Who Turned the Mechanical Ideal into Mechanical Reality?

ROBERT B. GORDON

In 1884 Charles Fitch described interchangeable manufacture as a *mechanical ideal* accomplished by American inventors, entrepreneurs, and mechanicians who in fifty years had transformed the United States from an agricultural nation dependent on imported manufactured goods into a country that was exporting sophisticated production machinery to European customers.[1] The work of Thomas Warner and Cyrus Buckland at the Springfield Armory in the 1840s and 1850s is prominent in Fitch's account because he believed they were most instrumental in converting the abstract concept of interchangeability—a late-18th-century idea officially adopted as an ideal by the Ordnance Department in 1813—into a working system of manufacture at the national armories.[2] The evolution of interchangeable manufacture continues to interest historians because it is one of the roots of American success in large-scale manufacturing. Moreover, because interchangeability implies reliance on machines, they regard it as underlying the removal of traditional artisan skills from the production

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[1]Charles H. Fitch, "The Rise of a Mechanical Ideal," *Magazine of American History* 11 (1884): 516–27.

[2]Simeon North's contract of 1813 for manufacture of pistols was the first to require interchangeable parts. S. N. D. North and R. H. North, *Simeon North: First Official Pistol Maker of the United States* (Concord, N.H., 1913). Most scholars today would add John Hall too.

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process. Authors who have studied American production machinery include Fitch, Robert Woodbury, and Edwin Battison.[3] Others, interested in American entrepreneurs and inventors, have cast their favorites in heroic molds and exposed the blemishes of the favorites chosen by others.[4] Within the last decade Merritt Roe Smith has added a new dimension to these studies, the role of the communities in which the entrepreneurs worked, and David Hounshell has explored the evolution of mass production from the 19th to the 20th century.[5]

Noticeably absent from this scholarly research is consideration of the role of the individual artificers who had to use the methods of Fitch's mechanical ideal to make material products. I will examine their contribution here.

The Mechanical Ideal

Accounts of the mechanical ideal have been based largely on statements by contemporary observers. These observers emphasized how making parts to gage with the self-acting, power-driven machinery introduced in American factories from the beginning of the 19th century onward eliminated much of the need for skilled artificers.[6]

[3]Charles H. Fitch, *Report on the Manufactures of Interchangeable Mechanism,* Tenth Census of the United States, 1880, deals with forging, woodworking, and metal-cutting machinery; Robert S. Woodbury, *Studies in the History of Machine Tools* (Cambridge, Mass., 1972), covers lathes, milling machines, and grinders; Edwin A. Battison, "Eli Whitney and the Milling Machine," *Smithsonian Journal of History* 1 (Summer 1966): 9–34, is a study of the origin of milling technology. Battison's article is of particular interest because of his use of evidence from artifacts to supplement the rather sparse and unreliable documentary record.

[4]Eli Whitney's reputation has undergone a particularly large share of revision and counterrevision, a reaction to the persisting, uncritical assessment of him as the originator of interchangeable manufacture.

[5]M. R. Smith, *Harpers Ferry Armory and the New Technology* (Ithaca, N.Y., 1977); David A. Hounshell, *From the American System to Mass Production 1800–1932* (Baltimore, 1984), pp. 38, 44.

[6]According to Robert Woodbury the system of manufacture of interchangeable parts that finally matured in the United States includes use of (1) precision machine tools, (2) precision gaging, (3) uniformly accepted standards of measurement, and (4) techniques of mechanical drawing ("The Legend of Eli Whitney and Interchangeable Parts," *Technology and Culture* 1 [1960]: 235–53). Paul Uselding added uniform materials to this list ("Henry Burden and the Question of Anglo-American Technological Transfer in the Nineteenth Century," *Journal of Economic History* 30 [1970]: 312–37); on the problem of the uniformity of iron see also R. B. Gordon, "Materials for Manufacturing: The Response of the Connecticut Iron Industry to Technological Change and Limited Resources," *Technology and Culture* 24 (1983): 602–34. Throughout most of the 19th century interchangeable manufacture did not entail Woodbury's items 3 and 4; products were made interchangeable by the duplication of a master pattern or a model rather than by manufacture to absolute dimensions specified on drawings. I use the term

George Talcott's report on the Springfield Armory written in 1841, for example, asserts:

> Soon after the war [1812] the system of *piece-work,* instead of day work, was extensively introduced. Previous to this, an *armorer* was a very different kind of mechanic: the skill of the eye and the hand being highly valued and indispensable. A "lock filer" filed up and fitted all the parts of a lock. The change of the system caused each one to devote his skill and energies to the completion of some single part and in time it was difficult to find many men who were able to file up all the parts equally well; and whenever it became necessary to change men from one limb of the lock to another . . . much difficulty occurred. Machines for performing the work (that was formerly done by the skill of the eye and the hand) have been gradually introduced from time to time, until at length the machines perform nearly all the work leaving the workman nothing to do but fix the article in a proper position, apply the necessary oil, and set the machine in motion. A great portion of the severe hand labor is thus dispensed with. The machines are usually so constructed as to stop when the work is done without the aid of the overseer. In this way a man can attend two or more machines. The excellence of this mode of working is fully exemplified at Hall's rifle works at Harpers Ferry, where machines are generally attended by *boys* and *young men,* who place and replace the pieces to be wrought, and only a *few men* are required to keep the machine in good order. In this way the skill of the armorer is but little needed: his "occupation's gone." A boy does just as well as a man. Indeed, from possessing greater activity of body, he does better.
>
> The difficulty of finding good armorers no longer exists; they abound in every machine shop and manufactory throughout the country. The skill of the eye and the hand, acquired by practice alone, is no longer indispensable; and if every operative were at once discharged from the Springfield armory, their places could be supplied with competent hands within a week.[7]

Again, in a letter to Julius Rockwell of Pittsburgh, August 7, 1845, Talcott states: ". . . The fact that hand labor is dispensed with and everything being now effected with machinery puts at rest all fears of

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"artificer" to mean a skilled mechanic who makes metal or wooden products with hand or power tools. Inventories of the equipment at the Springfield Armory between 1834 and 1838 list the tools used by "artificers" separately from those used by "armorers and smiths," and it appears from these lists that the "artificers" were actually millwrights.

[7]Stephen V. Benet, ed., *A Collection of Annual Reports and Other Important Papers, Relating to the Ordnance Department* . . . (Washington, D.C., 1878), 1:395.

the kind [of a shortage of skilled workers]. Indeed, the skill of the eye and the hand of the old practical armorer is entirely dispensed with, and any good mechanic from a machine shop can perform the work at an armory, the machines having effected a total revolution, improving the quality of the work and reducing the cost there of . . . ."[8]

Felicia Deyrup has concluded from Talcott's statements that "The skill of the average arms worker continued to decline as a result of increased mechanization . . ." and that ". . . the development of machine tools was clearly recognized at the time as a factor of major importance in the reduction of skill. . . ."[9] Hounshell has carried this notion further with his assertion that at the Springfield Armory Thomas Blanchard's new machines "had eliminated the use of skilled labor in stockmaking by 1826" and that by 1850 "virtually all of the fabrication of the musket (except barrel welding) was carried out by machines . . . ."[10] A popular way of summarizing these claims is to say that "skill was built into the machines" and that the introduction of these machines began the process of deskilling.

The motives of those who wrote about the new manufacturing methods should be considered before their statements are accepted as objective descriptions of the way mechanical work was carried on. Talcott's letter to Rockwell is his response to an attempt to keep Lemuel Pomeroy of Pittsfield at work on contract arms, which Talcott opposed. He prepared his "Notes on the Springfield Armory" in August 1841, on the basis of a ten-day visit to the armory to investigate the high cost of labor there. He lists an expenditure of $21,829.67 on labor-saving machinery from 1820 to 1840, which, according to the master armorer, reduced the actual labor required to make a musket by one-third. Talcott wanted to realize a savings in labor costs from this investment by reducing wage rates.[11] Though he was an experienced inspector of arms and armories, Talcott was not an artificer; his descriptions of manufacturing are really attempts to rationalize administrative actions he sought to bring about.

I wish to challenge the notion that the precision of machines replaced the mechanical skills of artificers in the 19th century. To do this, I will use material evidence to show how representative products were made. Then I will define what I mean by skill and ask how much of the realization of the mechanical ideal was dependent on the performance of the artificers who used the new methods and to what

[8]Ibid., 1:52.

[9]Felicia J. Deyrup, *Arms Makers of the Connecticut Valley* (Northampton, Mass., 1948), p. 160.

