making nickel steel in 1888. All these advances derived from the new science of metallography, the study of the structure of metals, which emerged from the experiments of Rene Reaumur in France, H. C. Sorby and Michael Faraday in England, and Adolf Martens in Germany. From the discovery of X-rays in 1895 by Wilhelm Roentgen came, among other things, the science of crystallography, which led to further refinements in the uses of metals.

Matching the development of mass production techniques in smelting, finishing processes also underwent improvement in the latter part of the 19th Century. Hammer forging gave way largely to rolling processes. A basic refinement was the reversing mill, which passed the metal ingots and sheets to and fro with major savings in time. The three-high mill used a third roller to pass the metal back without reversing the machinery; the continuous mill had roller-stands in a series of diminishing size and power. All these methods appeared in the 1860s and underwent subsequent refinement.

Aluminum and Aircraft

Aluminum, which has become the basic material of the modern aircraft industry, was first produced experimentally in 1827 by Wohler.* The French chemist Sainte-Claire Deville managed to make aluminum spoons for Napoleon III's state banquets, as well as a rattle for the Prince Imperial; but the process was too expensive for widespread application. In 1886 Charles Martin Hall developed a process of electrolytic production of aluminum from molten alumina (oxide of aluminum) dissolved in molten cryolite (mined in Greenland but later produced synthetically). This inaugurated the age of light metals and their alloys, based on mass production with cheap electricity. To make a ton of aluminum in this way requires about 18,000-20,000 kilowatt-hours of electricity. Owing to their possession of unlimited sources of cheap water power, the Swiss were for many years the chief producers of aluminum. Commercial production was also facilitated by K. J. Bayer's

* Forbes, Man the Maker, 281; Derry and Williams, History of Technology, (p. 494) say 1845.

improvements in the basic preliminary process of purifying the bauxite ore with caustic soda and heating the purified alumina in chlorine to produce aluminum chloride; by exposure to hydrogen and liquid sodium this was reduced to metallic aluminum. Aluminum and magnesium alloys, with other light metals, have challenged steel and copper in many fields of manufacture which the latter formerly dominated, such as air transport, electric power transmission, cooking utensils, and building construction. Since World War II aluminum and its alloys can be cast, forged, extruded, rolled, spun, beaten, and sprayed to meet many applications.

THE 19th CENTURY REVOLUTION IN MILITARY TECHNOLOGY

The transformation of warfare that occurred in the century following the defeat of Napoleon in 1815 was a prolonged revolution created and sustained by many forces--political, economic, and social--of which technological advance was only one, though in many ways the most dramatic as well as most profound. In the realm of technology, the developments with which we are here concerned--metallurgy, chemistry, and ballistics--were prominent but far from all-embracing factors in the military revolution. The new weaponry of this revolution, along with the immense volume and variety of mass-produced tools and consumable articles of the new industrial civilization, were also products of machines, themselves the creation of a revolution in mechanics and engineering without which the new knowledge of metals and new sources of power would have remained as sterile as the scientific theories and gadgets of the Greeks two thousand years earlier.

Throughout the 19th Century the application of new scientific and technical knowledge to military technology characteristically lagged behind other applications. As late as 1860, as Bernard Brodie has pointed out, the naval guns in actual service did not differ in essential respects from guns in use three centuries earlier. The Royal Navy's 68-pounder smoothbore, for example, which had been adopted in 1840 and was the heaviest gun then in service--so heavy and violent in recoil that it was used as a pivot gun only on the largest warships--was almost exactly like some of the naval guns of Queen Elizabeth's day. This is not to ignore the numerous improvements and refinements that had occurred over the intervening centuries--and particularly the last--in the quality of casting, the mixing of powder, and the precision of boring. But the basic principles of gun construction remained the same.

Yet great changes were already in the making, and many were in fact already proved and known, even though they had not yet made their way into the standardized equipment of armies and navies. By 1863, only three years later, in the sphere just alluded to--large naval ordnance--virtually all the basic principles embodied in the modern naval gun had been introduced into the ordnance of the period.* In other types of naval materiel, and in the weaponry of land combat, changes of almost equal moment had also made their appearance. Thereupon, for another quarter-century or more, a lull ensued while armies and navies endeavored to assimilate the new technology.

In order to relate the new developments of this first phase of the 19th Century military revolution to the technologies under consideration, it will be necessary to retrace our steps somewhat to pick up the slender threads of antecedent knowledge in the fields of chemistry and ballistics.

Chemistry

To the historian of military technology, one of the most striking features of the evolution of that technology before the 19th Century is its almost complete divorce from the growth of scientific knowledge. This is evident in both chemistry and ballistics. In chemistry, it can be said virtually without qualification that no scientific knowledge existed before the 18th Century. The 17th had, of course, seen a great flowering of science, both theoretical and applied, but mainly in mathematics, engineering, mechanics, physiology, and physics. In chemistry, development was slower. The tradition of alchemy died hard--even Newton dabbled in it--and although by mid-century most chemists knew the common metals, their alloys and salts, this was virtually the extent of knowledge.

It was the following century which saw the real birth of modern chemistry. Significantly, the new developments were mainly in the field of industrial chemistry and had little impact on war technology. For the first time chemists began to learn the inner processes of molecular transformation that occurred in metalworking. Reaumur's Art of Converting Wrought Iron into Steel (1722) described some of these processes with

* Bernard Brodie, Sea Power in the Machine Age (Princeton, 1941), p. 198.

remarkable accuracy. James Watt, Joseph Black, and Joseph Priestley all made important contributions to the knowledge of the nature and behavior of gases, and Antoine Lavoisier at the end of the century laid the basis of modern chemistry in his Traite Elementaire de Chimie. He devised the nomenclature still used for classes of chemical substances and established mass as the basic property of the elements and their compounds. Systematic study of gases was also furthered by Henry Cavendish, especially in relation to combustion, oxidation, and reduction; Jacques Charles showed the relationship between temperature and volume of gases. Analytical chemistry, in the latter half of the century, also led to the discovery of some new metals: chromium, manganese, molybdenum, uranium, zirconium, cerium, and titanium.

But chemists and chemistry alike continued to shun war. When the revolutionary government of France attempted to mobilize science in defense of the nation, the major effort naturally went into its technical applications in the production of munitions. The result was a triumph of organization and administration in the mass production of weaponry, but the cannon, muskets, powder, and shot produced were the primitive instruments already in existence. It was still necessary, for example, to collect saltpeter from offal heaps all over France.

In the 19th Century chemistry made tremendous strides and for the first time had a direct impact on military technology. A major development was the isolation and identification of chemical elements and compounds, by Davy, Dalton, and others; by 1860 some 60 elements had been discovered. As already noted, the sciences of metallography and crystallography also emerged in this century. Most of the modern explosives were discovered in the same period, though the military applications of some did not come until later.

Apart from the expanding chemistry of metallurgy, the concrete applications of the new chemistry to war during the 19th Century were relatively few. One of the most important was the percussion cap, which brought about marked changes in the infantry musket. In 1798 L. G. Brougnatelli discovered silver fulminate, and in the year following, E. C. Howard produced fulminate of mercury; these were the first of several explosives which could be ignited through concussion. In 1807 the Reverend Alexander Forsyth, a Scottish clergyman, succeeded after years of experimentation in developing a mercuric fulminate that would readily explode under a hammer blow and communicate the flash through the touchhole of the gun to the powder charge in the

barrel. A percussion cap employing this powder was invented in 1814 by Joshua Shaw of Philadelphia, using successively iron, pewter, and finally copper caps. After being slowly adopted, the percussion cap became the basic method of igniting the propelling charge in both small arms and artillery. Used at first in the form of a separate cap, which the user had to affix to a nipple beneath the weapon's hammer, it was subsequently incorporated in the combined cartridge and projectile.

No real improvement in gunpowder itself was achieved until about 1860, when Major Thomas Rodman of the US Army discovered the principle of progressive combustion. He found that the rate of combustion and therefore the pressure of the expanding gases in the bore could be slowed by compressing the grained powder into pellets of greater density. Since the compressed pellets exposed a smaller surface initially to be ignited, less gas was evolved during the early instants of combustion, and the evolution of gas continued as the projectile moved down the bore. The result was higher muzzle velocities and lower maximum pressures. This discovery resulted in successive improvements in the ordinary black powder which continued to be the basic propellant for small arms throughout the remainder of the century. It had an important consequence in the development of rifled artillery, by making it possible for a gun of any given caliber to eject a heavier projectile than formerly; by lengthening the bore, greater muzzle velocities could be attained. By the end of the century, as a result, muzzle velocities had mounted to almost 3,000 feet per second, and ranges increased in proportion.

The development of slow-burning powders was associated with smokeless powders which began to come into use late in the century. The first satisfactory smokeless powder was produced by a French chemist, Vieille, and the Swedish inventor Alfred Nobel in 1890 developed ballistite, an early nitroglycerine smokeless powder. Cordite also appeared about this time. Apart from the advantage of not betraying a gun's position, the new powders were also relatively slow-burning, giving the thrusting type of propulsion described above. Their most effective use was in rifled pieces (which now could be made larger since the pressures to be sustained were smaller), whose elongated projectiles were both more accurate at the longer ranges than spherical shot and could sustain higher velocities against air resistance.

Late in the century, largely through Nobel's work, the nature and the technique of detonation of the new explosives--

TNT, tetryl, picric acid, PETN, cyclonite--became known. Picric acid was first used in battle in the Russo-Japanese War (1904-1905); TNT became a standard explosive only in World War I.

Other applications of chemistry to military technology, which can only be mentioned here, were the whole field of toxic chemical agents; the internal combustion engine; rocket and jet propulsion; and the improved ordinary and high explosives of the 20th Century. In this connection, too, should be mentioned the solution of the ancient problem of gunpowder shortages resulting from the scarcity of saltpeter--first, through the discovery of abundant sources of saltpeter in the nitrate deposits of India and Chile, and later through development of processes for extracting nitrogen from the air and from byproducts of the manufacture of coke.