[10]Hounshell (n. 5 above), pp. 38, 40.

[11]Deyrup (n. 9 above), p. 196.

degree the mechanical ideal was built into the new machinery instead of the abilities of the artificers. I will argue that the new methods of manufacturing metal products introduced in the 19th century not only fully engaged the traditional mechanical skills of artificers but also made new demands on their skills. The development and learning of these skills took many years and was, in fact, the factor that limited the progress of the new technology.

The role of the artificer's skills has been overlooked in previous research not perhaps for want of scholarly interest but for want of evidence. Documentary sources reveal little about what was required of the artificers engaged in manufacturing in the 19th century. The problem must be approached by archaeological methods. The surviving examples of 19th-century products are a source of information about the work of those who made them; they give us a kind of direct contact with the individual artificers that cannot be attained in any other way. Heretofore there has been little progress in interpreting many of these artifacts, for want of appropriate methods of analysis. But now appropriate methods are available.

Archaeologists have developed methods of identifying the way that tools have been used or objects made from analysis of lithic materials.[12] More recently, similar methods have been developed for analyzing metallic artifacts.[13] Reconstruction experiments, in which equipment of ancient design is built and operated in the laboratory or in the field, have proved to be a useful way of discovering the skills required to carry on old industrial processes.[14] But little use has yet been made in industrial archaeology of the many opportunities offered us by this technique; hence, the interpretation of artifacts is currently our best source of information on manufacturing technology.

Artifacts Examined

Many of the surviving examples of 19th-century manufactured goods could serve our purpose, but most suitable would be a manufactured product of some complexity, difficult to make, meeting demanding service requirements, and produced in large quantities at a place where new manufacturing technology was devised and for which documentary evidence has survived. Examples should be datable and

[12]Brian Hayden, ed., *Lithic Use-Wear Analysis* (New York, 1979).

[13]R. B. Gordon, "Laboratory Evidence of the Use of Metal Tools at Machu Picchu (Peru) and Environs," *Journal of Archaeological Science* 12 (1985): 311–27.

[14]For an excellent example of the investigation of ancient technology through the use of reconstructed equipment, see R. F. Tylecote, J. N. Austin, and A. E. Wraith, "The Mechanism of the Bloomery Process in Shaft Furnaces," *Journal of the Iron and Steel Institute* 209 (1971): 342–63.

there should be no major design changes in the time interval under consideration. Possibilities include clocks, cylinder locks, sewing machines, edge tools, railway equipment, textile machinery, and artillery, but military small arms best fit the above criteria. Although over-represented in discussions of the history of manufacturing technology, they nevertheless have some important advantages for our purposes. Arms collectors have identified date and place of manufacture for many museum specimens. The lock mechanism, stock, and barrel of the military small arms made in the United States, principally at the Springfield Armory, changed little in basic design until the bolt-action rifle was adopted in 1892.[15] Small arms also were made in the first part of the 19th century by a number of contractors, whose work can be compared to that done at Springfield.

There are about twelve essential parts in a percussion lock (illustrated in fig. 1) and a few more in a flintlock, and it is helpful to pick one part that can be studied in detail. I have chosen the tumbler (marked *T* in fig. 1). It has a complex shape and is subject to large forces as the lock operates. The hard service to which tumblers were subjected in use is evidenced by the breakage rate in the middle of the 19th century, about 2 percent per year.[16]

The form of the tumbler and its function are illustrated in figure 2. When force *T* is applied to the sear by pulling the trigger, the tumbler accelerates through about a quarter turn under the action of the force *F* applied by the mainspring, thereby driving the flint against the frizzen or the hammer against the percussion cap. To operate successfully, the tumbler must fit properly into the lock mechanism. Some aspects of this fit are particularly important. The axes of the spindle and the pivot of the tumbler must be concentric (see fig. 2) if it is to turn in its rigid metal bearings without developing large internal stresses. The notch engaged by the sear must be parallel to the axis of rotation and well hardened (if it is not, the notch and sear will be subject to damage as the tumbler is released), and the safety notch must be undercut sufficiently to hold the sear in place when the trigger is pulled. The flats on the spindle must be a close fit on the square hole in the cock or hammer; if they are not, working of this joint will damage both parts. In addition, the shoulder at the end of the spindle must be perpendicular to the axis of rotation, sufficient relief must be provided to keep the side from rubbing on the lock plate, and the heat treatment must give a hard surface at the notch and spring bearing points but leave

[15]The adoption of percussion ignition in place of flint in 1842 and of breech loading after 1865 resulted in little change to the lock mechanism of Springfield arms.

[16]Anon., *Ordnance Manual* (Washington, D.C., 1850), p. 194.

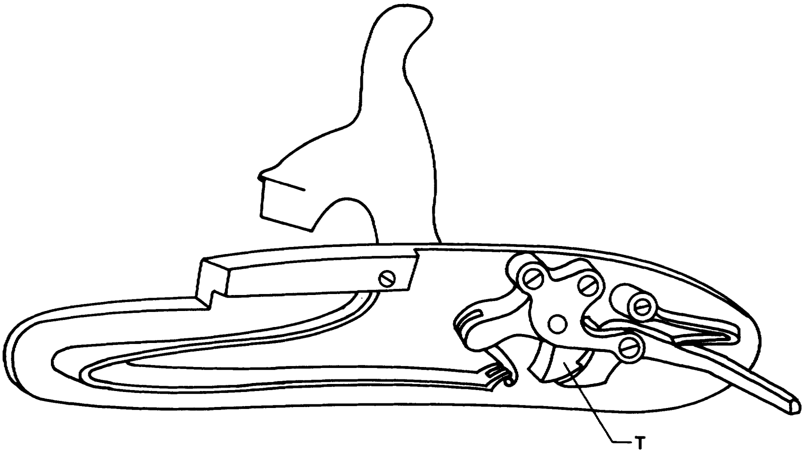

FIG. 1.—The mechanism of a percussion lock. The tumbler is marked *T.* There was little change in the design of this mechanism throughout the 19th century.

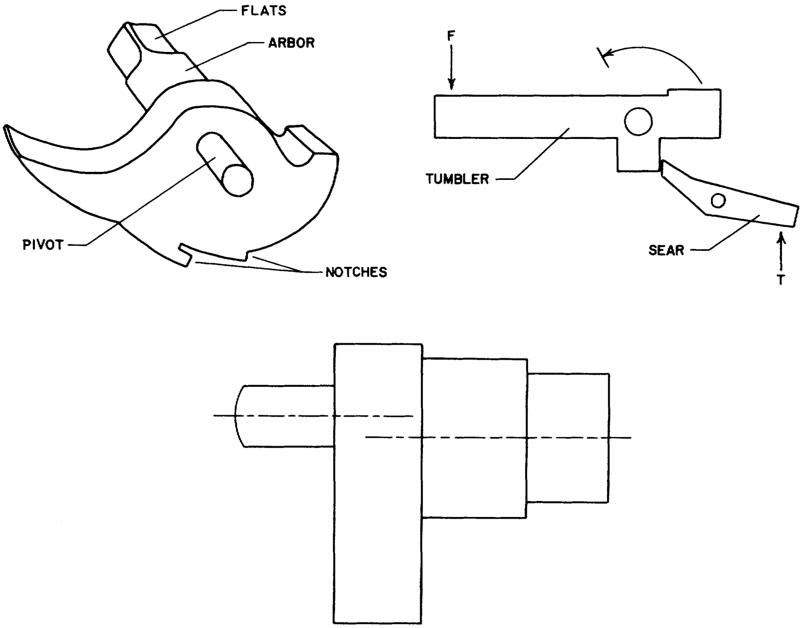

FIG. 2.—The principal parts of a tumbler (upper left). The hammer fits on the flats and the tumbler rotates on the arbor and pivot. Diagram of the mechanical action of a lock tumbler (upper right). Pulling the trigger (not shown) applies force *T* to the sear causing it to release the tumbler, which then rotates under the action of the force *F* applied by the mainspring. Offset of the centerlines of the arbor and pivot of an imperfectly made tumbler (bottom). The distance measured between these centerlines on artifacts is called the "eccentricity."

the metal sufficiently tough to resist the shock generated at the end of its rotation. Less important characteristics of the tumbler are the exact profile of its edge (most of it does not bear on any other part), the exact radial distance to the notches (the sear is spring loaded), and the central placement of the threaded hole for the retaining screw for the hammer or cock.

An artificer will encounter several difficulties in making a tumbler. The profile is an irregular curve, but flat, square, and round surfaces also have to be formed; a deep hole has to be drilled and tapped; and the part has to be heat treated to the requisite degree of hardness and toughness. Examination of the finished product will show how these manufacturing problems were handled.

Documentary Evidence

Surviving documents on the manufacture of lock mechanisms in the 19th century contain little technical detail. One of the most complete accounts is a list of the operations at the Springfield Armory in 1878.[17] According to this account, the tumbler was first forged to rough shape ("blocked") from bar stock with a trip-hammer, then drop-forged in closed dies to bring it closer to its final form, then milled on both sides and across the edges. The arbor and pivot were clamp milled and the end split with a circular saw (probably also on a milling machine). A hole was drilled and tapped in the arbor to accommodate the retaining screw for the hammer. The tumbler was then jig filed and hardened. The amount of filing done and its purpose are not specified.

Earlier descriptions are less complete but indicate that the basic process of making tumblers remained unchanged through the 19th century. In 1810 the steps were described as forging, milling (otherwise unspecified), and filing.[18] In 1819–25 the process was the same but the filer was said to have been provided with a gage.[19] There were forty-two lock filers (who used one file per lock) and only nine machinists (who did all the drilling, milling, and turning on locks) at the Springfield Armory in 1819. Wrought iron was used for tumblers at Springfield until about 1850; the finished parts were hardened by

[17]The report on the manufacture of the M1873 Springfield names, but does not describe, each operation and illustrates some of the machines used. Stephen V. Benet et al., *The Fabrication of Small Arms for the United States Service* (Washington, D.C., 1878).

[18]John Whiting's report to the Secretary of War on the Springfield Armory is reproduced in James E. Hicks, *United States Ordnance* (Mount Vernon, N.Y., 1940), 2:129.

[19]James Dalliba, "Armory at Springfield," *American State Papers, Class V, Military Affairs II* (Washington, D.C., 1860), pp. 543–54, Document 246; C. Meade Patterson, "Musket-Making Operations at Springfield Armory in 1825," *The Gun Report,* April 1980, pp. 44–48.

carburization followed by quenching and tempering.[20] By 1852 the proportion of machine work to handwork had changed; there were twenty-four lock filers (using one-third of a file per lock) and twenty-six artificers engaged in milling. The filing jigs and gages had become quite sophisticated.[21] The decrease in both the number of files used per lock and in the ratio of filers to millers shows that by 1852 relatively more of the metal was cut away with machines than had been the case in 1819. Yet the amount to be removed from the forged workpiece was still quite large. For example, a forging for an M1855 lock plate examined by E. A. Dixie in 1908 was 1/8-inch oversize on its perimeter; this excess would need to have been cut away by machining and filing.[22]

Inventories of armorer's and smith's tools and of machinery at the Springfield Armory, which exist for most years between 1834 and 1844, provide further clues on the manufacturing process.[23] Files are by far the most abundant type of tool. Gages and filing jigs are the only other tools present in large enough numbers for each artificer to have had at least one. None of the inventories shows enough calipers, dividers, squares, or straightedges to supply more than about half of the artificers engaged in bringing parts to final dimensions. No graduated scales or rules of any kind are listed. Until 1839 the armory had eighteen milling machines. (Indirect evidence suggests that these were all for clamp and hollow milling.) Between 1839 and 1841, when the armory was being retooled for production of a new model musket, the number of milling machines increased to thirty. Several of the machines on the 1841 list were designated for milling the sides and edges of parts such as lock plates and tumblers, and we can take this as the date of introduction of machines using formed cutters for milling profiles. The number of "mills" (which I take to mean milling cutters) per milling machine increased from nine in 1834 to twenty-three in 1843. This increase implies that the machines

[20]An attempt to use steel for tumblers was made in 1832 but most of them cracked during hardening or when assembled into locks. In 1850 the armory ordered 2,500 pounds of 3/4-inch octagon cast steel for tumblers. Steel tumblers are quenched and tempered rather than case-hardened. Joseph Weatherhead to Roswell Lee, March 30, 1832; James Ripley to Fullerton & Raymond, July 3, 1850; documents at the Springfield Armory National Historic site.

[21]Anon., *Bessey's Springfield Directory for 1851–2* (Springfield, Mass., 1851), pp. 157–67; Jacob Abbott, "The Armory at Springfield," *Harpers New Monthly Magazine* 5 (July 1852): 145–61; E. A. Dixie, "Some Old Gages and Filing Jigs," *American Machinist* 31–32 (1908): 381–83.

[22]Dixie (n. 21 above).

[23]There are manuscript inventories of all the tools and equipment for several years between 1834 and 1844 in the Springfield Armory National Historic Site Library.

TABLE 1

DISTRIBUTION OF MAN-HOURS USED TO MAKE A TUMBLER IN 1864

	Percentage
By type of work:	
Forging	6.3
Machining	39.2
Hand	54.5
By labor grade:	
Ordinary blacksmith	6.3
Ordinary mechanic	39.2
Good mechanic	2.1
First-class mechanic	52.4

NOTE.—Percentages are calculated from the data in Dyer's table of the hours of labor required to manufacture a Springfield rifle musket (see n. 24).

were being worked harder in 1843 so that more spare cutters were required. The number of filing jigs per artificer remained about the same throughout this period, which suggests that, while there was increased use of power tools for roughing cuts on forged parts, finishing to gage was still done by filers.

Some quantitative information on the manufacture of tumblers in 1864 can be extracted from a table of the mechanical power and labor required to manufacture 500 rifle-muskets in ten hours. This table was prepared by A. B. Dyer from information supplied by the foremen at the Springfield Armory.[24] Eighteen operations and seven types of power-driven machinery were used in making a tumbler, but one operation, hand filing by "first class mechanics," accounts for more than half of the man-hours required (see table 1). Similar proportions hold for the other components of the lock (except for some of the screws) and the stock. The high proportion of work done by hand and by the most skilled class of artificers is clearly at variance with the claims made by Talcott. To find out why this was so, we must turn to the material evidence.

The tumblers studied are listed in table 2. Most of these are from weapons in the collections of the Springfield Armory Museum, and the distribution of dates reflects, in part, the distribution of arms in this collection. First, surficial markings left from manufacturing operations were examined to identify the tools and techniques used for the final shaping of each part studied. Second, the principal dimensions of the tumblers were measured. Third, hardness measurements

[24]Benet (n. 7 above), 4:859–77.

were made when possible to show the success of heat treatment. Fractography and metallographic examination were applied to broken examples that were available for study.

Material Evidence: Surficial Markings

In the 19th century the exterior parts of small arms were usually polished after they were shaped, but the interior surfaces usually retain the markings left by the last metal-cutting operation performed on them, the one that brought the part to its final dimensions. Parts that have been altered, damaged, or replaced must be avoided, and I have relied on the curators of the collections studied to help detect such parts.

Different types of tools used to shape metal or wood leave distinctive surficial markings on the workpiece. The identification of tools and methods by such markings is a large subject only now being explored by industrial archaeologists, and we lack a general demonstration of the extent to which a specific tool and method of work can be uniquely associated with a given surficial mark. For our immediate purpose, however, two factors enable us to use surficial markings. First, research in the last few decades on the mechanism of metal cutting provides a theoretical basis for the interpretation of tool markings. Second, we need ask only two specific questions of the interpretation of the tool marks found on lock parts. First, can handwork be positively distinguished from machine cutting? Second, can certain specific milling processes, such as hollow milling or clamp milling, be recognized from the marks that they leave? These questions were answered by making reference surfaces with files and mills for comparison with the lock parts studied. It was found that filed surfaces can be distinguished with confidence from those finished by machine tools, that hollow and end milling can be easily identified, and that clamp milling can also be recognized, but with somewhat less confidence.[25] I will describe the surficial markings on two of the tumblers studied and then note important differences observed on the other examples.

M1812 musket made circa 1820.—This musket was made at the Whitney Armory after Eli Whitney had gained twenty years' experience in the manufacture of firearms. The tumbler, shown in figure 3, has been damaged by corrosion, but the tool marks on its surface are still visible. The edges of the tumbler were formed by transverse cuts with a coarse file, probably without a filing jig since the curves are not well blended and the tilts of the edge are not all in the same direction.

[25] R. B. Gordon, "Material Evidence of the Manufacturing Methods Used in 'Armory Practice,' " *IA: Journal of the Society for Industrial Archeology* 14, no. 1 (1988): 22–35.