Ballistics

In the evolution of the science of ballistics before the 19th Century, as in that of chemistry, one notes the same absence of military applications and the same difficulty in determining at what point in time a genuine science can be said to have emerged. One of the presumed founders of ballistics, the 16th-Century mathematician and engineer, Niccolo Tartaglia, wrote two treatises on artillery and one on fortification and tried to compute the ranges of cannon by tables derived from a theory of dynamics--but he was devoid of military experience and had no technical knowledge of artillery. His most useful contribution to posterity was a gunner's quadrant, a tool for measuring true angle of elevation. Tartaglia's numerous academic successors wrote voluminously and spun many refinements of his basic theories, but failed to correct his errors (which were fundamental) and added nothing useful.

In the following century, Galileo revolutionized the whole approach to ballistics as one aspect of his study of the laws of physics and dynamics. Fascinated by the theory of projectiles, he studied the artillery pieces of his day as the best means of testing his mathematical theories. From his studies came the parabolic theory (1638), which although itself erroneous, did correct the most basic efforts of Tartaglia's theories. Tartaglian theory retained its hold on popular belief until a popularization of Galileo's views appeared in 1674, after which Galilean theory was accepted as gospel well into the 18th Century.

The art and practice of gunnery and of gun design, meanwhile, remained unaffected. As Albert R. Hall has pointed out in his pioneering study, Ballistics in the Seventeenth Century, the ballistical theories of the text-books, whether scientifically accurate or not, were scarcely relevant to the warfare of the time, in which virtually all firing was at point-blank ranges, while the utter lack of uniformity in firearms and the erratic, wholly unpredictable path of a projectile's flight, made experimentation almost meaningless. When Benjamin Robins, a British mathematician, did attempt to experiment in the 18th Century, he found that at a range of 800 yards the cannon ball diverged as much as 100 yards to the right or left of the line of fire, and varied as much as 200 yards in the first contact with the ground.* Only in the growing use of mortar fire in late 17th Century warfare did there appear to be some connection between theory and practice, and even here the imperfections of the materiel made the theories of the scientists useless from the gunner's point of view.

Benjamin Robins, however, did achieve a first measure of success in providing a scientific basis for gunnery. He studied not only exterior ballistics, the subject of all previous theorizing, but also interior ballistics (the motion of projectiles inside the gun) and terminal ballistics (their behavior at the end of flight). Robins perceived the many errors in the theories of Galileo and Newton--such as ignoring the effect of air currents--and perfected the ballistic pendulum, invented by Cassini in 1707, into an effective instrument for measuring the velocity of a projectile. His New Principles of Gunnery (1742) exerted a wide influence.

The triumph of scientific ballistics came in the 19th Century. Only then had metallurgy and mechanics reached a stage of development that made possible the design and manufacture of weapons sufficiently precise in their dimensions and predictable in their behavior to provide a basis for scientific analysis. Its effects on military technology can best be viewed along with those of the new scientific metallurgy in the general context of the military revolution of the 19th Century.

The New Military Technology

In land warfare, the earliest significant technological change in this century, the invention and introduction of the percussion cap, has already been described. It eliminated most

* Hall, pp. 52-56.

of the uncertainty from what had been for centuries one of the most uncertain of the many actions involved in using a hand firearm on the battlefield, namely the act of firing itself. Even more revolutionary, however, was the cylindro-conoidal bullet, which finally made practicable the replacement of the inaccurate, short-ranged smoothbore musket by the highly accurate, much longer ranging rifle, as the basic infantry weapon.

The rifled musket itself was not a product of either the new metallurgy or the new ballistics, since the principle of rifling was already well known. The development of rifled weapons in the 19th Century profited greatly, however, from the increase of knowledge in both these fields. With the improved techniques and machinery of metal working that became available, it was possible to bore and rifle barrels with far greater precision than ever before. For centuries the manufacture of hand guns had been the task of the skilled gunsmith, who produced each weapon as an individual product, often a work of art. The basic metal had been wrought iron, the usual process one of wrapping and welding a strip of metal around a core. The first rifled barrel drilled in a bar of cast steel was made in the 19th Century New York Remington gun factory, and the Remington shop was one of the first to develop assembly-line techniques of production, based on the principle of interchangeable parts introduced early in the century by Eli Whitney and others. In the new rifled weapons of this period, the science of ballistics found a medium for systematic experimentation and rapid accumulation and refinement of knowledge of all aspects of the behavior of projectiles.

Breech-loading was another feature of early firearms, long in disuse, which the science and technology of the 19th Century liberated from its ancient disabilities. Traditionally the difficulty with breech-loading weapons in the days of imprecisely fitting metal parts had been the leakage of gas and flame from the exploding charge through the seams of the breech.

Associated with the development of 19th Century breech-loading weapons was the metallic cartridge, which combined projectile, powder charge, and percussion cap in a single capsule. Made from a special alloy of copper or other soft metal, its expansion under the heat of the explosion effectively sealed off the rearward escape of released gases.

The principal and only really basic subsequent development in small arms was the principle of repeating and, later, automatic fire, which found an immense variety of applications in

the late 19th and 20th Centuries. These did not stem from new metallurgical developments but from mechanical invention, made potent by the earlier metallurgical and ballistic advances.

Artillery

It was in the development of artillery, especially large ordnance, that the new metallurgy, chemistry, and ballistics of the 19th Century had their most spectacular effects. Cavelli in Italy made the first successful rifled cannon in 1846--breechloaders bored with two spiral grooves and using cylindrical shot. A little later, Joseph Whitworth, a leading English gun maker, produced a "rifled" gun, also a breechloader, in which a twisting hexagonal bore was substituted for spiral grooves.

In the Italian War of 1859, Napoleon III's rifled artillery proved decisively superior to the smoothbores of the Austrians both in range and accuracy. Yet most armies clung to smoothbores until well into the third quarter of the century, partly because of their cheapness and greater reliability. In the American Civil War, both rifled and smoothbore artillery was used on both sides, but the favorite piece, for Federals and Confederates alike, was the muzzle-loading, smoothbore, bronze Napoleon. This serviceable gun, actually a 12-pounder gun-howitzer, was already obsolete in Europe, and its days were numbered in America. The comparative softness of bronze had always been a serious shortcoming, and the new metallurgical techniques, together with the scientific study of interior ballistics, now made it possible to exploit the superior hardness and durability of iron.

The first crucial developments were in heavy ordnance, especially naval guns. What was essentially an improved version of the traditional solid-cast iron naval guns were those developed by Dahlgren and adopted by the US Navy in 1856. The Dahlgren guns were muzzle-loading smoothbores, but their distinctive feature was their smooth exterior shape, resembling a beer bottle, which was scientifically designed to place the greatest thicknesses of metal at the points of greatest stress. In 1860 Major Rodman, US Army, invented the hollow-casting process by which the gun was cast around a core chilled by a coil of running water. This method caused the interior of the bore to harden first, so that the outer layers of metal, shrinking inward as they cooled, exerted continuous compression on the hardened interior. The explosive force of the charge was

thus absorbed by the entire thickness of metal surrounding the bore, rather than by successive layers expanding outward. The hollow-casting technique was applied in the construction of Dahlgrens and most other heavy cast-iron guns of the US Navy during the Civil War and for 20 years after. The effectiveness of the great Dahlgren and Rodman smoothbores, cast in calibers up to 15 inches, in smashing through the armor of Confederate ironclads, caused them to be rated as the best guns in service in their day.

Parellel with these developments, efforts were being made to adapt steel to the manufacture of artillery. As noted earlier, the Krupps of Essen early seized and held the lead in this sphere, and with the perfection of the Bessemer process in the late 1850s, cheap cast steel of good quality became available. The Prussian Army's breech-loading, rifled steel artillery, made by Krupp, proved overwhelmingly superior to the French bronze guns in the war of 1870. After about 1880 steel was used universally in artillery of all kinds.

The most revolutionary innovation in 19th-Century ordnance, and the one most directly an outgrowth of improved metallurgy and scientific interior ballistics, was the hooped or built-up gun which, in conjunction with rifling at a later stage of development, made the first long step toward the powerful ordnance of the 20th Century. The evolution of this technique of design and construction is usually associated with the race between ordnance and ship armor which forms the central thread of naval technological development during the latter half of the 19th Century. Yet the impetus to make guns more powerful did not come originally from the challenge of the armorclad warship. Experimentation with hooped gun construction went back long before the advent of armor, at least to 1829, when a French naval officer, A. Thiery, succeeded in shrinking a wrought iron envelope over a cast-iron barrel. As early as 1843, Professor Daniel Treadwell of Harvard University constructed a few built-up guns by this method for the US Government.

What this method accomplished was the exertion of a strong compressive tension on the barrel, so that the expansive force and heat of the exploding powder charge encountered the resistance of this compression from the first instant of the explosion. Not only would this type of construction not have been possible with the techniques of casting and forging available 50 or 100 years earlier, but its very purpose would not have been understood without the knowledge of the properties of metals and of interior ballistics that had developed in the interim. It seems

evident, in fact, that the weapon was a direct product of the growth of knowledge and technique, and was not responsive to the pressure of any specific need; necessity was not the mother of this invention.

It must be immediately added, however, that the technique of the built-up gun did not develop rapidly, nor were the new weapons adopted on any considerable scale by naval services, until the challenge of iron armor presented itself. It was not until 1859 that the British Admiralty Board ordered a large number of 40-pounder and 70-pounder rifled guns of built-up construction then being produced by the prominent gunmaker William Armstrong; the threat to which they responded was the impending completion of the French ironclad warship, Gloire.

Armstrong's guns, which were of very advanced design, actually combined four features of the new ordnance technology; breech-loading, rifling, built-up construction, and the use of soft metal bands on the projectile to be gripped by the grooves of the rifling. What the naval officials were primarily interested in was the second of these features--presumably along with the fourth. Rifling was, in fact, widely regarded as the best answer to armor; built-up construction had as yet attracted little attention. There was, however, a close interrelationship between the two. Rifling, which had been introduced in land warfare mainly in the interests of improving the accuracy of weapons, placed extra strains on the tensile strength of the barrel of large guns, owing to the tight fit of the projectile and the consequently greatly increased pressure from the exploding powder on the walls of the barrel. In addition, the use of elongated projectiles--a natural corollary of rifling, since they permitted both greater range and greater accuracy--placed a heavier inert mass before the powder charge than did spherical shot of the same diameter. As a result, early rifled cannon were prone to burst. The barrels had to be made stronger.