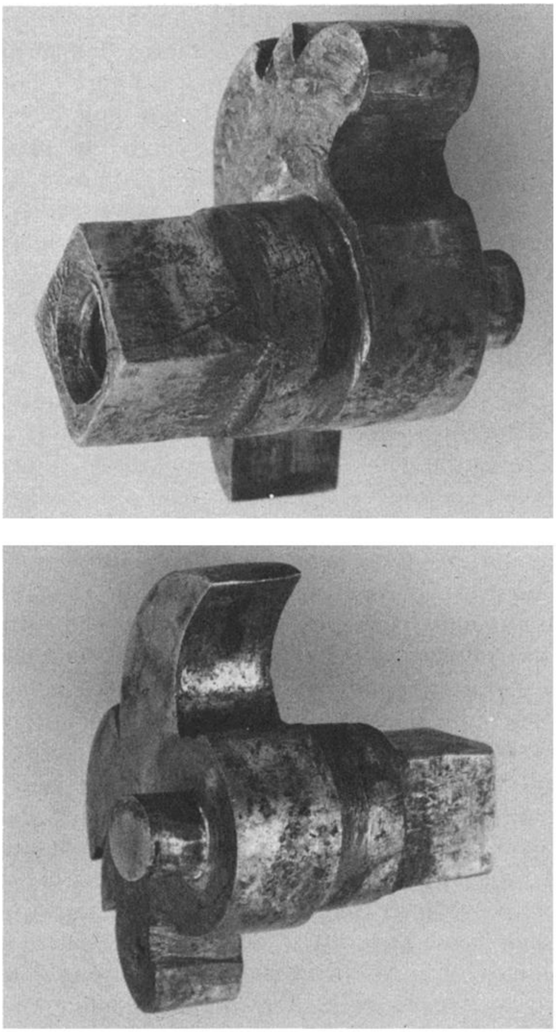

FIG. 3.—Two views of a tumbler from an M1812 musket made at the Whitney Armory about 1820. Note the flat facets on the pivot caused by hand filing. A crack running through the arbor and flats is visible in the upper photograph. (Weapon from a private collection; photographs by William Sacco.)

The final finish on the top edge was made by curved strokes with a fine file; the areas that are more difficult to reach retain coarse file marks. The face of the tumbler on the pivot side shows no machine marks; file cuts in various directions were used to form this face. The face on the arbor side shows the characteristic marks of hollow milling. The cutter used chattered badly, producing deep gouges. At least two hollow mills were used; one formed the shoulder and the arbor, the other the relief on the face. The latter is a more demanding task, and the performance of the milling machine was poorer. The cylindrical surface of the arbor was formed by the hollow mill, but the flats that engage the square hole in the cock were filed. The pivot was made by transverse strokes with a hand file rather than by milling. Each stroke has left a facet on the surface of the pivot, which can be seen in the lower photograph of figure 3. (The arbor and pivot are off center by .030 inches.)

The evidence of the use of a hollow mill to form the arbor face is very similar to that described by Battison for a tumbler from the same model musket.[26] Comparison of his figure 4 with the tumbler studied here shows that the pattern of file marks on the edges of the two tumblers is different, which implies that there was no standard way of working among the makers of tumblers at the Whitney Armory at this time.[27]

M1841 rifle made 1851.—The M1841 rifle was made by a number of contractors, including the Whitney Armory, which was then under the management of Eli Whitney, Jr. Comparison of figures 3 and 4 shows that the quality of the mechanical work on the 1851 tumbler is greatly improved over that of 1820. The superior regularity of form evident in the picture is confirmed by the dimensional data presented below. Four types of surficial markings resulting from the use of coarse and fine files with longitudinal and transverse strokes can be recognized around the edge of this tumbler. Both faces were formed by hollow milling, probably with a double milling machine.[28] An additional hollow mill with a larger hole was used to make the shoulder on the arbor side. The accuracy of the work was sufficient to form a shoulder only 0.008 inch high, but the surface finish attained was poor and it was cleaned up with a file. Circular grooves with a slight inclination due to the feed rate of the mill are observed on the arbor and pivot and were probably made by the same milling operation that was used to form the faces. The flats were filed with transverse strokes.

[26]Battison (n. 3 above).

[27]Although Battison implies that the pivot on the example he studied was formed with a hollow mill, it may have been filed, as in the example described above. I believe that the Whitney Armory did not have a double milling machine in the lifetime of E. Whitney the elder and that Whitney's deathbed sketch of a tumbler mill (reproduced as fig. 23 in Battison's article) was his unexecuted plan to rectify this deficiency in his equipment.

[28]Battison (n. 3 above), p. 30, points out that "double milling machines" were included in the equipment made by Robbins & Lawrence for the Enfield Armoury in the 1850s and suggests that these machines had two spindles on the same axis for milling the arbor and pivot of the tumbler.

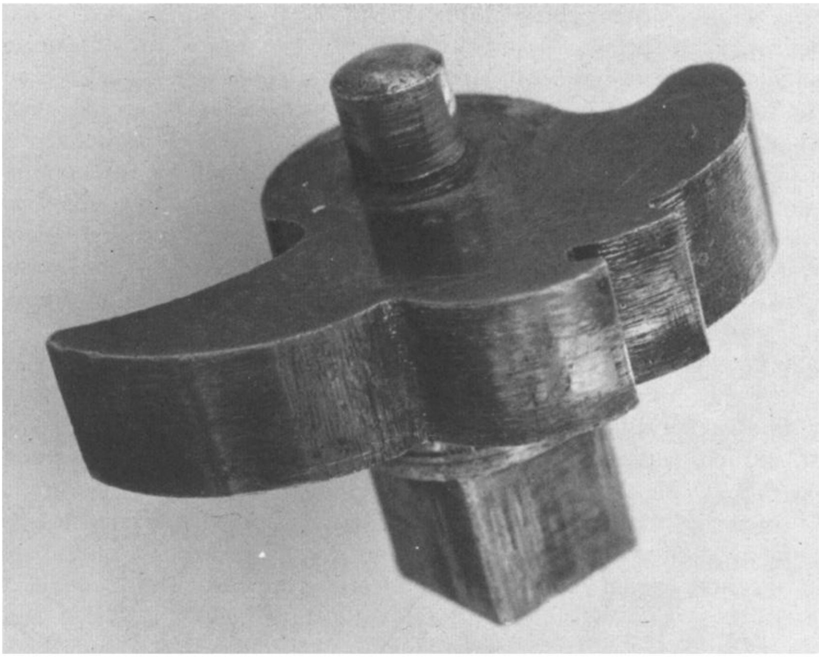

FIG. 4.—Tumbler of an M1841 rifle made at the Whitney Armory in 1851. Both the pivot and the arbor have been milled, but hand filing was used on the other surfaces as in the 1820 example. Comparison of figs. 3 and 4 shows the improvement in the quality of the filing achieved between 1820 and 1850. (Weapon from a private collection; photograph by William Sacco.)

Except for the milling of the pivot, no more machine work to final gage is present on the 1851 tumbler than on the 1820 example, but the quality of the handwork is enormously improved. The use of the hand file for the final shaping of the profile of the tumbler shows that the machines in use in 1851 at the Whitney Armory were not capable of finishing a product that would be to gage; handwork was required.

Springfield Armory.—Both faces of a tumbler made in 1803 were found to be hollow milled; it is filed on all except the arbor face, and the quality of the file work is somewhat better than on the Whitney 1820 example. An example for 1812 was made by the same methods as that for 1803, but the quality of file work is much lower. The number of artificers at the Springfield Armory doubled between 1808 and 1810. The decrease in quality suggests that the learning time for this work was at least two years.[29] There is a marked improvement in the

[29]There may have been a shortage of machinery as well. Whiting (n. 18 above) states that side screws were milled with waterpower, but the side screws in the 1812 Springfield musket examined in this study were hand filed.

appearance of Springfield tumblers by 1830; the example studied has been filed in the same places as the earlier examples, and the inner edge of the pivot has been damaged by careless filing (see fig. 5), but the filed faces are more nearly parallel, and the crown and slant of the edges are reduced. A tumbler for the same model musket made in 1839 is similar in appearance, but there has been a further improvement in workmanship, illustrated by the absence of damage to the edges of the pivot caused by the filing of the pivot face. Equivalent areas on the 1830 and the 1839 tumblers show similar patterns of file strokes, although within these areas there are differences in the angles and uniformity of the strokes. This suggests that a generally accepted way of doing the job had been established but that the details of carrying it out were left up to the individual filer.