By the early 1860s large rifled ordnance had fallen into temporary disfavor, since it appeared to be less effective than giant smoothbores, firing spherical projectiles, in smashing armor. It should have been obvious, but was frequently overlooked at the time, that spherical shot could be used with heavier charges than elongated projectiles of the same caliber, and therefore could deliver a more powerful blow at short ranges. This was demonstrated over and over again during the Civil War by the success of the great Dahlgrens and Rodmans against Confederate ironclads. The full potentialities of heavy rifled ordnance were not utilized, in fact, until the

development of slow-burning powders in the 1860s, which gave the projectile a comparatively prolonged rather than an instantaneous propulsion, and therefore could hurl heavier projectiles and attain higher muzzle velocities than could the quick-burning powders.

At about the same time that the Armstrong built-up guns were coming into vogue, Captain A. T. Blakely developed and systematized the principles of reinforcing gun tubes by hoops shrunk on at points of greatest stress, and also the technique of concentric tubes of different degrees of elasticity. As we have seen, steel guns also became more common with the advent of cheap Bessemer steel, and combinations of steel, wrought iron, and cast-iron were produced, using the techniques of hooped and built-up construction. After about 1881, the use of steel became general, following the perfecting of the Siemens-Martin open-hearth process of steel making, which made possible more complete control over quality. Thereafter, the most powerful naval guns had cast steel tubes with forged steel or wire-bound reinforcing tubes. Even as the refinement of steel metallurgy was vastly increasing the strength that could be built into a gun, the slow-burning powders, with their greater propelling force combined with reduced pressures in the powder chamber, were reducing the need for strength--which made it possible to construct longer, slimmer, and immensely more powerful guns than ever before.

The smokeless powders of the 1880s allowed clear vision for repeated firing and this quick firing was made possible by an engineering development--the recoilless carriage. New explosives were then applied to shell development, and the high-explosive shell became the final essential element of World War I artillery.

Electronic Developments in Weaponry
(Part B)

by

Edward S. Gilfillan, Jr.*

Just as new weapons developments of earlier centuries were made possible by advances in chemistry and metallurgy, the most significant weapons developments of the 20th Century have been made possible by discoveries and inventions in the fields of nuclear science and electronics. Man's understanding and manipulation of subatomic particles have greatly enhanced the effectiveness of familiar weapons and have led to tremendously more lethal new ones.

ELECTRONICS AND WEAPONS

It is doubtful that anyone has yet been killed by military action with a purely electronic weapon. The military function of electronic devices has been, throughout their history, to enhance the lethality of weapons. The earliest were devices to send orders, information, and firing data from point to point without the inherent physical limitations of voice, signal, and messenger.

The Telegraph

The telegraph appears to have been brought into commercial use almost simultaneously in Europe and America about 1830. The device consisted of a single wire between the places in

* Dr. Gilfillan's original paper on this subject has been revised by Gay M. Hammerman for inclusion in this annex.

communication, a battery at one or both of them, a manually operated switch, called a key, by which connection of the battery to the wire could be made or broken, and a coil of wire wound on an iron rod. When current flowed through this coil the iron became magnetic and attracted to itself a movable piece of iron; the click produced when the two came together was noted and interpreted by the operator at the receiving end. The intervals between clicks at the receiving end were the same as operations of the key at the sending end and a code attributed to Samuel Morse, one of the American inventors of the telegraph, translated sequences of clicks into the letters of the alphabet. It was possible to transmit as many as 50 letters per minute.

Two stations could communicate through intermediate points by means of a "relay" which had the same coil and iron rod as the telegraph sender but in which the movable iron part operated a "key." The relay was in one circuit; the key in another. The relay was in fact an amplifier, the first of its kind. It permitted lines indefinitely long to be interconnected and used.

Transoceanic cables came into use about 1890. At that time, and until quite recently, relays could not be used in them because of the maintenance problem. The construction of waterproof cable with sufficiently low electrical leakage to be operable over distances of up to 2,000 miles was a technical accomplishment of high order. Progress of the signal along such cables was slow, but the signal went virtually undistorted. Such wrapped cables are now universally used, but modern ones contain, at intervals along the bottom of 30 to 50 miles, electronic amplifiers so well constructed that they require no maintenance for 50 years or more.

The physical appearance of telegraphic apparatus changed very little between the mid-1800s and the early 1940s when it was superseded, abruptly and completely, by the teletype, which does the same things, but faster, and without the operator having to learn the code. Sender and receiver both look like typewriters; at the sending end one types on the usual keyboard and at the receiving end a typewriter prints out the message with no operator present.

The telegraph originated in an industrial environment which could furnish almost nothing to support it; the wires, bare and insulated, the pole insulators, and the batteries were completely new in their time. The volume of telegraphic instruments manufactured was never sufficient to stimulate new industrial forms or products. It was the appearance of the electric light, not

the telegraph, which made such equipment available for industrial exploitation in new industries.

When the radio and telephone appeared, they were more effective and eclipsed the telegraph in military importance. Recently, however, the telegraph has come back into its own, in the form of the teletype and more sophisticated devices. It can process information far more rapidly than is possible verbally, and it is the natural means of communication between the robots that loom ever larger on civil and military horizons. No one who took part in World War II will forget the chaos that resulted when many voices came on the air together, or will regret the change back from voice communications to more sophisticated forms of telegraphy.

The Telephone

Like the telegraph, the telephone appeared almost simultaneously at several places in America and Europe. It is usually attributed to Alexander Graham Bell and dated 1876.

The telephone differs from the telegraph by producing, at the receiving end of the line, a sound which is a replica of that spoken into the transmitter at the other end. There are various types of microphones which pick up the sound of the voice at the sending end and produce an electrical signal which, when it arrives at the "receiver" or "speaker," reproduces a good approximation of the original sound.

Both microphone and receiver use a metal or plastic diaphragm to pick up and regenerate the voice sounds. Sound is varying atmospheric pressure, and varying pressure produces mechanical movement of any light, resilient body. In the microphone used in all telephones today the motion of the diaphragm is mechanically transmitted to carbon granules, thus changing momentarily their electrical resistance and varying the current passed through them by a battery. This varying current is what passes along the line. At the receiving end the current passes through a coil on or near a permanent magnet; the force of this magnet is varied by the current and the varying force so produced is transmitted mechanically to a diaphragm. The moving diaphragm produces momentary changes in the pressure of the air and these are perceived by the ear as sound.

The relay, which had made telegraphy over long distances possible, would not work for the telephone and at first there was no kind of amplifier to take its place.

The three-electrode vacuum tube was invented by de Forest about 1905. He was not trying to produce an amplifier and was not engaged in the telephone industry; it was a chance discovery. De Forest soon recognized the amplifying properties of his tube and the possible application to the telephone. His product was used in all long-distance telephone circuits until the advent of the transistor in 1950; it is still used in most of them.

There was an electrical industry ready to support the telephone when it appeared. This derived mostly from the electric light trade and the electricity generating system which supported it. There were also the beginnings of a mathematical theory of the flow of electricity through long lines. This had come from efforts to improve the telegraph.

The telephone was first used in military operations in World War I. It had no demonstrable effect on tactics. It was much more widely used in World War II, where it greatly aided the rapid massing of artillery fire. It should be noted, also, that without the telephone World War II could not have been fought as it was. The Remagen Bridge would not have been captured without the rapid voice communication between old friends which led to the decision to cross it. The telegraph would have been too impersonal and too slow.

Radio

Radio can be used to transmit telegraphic, telephonic, or more complicated types of signal. Its essential feature is the absence of wires, which allows communication between mobile stations, or between these and fixed stations.

Radio signalling is accomplished by setting up rapidly varying electric currents in a metallic structure known as an antenna. These currents produce electric and magnetic fields in the air or space surrounding them. Collapse of electric fields generates magnetic fields, and conversely; the successively collapsing fields radiate outward with the speed of light carrying with them both power and signal.

Radio phenomena were first demonstrated in Germany by Heinrich Hertz in 1885 but were first adapted to communications by G. Marconi about 1903.

Although radio later developed about de Forest's three-electrode tube and more recently about the transistor and more exotic devices, no such equipment was available to Marconi, who used the strong and rapidly varying currents produced in an electric spark. He controlled these by means of a key, regulated the rate of variation by means of coils and condensers, and fed the result to an antenna. As with the telephone, the difficulty was that the signal actually reaching the receiving end was very feeble and could just be rendered audible in a sensitive receiver. All the power to operate the receiver had to come from the transmitter; this required relatively high powers at the transmitter and restricted communication at first to ranges of a few hundred miles. Later very powerful spark installations were able to span the Atlantic.

Marconi encountered, for the first time, the phenomenon of "noise" which is now recognized as a fundamental limitation on all electronic equipment. The sound from his receivers contained not only the desired signal but other sounds, some originating from lightning, which came to be called "static" because the accumulation of static electricity on dry days could also cause them.

Spark equipment and elementary receivers were used right through World War I, in which radio was a decisive factor in defeating the German sea raiders. Immediately after World War I, the three-electrode tube was found to be more effective than the spark for generating and controlling transmitter power, and the amplifier based on smaller versions of this tube came into use in radio receivers. The signal power available in receivers no longer depended on what could be had from the transmitter and became, in fact, practically unlimited. The former large antennas (some of them miles long) were no longer needed and the equipment could be mounted in aircraft. Signal power requirements were also much reduced; where formerly it had required kilowatts to reach a few hundred miles, a few watts now sufficed to girdle the earth. Introduction of the three-electrode tube and its more complicated descendants also made possible the transmission of voice over the radio. Spark sets were unable to do this and were restricted to telegraphy. These developments made possible voice radio and greatly facilitated coordination of the several arms within the combat team.

In contrast to the telegraph and telephone, radio was developed largely by military authorities. In the period between the World Wars the US Navy took the lead in this effort. There appears to have been no opposition to innovation in the fleet; new developments were accepted as fast as they became available--too fast, as it turned out. The second battle of Savo Island was lost by dependence on new radio equipment before its use was understood. It is noteworthy that although the requirements which developed radio were largely military, the work was done almost entirely in private industrial laboratories.

Radar

Radar is a form of radio which measures angles and distances directly by the use of strongly directional antennas and by comparing echo times with the speed of light.