The first indication of a difference in the machine work on the Springfield tumblers is found in the example for 1844, where it appears probable that clamp milling was substituted for hollow milling to form the cylindrical surfaces of the arbor and pivot. This change came at a time when the armory was making substantial additions to its machine-tool inventory. A tumbler for the same model musket

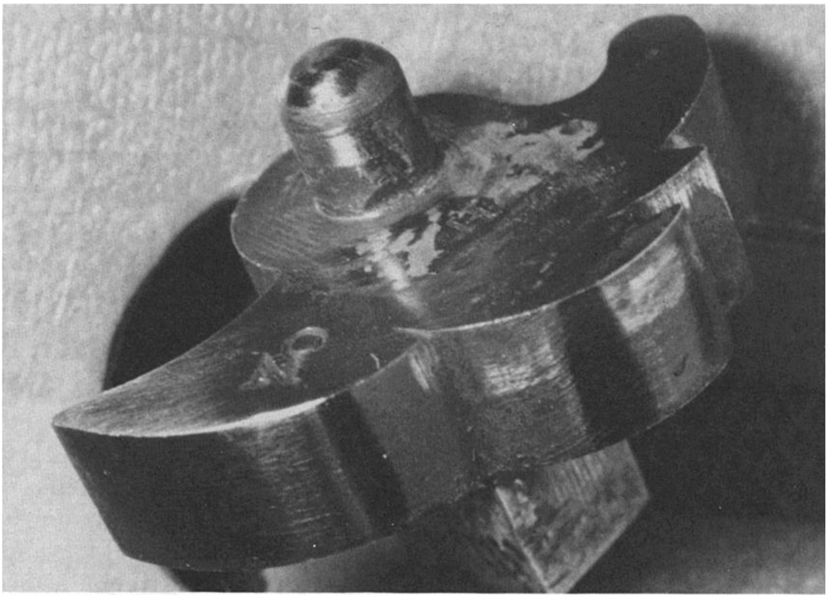

Fig. 5.—Tumbler of an M1816 musket made at Springfield in 1830. The inner end of the pivot has been damaged by hand filing of the tumbler face but the quality of the workmanship is much improved over that found in arms made in the first two decades of the operation of the Springfield Armory. (Photographed at the Springfield Armory Museum.)

(1842) made in 1852 is very similar and has the same pattern of filing marks but is not numbered. This shows that the practice of assembling locks by groups of parts had been dropped and that a generally accepted procedure for filing was in place. The tool marks on the examples for 1873 and 1884 are nearly identical. The upper, front, and bottom edges of these tumblers are described as being milled after forging, but the surficial markings show that these surfaces were brought to their final dimensions by filing. This includes the notch, which we know to have been jig filed. The quality of the file work is very high; the crown of the edges is barely detectable and the edges are perpendicular to the faces. The need to file the edges of the tumbler shows that as late as 1884 the milling machinery was still not capable of bringing tumblers to gage dimensions. How good the filers were at this task will be shown in the discussion on dimensions.

Other armories.—Examination of tumblers of M1841 rifles made by Harpers Ferry, Tryon (Philadelphia), Robbins & Lawrence (Windsor, Vt.), Remington, and Whitney shows that the same set of manufacturing operations was used on all of them and that these operations were the same as those used at the Springfield Armory for the M1842 musket (except that there is no evidence of clamp milling of arbors and pivots outside of Springfield). Although the overall quality of workmanship at the different armories is about the same, there is evidence of minor differences in artificers' techniques. At Harpers Ferry, for example, both faces of the tumbler were left as milled (this was noted on an M1842 Harpers Ferry musket tumbler also), and the milled faces have been deeply gouged by chatter marks. The Tryon tumbler is the only example stamped with letters, probably the initials of the artificer who made it. The milled surfaces of the Whitney examples are rough. The differences between the two Whitney examples show that they were finished by handwork.

The pattern of filing in all the examples indicates only minor differences in technique; an accepted procedure for carrying out this task was in place at all the armories by 1850. Since it is unlikely that each maker independently reached exactly the same conclusions about the best way to go about making a tumbler or that such details of method were imposed by contract terms, the exchange of ideas through the network of mechanicians must have been very effective in diffusing an accepted "right way" to do this job.[30]

[30]Such information was transmitted by interchange of experienced mechanicians from one works to another, as e.g., Thomas Warner's move from Springfield to Whitneyville in 1842, as well as by the migration of artificers. A. F. C. Wallace, *Rockdale* (New York, 1978), pp. 211–26, discusses the effectiveness of communication among mechanicians in the first part of the 19th century.

Material Evidence: Tumbler Dimensions

Reproducibility of dimensions.—Figure 6 shows the dimensions that were measured on the tumblers. In addition, the squareness of the edges to the faces and the amount of crown on the edges of each tumbler were examined, and as many of the dimensions as could be determined on each tumbler listed in table 2 were measured. The

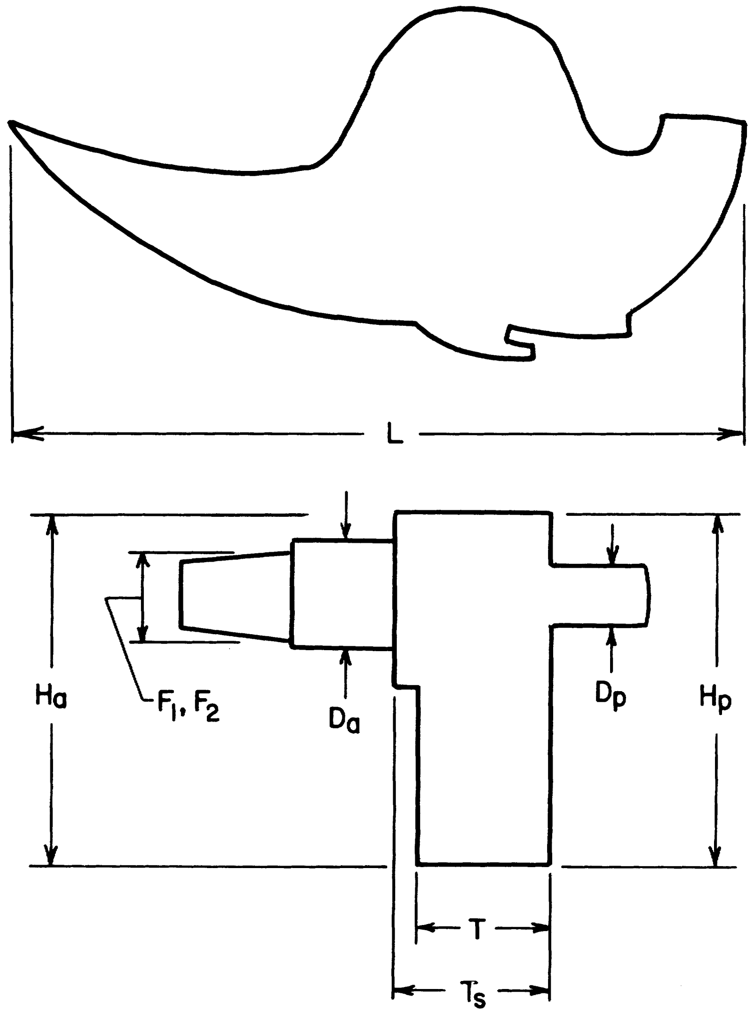

FIG. 6.—Diagram of the dimensions measured on the tumblers studied. Any difference between H_a and H_p shows that the edges are not square to the faces. F_1 and F_2 are the widths of the inner ends of the two pairs of flats.

TABLE 2

LIST OF TUMBLERS EXAMINED

Model and Maker	Date of Manufacture
M1795:	
Springfield	1803
Springfield	1812
M1812:	
Whitney	ca. 1820
M1816:	
Springfield	1830
Springfield	1839
M1842:	
Springfield	1844
Springfield	ca. 1850 (2 examples)
Springfield	1852
Harpers Ferry	1844
M1841:	
Harpers Ferry	1851
Tryon	1845
Robbins & Lawrence	1850
Remington	1853
Whitney	1851
Whitney	1854
M1855:	
Springfield	ca. 1855 (2 broken examples)
Tower (London)	1862
M1873:	
Springfield	ca. 1873
M1884:	
Springfield	1884

NOTE.—The locks for the M1873 and M1884 are identical.

mean of all the measurements of each dimension on all the examples of a given model lock was calculated. The average of the deviations of each dimension from the mean of all the measurements of that dimension on each model of lock is a measure of the consistency of size and shape attained in the manufacture of the tumblers. The calculated average deviations are shown in figure 7. The individual data points represent averages of from sixteen to forty-five measurements, depending on the number of examples available. The results show that there is a continuous improvement in the consistency of the dimensions along what may be described as a learning curve. By about 1880 the average deviation becomes less than 1/1000 inch.