The essential feature of radar is the use of electric currents varying so rapidly that the characteristic distance associated with them is small compared with the dimensions of a maneuverable antenna. The antenna itself is a composite of a dish-like structure and a much smaller radiating element. Ordinarily the whole antenna is maneuverable in deflection and elevation like a gun. The results of the radar transmissions are displayed visually in structures which are essentially television tubes.

Radar was entirely a military requirement and development. There were no civilian applications of it until after World War II.

The first practical demonstration was at the US Naval Research Laboratory about 1938. The decisive advance was made in England about a year later. This was the invention of the magnetron, a vacuum tube quite different in concept from the three-electrode tube which permitted the generation of high powers at very high frequencies in brief bursts. From that point forward development was about equally rapid and effective in the United States, Britain, and Germany. Japanese radar was late and ineffective; the Italians had none.

With the exception of the magnetron the components of radar were already available from the large civilian radio and telephone industries. Television is a descendant of radar and was

commercialized largely from the results of experiments with radar, though there was a small amount of noncommercial television as early as 1938.

Decisive at sea and in the air, radar had no demonstrable influence on the tactics of land warfare.

Sniperscope

Every living person radiates heat (a form of light but of greater characteristic distance than visible light). This heat travels in straight lines from the source and can be focused to form an image of the radiating object. In the sniperscope this image is formed on a screen which emits an electric charge where the light strikes it. This charge, whose distribution over the screen reproduces the image in detail, is then picked up in what is essentially a television tube and made to produce a visible image on a second screen. The image there is not as good as that formed by optical systems (not good enough, for instance, to permit recognition of an individual), but it is good enough to serve as a point of aim for a rifle.

The sniperscope originated as a military requirement and was developed for the US Army by the Office of Scientific Research and Development. It was never issued to troops in sufficient number to influence tactics. Its use did strengthen defensive perimeters at night.

Proximity Fuze

This device was used late in World War II at the Battle of the Bulge, against V-1s in England, and in anti-aircraft fire in the Pacific.

The fuze fits into an ordinary artillery shell. It is a small radar set which detonates the shell when it senses any electricity-conducting body near it. Proximity to trees or terrain activates it; the effect is an air burst 20 to 50 feet above the ground.

The proximity fuze was initiated as a military requirement. First development was by the British, who used not a radar set but a device to detect changes in the atmospheric electric field.

In 1941 the work of producing new weapons was divided between the United States and Britain, and the United States got the proximity fuze. It was decided at that time that the electrostatic device held less promise than a radar device, and this was the form taken by the ultimate development.

Apparently the fuze had no effect on tactics. It was at first held back from use for fear it might fall into enemy hands. Discrepancies between the Allied and German accounts of the Battle of the Bulge preclude assessment of it there. In clear weather, strafing and bombing aircraft was deadlier and tended to obscure the effect of the new fuze. However, the devastating effect of splintering in densely wooded areas caused by proximity-fuzed shell bursts was plainly noted in ground combat; it is a factor to be reckoned with in considering the use of cover.

Nuclear Energy and Weapons
(Part C)

by

George C. Reinhardt*

The electronic developments just discussed were made possible by controlled activity of particles from the outer orbits of atoms. Even more dramatic military results came from man's penetration of the atomic nucleus.

A conventional explosion results from a rearrangement of atoms. In a nuclear explosion a redistribution of the extremely small particles among the nuclei of the atoms takes place, leading to very rapid liberation of enormous amounts of energy. The fundamental reaction in the atomic bomb is the fission of certain atomic nuclei (notably the uranium isotope 235 or plutonium 239) by neutrons. The fission reaction releases vast amounts of energy, as represented in the Einstein equation $E = mc^2$ where "E" is the energy equivalent of mass "m" times "c," a constant equal to the speed of light. When uranium 235 undergoes fission into two approximately equal parts which differ considerably from the original nucleus in atomic number and mass, there is a decrease of about 0.1% in the original mass and a resultant energy release.

This fission process, initiated by neutrons, is accompanied by the almost simultaneous emission of more than one neutron for each nucleus undergoing fission. These neutrons induce fission in other nuclei to produce a chain of fissions increasing at a tremendous rate. Since some neutrons "escape" at the exterior of the fissionable material, the ratio of the surface area to

* Colonel Reinhardt's original paper on this subject has been revised by Gay M. Hammerman for inclusion in this annex.

the volume determines the "critical size" for a chain reaction. This phenomenon led to the belief that "a small effective atomic bomb cannot be made."

Due to the presence of stray neutrons in the atmosphere, a critical mass would be liable to deterioration or even to premature explosion. Thus, a bomb must "consist of two or more separate parts, each less than critical size, which are brought together very rapidly to cause an explosion."

Methods for changing a subcritical to critical mass are:

1. Bringing two or more pieces of fissionable material together very rapidly as in a gun-barrel device in which an explosive propels one subcritical piece into another.
2. By compressing fissionable material, increasing its density, it can become critical. When the fissionable material is surrounded by a spherical arrangement of high explosive to be set off by multiple detonators, the method is termed implosion.

In addition, the critical mass can be decreased by surrounding fissionable material with elements of high density which reflect neutrons and serve the function of tamping in dynamite blasts.

Production of fissionable material requires separation of the scarce U-235 from the more abundant U-238 existing in nature, or the artificial making of plutonium in a chain-reacting pile or nuclear reactor. Pure uranium (99.3% U-238, 0.7% U-235) cylinders in a lattice of graphite undergo controlled fission to form U-239 and, in turn, long-lived plutonium. The latter is then chemically separated from the uranium by a process complicated by the intense radioactivity of the materials but originally regarded as easier than isolating the two uranium isotopes.

The now-famous experimental pile under the stands of the University of Chicago's Stagg Field "became a self sustaining system Dec. 2, 1942 . . . at a power level of $\frac{1}{2}$ watt." This tiny output proved the potential of all later power-generating reactors and from it was produced about half a gram of plutonium that was successfully separated from the uranium and the fission products by chemical procedures deemed adaptable to mass operations. This epic achievement did not of itself establish the certainty of a bomb.

The problems of making a bomb, most notably the instantaneous assembly within a size and weight that assured portability were, together with immense procurement and processing projects, successfully handled in the amazingly short period of 30 months. (A consensus of scientific judgments in 1941 had set three to four years as the minimum after achieving a chain reaction.)

In theory, one pound of uranium releases during fission as much energy as 8,000 tons of TNT. Actually much less than 100% efficiency is achieved. Computations in 1940 by scientists of the Uranium Committee of the newly organized National Defense Research Committee had indicated 100 kilograms of U-235 as the critical size of a bomb.

While nuclear fission uses heavy uranium or plutonium nuclei, nuclear fusion involves some of the lightest (low atomic number) nuclei. In fusion, two light nuclei unite to form a nucleus of a heavier atom--notably deuterium, an isotope of hydrogen, becomes helium--with release of energy. Fusion of all nuclei in one pound of deuterium would approximate the energy of 26,000 pounds of TNT but here, too, efficiencies are less than 100%.

The term thermonuclear refers to the fact that fusion reactions can be brought about by means of very high temperatures, several million degrees. The "only practical way such temperatures can be obtained on earth is by means of a fission explosion".*

The energy of a typical air-burst fission bomb is distributed:

blast and shock: 50%
thermal radiation: 35%
initial (approximately one minute) nuclear
radiation: 5%
residual nuclear radiation: 10%

* The practicability of making a pure fusion bomb, popularized vaguely as the neutron bomb, was first discussed on the Senate floor by Senator Dodd on May 12, 1960; argued more technically by Russian scientist L. A. Artsimovich before the United Nations at Geneva in 1958; and implicitly accepted by Freeman Dyson in an article, Bulletin of Atomic Scientists, September, 1961, considering its implications for US policy.

For thermonuclear weapons in which explosive energy is about equally divided between fission and fusion the residual nuclear radiation percentage is halved. Yield designations, in terms of tons of TNT equivalent, do not include the energy that goes into residual radiation.

The elevation above the earth's surface at which a nuclear explosion occurs not only influences the effects on the ground but can materially alter the energy distribution as well. Above 100,000 feet in altitude, due to the low air density, more than 50% of the energy goes into thermal radiation and the blast energy is reduced. The fraction going into nuclear radiation is independent of burst height, but since initial nuclear radiation attenuates in proportion to the amount of air through which it travels, ranges of nuclear effects increase as air density drops.

Residual nuclear radiation from true air bursts (i.e., where the fire-ball does not touch the earth's surface) spreads over a very large area (thousands of miles) and is of only minor consequence on the ground. However, when the fire-ball does touch the ground, fission particles may fuse with particles of earth to be carried aloft in the characteristic cloud and then fall relatively near ground zero, contaminated with radioactive material dangerous to living organisms.

This "fall-out" phenomenon, discernible at Alamogordo, was widely appreciated only after the Bravo shot (Castle Test series) on February 28, 1954, loosed some 15 megatons of energy on the coral of Bikini atoll. Meteorological conditions, nature of the surface beneath the explosion, height of the burst, and especially yield, all significantly affect the distribution and intensity of fallout. It is clear, however, that residual nuclear radiation can represent a serious hazard at great distances (several hundred miles) from the explosion. Plans to minimize this hazard must be flexible.

Landmarks in nuclear technology might be listed as:

1. Discovery of nuclear fission in 1939
2. President Roosevelt's decision to prosecute research toward a bomb, October 1939
3. Chain reaction achieved, University of Chicago, December 1942
4. First nuclear explosion, Alamogordo, New Mexico, July 1945

5. President Truman's decision to develop the hydrogen bomb, 1950

6. Thermonuclear device successful, October 1952

Whether or not other, later developments (possibly the neutron bomb) should be added is not for the judgment of the layman possessing only unclassified information.

Development of nuclear technology has been inextricably meshed with national policy, quite unlike that accompanying other military development, since the tremendous potential of nuclear weapons was recognized by constantly wider circles of people as progress was made. Difficulties in the way of winning the support of heads of state for initial development and the sharply different reception of the idea at Washington and Berlin are well-known tales--as is President Truman's decision to use the bomb against Japan. More obscure are the details attending the same President's decision to proceed with developing thermonuclear weapons, but the intensity of that controversy could not be concealed. Further nuclear development continues to be a controversial question at national, as well as military and scientific, levels.