Recently discovery was made of a manuscript report on the inspection of 100 Springfield muskets in 1828 by Benjamin Moor, mas-

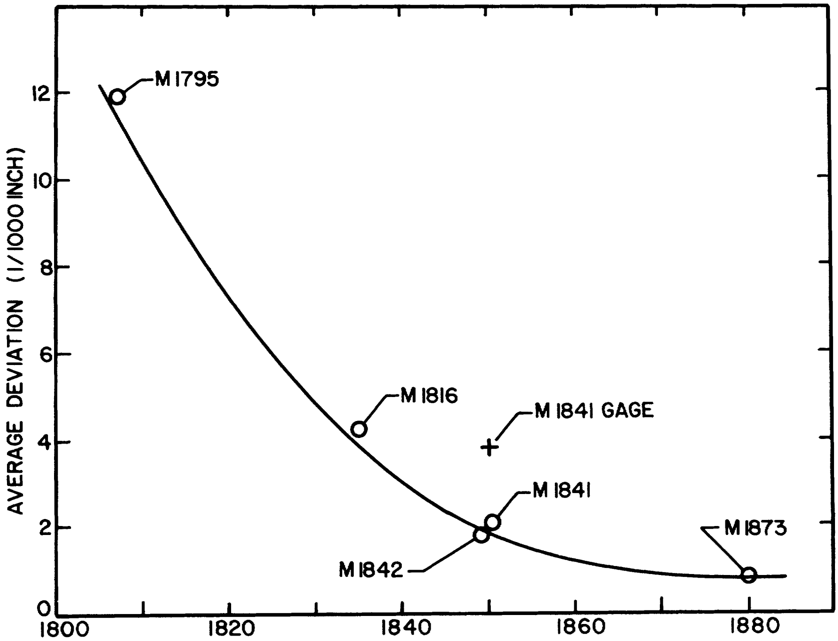

FIG. 7.—Average deviations (in units of 0.001 inch) of the dimensions of the tumblers for each model of lock examined from the mean of each dimension for that model. If all the tumblers of a given model were identical, the deviations would be zero. The average deviation is a measure of the degree to which the tumblers of a given model vary among themselves. The numbers of measurements averaged for each datum point are: M1795, 17; M1816, 14; M1841, 45; M1844, 30; and M1884, 16. The average departure of the measured dimensions from those set by the inspector's gages for the M1841 rifle is shown by the cross. It is slightly greater than the deviations of the tumblers among themselves.

ter armorer at the Pittsburgh Arsenal.[31] Moor tested the action of the locks and attempted to interchange parts among a sample of the muskets, finding that practical interchangeability had not been achieved. His report includes the greatest and least values of a large number of dimensions measured on the muskets examined. (Unfortunately, the individual measurements are not reported so a statistical description of them is not possible.) The dimensions that I measured

[31]Anon., *Report on the Inspection of 100 Springfield Muskets* (1828), manuscript at the Springfield Armory National Historic Site. A sample of 100 model 1816 muskets made in 1819 and 1820 at Springfield were inspected by Benjamin Moor. (See Smith, *Harpers Ferry* [n. 5 above], p. 278, for an account of Moor's technical qualifications.) The measurements on lock parts are given to either the nearest hundredth or half-hundredth of an inch. This suggests that the measurements were taken with a vernier caliper reading to hundredths of an inch and that the inspector estimated between divisions for the half-hundredths.

on the two M1816 tumblers at the Springfield Armory fall within the range of extremes given in Moor's report except for one measurement that was 0.01 inch smaller than the minimum reported.

Eccentricity.—The arbors and pivots of all the tumblers except one made at the Whitney Armory circa 1820 were milled, and any departure of their axes from coincidence (the "eccentricity," defined in fig. 2) shows a lack of accuracy in the machines used. The results of the measurements of eccentricity on the tumblers are shown in figure 8. There is a considerable scatter in the data for the early years, but the upper bound (lines in fig. 8) shows that there was a steady improvement in milling-machine accuracy, reaching 0.001 inch by the 1870s. The eccentricity of the tumbler of a British Tower musket of 1862 is shown for comparison; it is worse than that of contemporary American examples. The eccentricities (fig. 8) are substantially larger than the variability of the tumbler dimensions (fig. 7). This suggests that the accuracy built into the milling machines used to form the arbors and pivots was lower than the dimensional consistency achieved by the handwork of the artificers who filed the tumblers until about 1870, and even then did not exceed the accuracy attained by the filers.

Comparison with gage dimensions.—The dimensions of the M1841 rifle tumblers studied were compared with dimensions taken from gage no. 30, described as a receiver gage with holes and grooves,

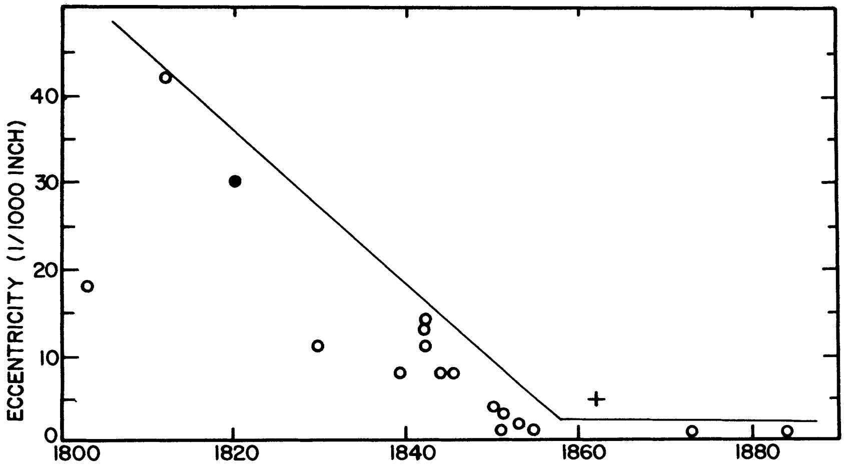

FIG. 8.—The eccentricities—the offsets of the centerlines of the arbors and pivots—of the tumblers examined. The datum for a British Tower musket is marked by a cross. The arbor and pivot are machined surfaces (except on one example among those studied, solid circle) and the eccentricity is a measure of the precision built into the machines used.

and no. 31, a tumbler pattern, in the set of inspection gages for the M1841 rifle now at the National Museum of American History. The dimensions shown in figure 6 as well as the lengths of the flats on the arbor were compared. The average departure of all dimensions of each tumbler from gage is shown in table 3.

In the fifty-four measurements made, the greatest departure from gage was 0.010 inch. On average, by 1850 the tumblers were being made to tolerances of better than 0.004 inch relative to gage dimensions. The accuracy of the work of the individual artificers who made the tumblers is actually better than this since the deviations in table 3 include errors due to deterioration the gages may have suffered, variations among the different gage sets for this model rifle, and any errors made in taking the dimensions of the gages. The average variation of the dimensions among themselves, a measure of the consistency to which the artificers worked, is only 0.002 inch.

Material Evidence: Metallurgy

Good mechanical work on lock parts goes for naught if the parts are not properly hardened after being brought to final size. In the 19th century the hardening had to be done without the aid of measuring instruments or scientific understanding of the processes used. Success depended on the judgment of temperature, control of the furnace atmosphere, and dextrous manipulation of the parts by the artificer entrusted with the work. Wrought-iron parts had to be carburized, and the carburized surface layer hardened; measurement of the depth of carburization and the surface hardness of artifacts can be used to determine the quality of the work, but a section cut from the tumbler is required to determine the depth of hardening. Hence, these data are available for only a few examples. Steel, used later for tumblers, was hardened by quenching and tempering after filing was

TABLE 3
COMPARISON WITH INSPECTOR'S GAGES

Maker and Year	Departure*
Harpers Ferry, 1851	4.2 (1/1000 inch)
Robbins & Lawrence, 1850	3.6
Remington, 1853	4.7
Tryon, 1845	2.6
Whitney, 1854	3.7
Average	3.8

*Average departure of tumbler dimensions from the dimensions of the inspection gages.

completed. To be hard enough to resist wear and simultaneously tough enough to sustain the shock loads to which they are subjected, steel or wrought-iron tumblers must be heat-treated to attain a hardness that falls in a narrow range. Difficulties may arise in attaining the correct temperatures for these operations or from decarburization of the surface of the part while it is at high temperature. The 1828 inspection report on Springfield muskets (see n. 31) states that 15 percent of the tumblers examined were too soft. Good control of the hardening process had not yet been attained.

Hardness data were taken on several tumblers that could be brought to the laboratory for study.[32] The surface hardness of the Whitney tumbler made in 1820 ranged from 1,033 to 560, very high hardness values that indicate a brittle surface. The combination of excessive hardness and poor surface finish would leave this tumbler susceptible to failure under the high stresses that would result because of the eccentricity of the arbor and pivot. This is the most likely cause of the crack that is present in the tumbler (see fig. 3). The Whitney tumbler made in 1851 has a surface hardness of 250–350. Since the hardness of iron is about 100, and fully hardened, high-carbon steel is about 900, this tumbler is hardly hardened at all. Metallurgical examination would be required to determine the cause; the most likely source of difficulty is surface decarburization due to exposure to an oxidizing atmosphere in the heating furnace.

Two M1842 musket tumblers were available for laboratory examination in section. One of them showed considerable wear on all its bearing surfaces and had a surface hardness of 137. When sectioned it was found to be only slightly carburized. The second, which was not worn from use, had a carburized case 0.002 inches thick with a hardness of 512. It had been correctly heat treated. Fragments of failed M1855 tumblers were found to be made of quenched steel only slightly tempered with a hardness of 635. They failed because the temper was not drawn enough; this left them susceptible to cracking caused by stress concentrations developed at the sharp corners at the shoulder with the arbor and by the poor finish of the milled surfaces.

[32]Microhardness measurements were used to avoid surface damage to the artifacts. Because the surfaces could not be polished for measurement, the data show more scatter than they would on prepared specimens, but comparison with data taken on sectioned specimens shows that the average hardness values obtained on the artifacts are reliable. The hardness numbers reported are Vickers microhardness (HV) measured with a 0.3-kg load on the indentor. Successful heat treatment of a tumbler requires that the hardness be between HV 520 and 580. (This corresponds to a Rockwell "C" hardness range of 50–54. The Rockwell C scale is frequently used today for hardness measurements on steel in manufacturing plants.)

An M1873 tumbler was found to have a hardness of 540, about correct for this type of service.

Before proceeding to an interpretation, I will summarize the material evidence. The tool marks and dimension measurements show that by 1850 artificers using hand files had learned to bring rough forged and machined parts of complex shape to final dimensions specified by gages to an accuracy of a few thousandths of an inch in routine production. This was achieved by artificers at the national armories and at the works of private contractors from Philadelphia to Windsor, Vermont. They achieved higher standards of accuracy than could be attained with machine tools throughout most of the 19th century. A generally accepted method of doing this handwork was followed at all of the armories. The metallurgical data suggest that hardening remained a difficult problem for the makers of lock parts long after good dimensional control had been achieved in production. Difficulties with heat treatment of lock parts persisted at Springfield at least through 1855. The excessive hardness of the broken M1855 tumblers suggests that the armory artificers had trouble developing control of heat treatment of the newly introduced steel used to make tumblers.[33]

Machine Tools

The principal change in an artificer's task brought about by the increased use of machine tools for the manufacture of small arms in the 19th century appears to have been reduction in the amount of physical labor required in removing metal. Calculations based on documentary and material evidence confirm this inference.

While no examples of forged but unmachined lock tumblers have yet been found, the amount of metal that had to be removed by machining and filing can be estimated from finished artifacts. A polished and etched cross section of an M1842 Springfield musket tumbler is shown in figure 9. The curved bands of slag and pearlite revealed by etching would have been parallel in the wrought-iron bar stock before forging. The metal flowed laterally when upset in the forging dies; the resultant displacement of the slag and pearlite bands shows the amount of flow and can be used to estimate the shape of the forging before it was machined. The estimated shape is sketched

[33] Heat treatment was still causing serious problems at Springfield as late as 1917, when there were difficulties with the bolts and receivers of the M1903 rifle. Julian S. Hatcher, "Metallurgical Improvements in Springfield Rifle," *Army Ordnance* 2 (1922): 351–53. This is another demonstration of the much greater difficulty that manufacturers in the United States had with metallurgical than with mechanical problems. See also Gordon (n. 6 above).

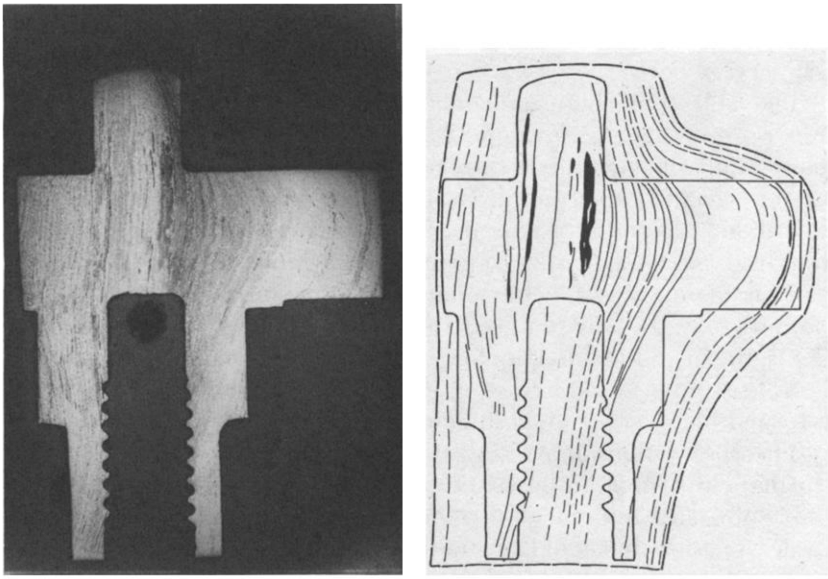

FIG. 9.—Polished and etched section cut through the center of the arbor and pivot of a tumbler for an M1842 Springfield musket lock made about 1850 (left). Black streaks are slag inclusions; grey bands are pearlite (regions of high carbon content) in the wrought iron. Flow of the iron during forging has displaced these streaks and bands. The shape of the forging before machining and filing inferred from these displacements is shown by dashed lines on the sketch at the right. (The scale of the picture is shown by the diameter of the arbor, 0.444 inch.)

in figure 9 and shows that between 1/8th and 1/4th of an inch of metal had to be removed from the forged piece to bring it to final dimensions. This is consistent with Dixie's report that the lock plate for the M1855 Springfield was forged 1/8th of an inch oversize (see n. 22).

Records of iron purchased and arms made show that a large part of the iron brought into the Springfield Armory never emerged in finished products and must, therefore, have been reduced to chips and scrap. From data on the number of arms made and the weight of iron in each, I estimate that only 31 percent of the iron purchased in 1852 emerged from the armory as components of weapons. This is an improvement on the 24 percent attained in 1823.[34] While the aggregated data do not show how the losses were apportioned among the different parts of a musket or the different processes used—and

[34]Data on the number of arms made, the weight of iron in each part, and the amount of iron purchased for 1852 are given in *Bessey's Directory* (n. 21 above). I assumed that there were no changes in the stock of iron held at the armory this year. The amount of iron required to make muskets in 1823 was estimated by Roswell Lee; see Deyrup (n. 9 above) p. 86.

some of the loss would have been in forging—they confirm that a substantial amount of metal removal was required of the armory artificers.

The table of machine and labor requirements for making rifle muskets prepared at the Springfield Armory in 1864 (see n. 24) lists the power and time required to machine each part; these data can be used to calculate that the physical work entailed in milling a tumbler was about 124,000 foot-pounds. From the number of hours of filing required as well as Rankine's estimates of the physical work done in various manual tasks,[35] I estimate that not more than 14,000 foot-pounds of work was required to file a tumbler after it was milled. Thus, the introduction of milling machinery before 1864 had resulted in at least a tenfold decrease in the physical labor required to bring a forged blank to the final dimensions of a tumbler.

The observations above suggest that the machine tools used at the Springfield Armory in the first two-thirds of the 19th century were capable of useful amounts of metal removal but were not capable of the same precision that could be attained by filing. Documentary evidence is scant, few examples of machines survive, and none of these have been subjected to careful analysis that would reveal likely sources of poor machine-tool precision. One possibility is inadequate support of the tool and workpiece because of loose bearings and light frames. Precise machining also requires accurate lead screws with graduated dials to control the positioning of the cutter and workpiece. Careful measurements of the lead screws in surviving machine tools dating from the first two-thirds of the 19th century have not yet been made, but it is likely that errors in pitch would have made precise graduation impossible. Finally, and probably most important, the carbon steel cutting tools then in use, while capable of precise work in cuts of short duration done at low speed, required frequent resharpening. The Springfield Armory had 548 cutters on hand for use on thirty milling machines in 1844, when only three models of arms were in production.[36] This implies a large reserve of cutters for each machine and the need for frequent resharpening, which was a difficult task until Brown invented the formed cutter, which retained its contour when reground.[37]

Artificers' Skills

The material evidence presented above shows that bringing lock parts to gage required handwork with a file at least through 1884.

[35]William Kent, *The Mechanical Engineer's Pocket-Book* (New York, 1903), p. 433.

[36]Springfield Armory inventory (n. 23 above) for 1844.

[37]Joseph W. Roe, *English and American Tool Builders* (New Haven, Conn., 1916), p. 206.

The dimensional tolerances and the quality of workmanship achieved by the artificers improved continuously along a learning curve. The improvement in product quality attained was primarily due to the superior mechanical skills developed among the artificers who made the lock parts, although better organization of the work and manufacturing procedures helped facilitate development of these skills. Clearly, the skills required to achieve interchangeability in the new system of manufactures was not "built into the machines" but remained in the hands of the artificers.

During the 19th century, science and engineering principles began to influence the development of mechanical technology in areas such as heat engines, water motors, bridge building, shipbuilding, structures, and, toward the end of the century, metallurgy. But the principles of metal cutting were not studied until the 20th century, and science and engineering theory had little effect on early manufacturing technology. This remained the domain of the mechanicians and artificers who solved problems through an understanding of the interaction between tools and materials. We call this "skill" because it cannot be adequately described in verbal or quantitative terms.

The skills in question here are those that have been described as "genuine" rather than "socially constructed."[38] I like to describe the skills required of mechanical artificers in terms of four components: dexterity, judgment, planning, and resourcefulness. *Dexterity* is the ability to manipulate tools with facility, and *judgment* is the capacity to gage size and shape by eye and goodness of fit between mechanical parts by feel. *Planning* and *resourcefulness* relate to decisions an artificer must make in organizing the way in which a task is to be undertaken and in responding to the unanticipated complications that inevitably crop up owing to inhomogeneity of the materials used or wear of the tools or machinery employed. All these elements of skill were required of artificers making small arms, but the relative importance of the four components changed throughout the course of the 19th century.

Planning.—Planning out a sequence of work is important when all the parts of a mechanism have to be made and fitted together without guidance from gages. Both documentary and material evidence show that the scope for the exercise of planning skills by artificers in the armories was reduced by division of labor, improved communication between mechanicians, and use of filing jigs. These factors required the artificer to focus on the narrower problem of making one part to gage according to a generally accepted method of working instead of

[38]Genuine and socially constructed skill are defined and discussed by Charles More, *Skill and the English Working Class* (London, 1980).

planning the way that the parts of an entire mechanism were to be fitted together.[39]

Resourcefulness.—The task of 19th-century artificers who specialized in making one particular lock part to gage never became entirely repetitious. Inhomogeneities in the material used, variations in the amount of metal left from the forging and rough machining, and wear of the files and jigs created contingencies to be dealt with differently in each successive part made. There is abundant evidence of deficient homogeneity in both the wrought iron and the American-made steel available to the armories in the first two-thirds of the century.[40] Nonuniformly distributed slag particles in wrought iron can cause small pieces of metal to break away during machining or filing, thereby thwarting attempts to attain the required dimensions. Although the uniformity of the iron may have improved during the century, the dimensional accuracy required of the filers also increased; it is likely that the vagaries of iron remained a problem for artificers until it was replaced by steel in the 1870s.

Dexterity.—The dexterity of an artificer is more than an ability to manipulate small objects, such as is tested in standard psychological tests; it includes the capacity, learned by practice and experience, to manipulate hand tools so as to produce work of superior quality. The dexterity achieved by the artificers who made lock mechanisms is directly visible in what they made: features such as smooth, continuous curves, flat surfaces, right angles at corners, and good finish. Many

[39]Use of dimensions in the manufacture of mechanisms was impractical until the micrometer caliper became widely available late in the 19th century. This will be discussed later. In a recent paper, John Harris has described the difficulties encountered in attempts to transfer technology in the 18th century with drawings or descriptions or even with purchase of machines. Transfer was difficult for the mechanical arts, but almost impossible for metallurgy. The same situation applied through much of the 19th century and placed a distinct limit on the effectiveness of communication between designers and artificers. The importance of the presence of a skilled artificer in the transfer of new technology is illustrated by the experience at the Springfield Armory with barrel welding in rolls. There were several unsuccessful attempts to introduce this process, which had been developed in England, before 1855. Success was achieved only when the machinery, the bar iron to be welded, and an experienced artificer were all imported from England. The production of welded barrels per welder went up tenfold the year after roll-welding was introduced. J. R. Harris, "Industrial Espionage in the Eighteenth Century," *Industrial Archaeology Review* 7 (1985): 127–37; Deyrup (n. 9 above), table p. 247; R. B. Gordon, "English Iron for American Arms: Laboratory Evidence on the Iron Used at the Springfield Armory in 1860," *Journal of the Historical Metallurgy Society* 17 (1983): 91–98.

[40]Difficulties with wrought iron were particularly severe in barrel making; much of the iron used for locks was left over from the barrel shops. *Bessey's Directory* (n. 21 above).

people find such features pleasing, but there is a scientific as well as an aesthetic basis for the standards of workmanship used to judge mechanical dexterity; smooth curves and the absence of deep tool marks reduce the stress concentrations that are the most common cause of cracks in the metal parts of mechanisms.

The introduction of filing jigs, which reduced the need for planning skills, placed new demands on the filer's dexterity.[41] The jigs necessarily contained hardened steel templates, and contact with these would quickly ruin a file. To achieve gage, the artificer had to manipulate the file so as to bring the work to the same profile as the template without touching the latter.

The poor workmanship found in the locks made before about 1830 shows that there was an absolute scarcity of artificers with the requisite mechanical dexterity. This observation is confirmed by the inspection report of 1828 (see n. 31); Benjamin Moor complains of poorly formed notches, variability of the curved edge, and deviations in the angular setting of the flats on the arbor in relation to the bearing of the mainspring. The quality of the workmanship observed in the locks improves as the dimensional consistency (shown in fig. 6) improves. By 1880, the quality of the filing done at the Springfield Armory was so good that it requires observations with modern micrometers and microscopes to distinguish this work from 20th-century machining.

Judgment.—A measure of the level of judgment skill required of an artificer is the number of variables that must be dealt with in completing a task relative to the amount of explicit information about these variables that is available. Little judgment is required when an artificer is supplied with exact information about the requirements to be met and the condition of his work at any stage of its progress—as, for example, when a dimension is gaged with a digital readout against established, numerical limits. A high level of skill is required when many decisions have to be taken, but only limited information is supplied by the designers of the product being made or the instrumentation available to monitor the progress of the task. In the first two-thirds of the 20th century, designers conveyed their intentions by means of drawings and dimensions (Woodbury's last two conditions; see n. 6). In much of the 19th century, however, models and, later, gages were used rather than drawings and dimensions; the artificer was required to duplicate the form and size of the model or gage in

[41]The term "jig" is supposed to have been derived from the complex, dancelike motions required of an artificer using this appliance. In the hands of the unskilled it was said to be "death to files." F. G. Parkhurst, "Manufacture by the System of Interchangeable Parts," *American Machinist* 24 (1901): 39–43.

the part being made, perhaps with the aid of fixtures and jigs.[42] I will argue that the methods of measurement and gaging introduced in the 19th century, instead of eliminating personal judgment, actually demanded increasingly sophisticated levels of judgment skills from artificers.

Reliable scales or rules were not available to American artificers before 1850, when J. R. Brown made a linear dividing engine suitable for graduating steel rules for shop use. In 1851 Brown began manufacture of a vernier caliper that made it possible for mechanical artificers to measure to 0.001 inch. But manufacture of the micrometer caliper, the instrument most useful in precision shop work, began in America only in 1868.[43] The difficulty of specifying dimensions in the absence of adequate measuring instruments is illustrated by the descriptions of bore gages issued by the Ordnance Office in 1822; the gages are required to match the diameter of a sphere of lead of specified weight rather than a specified diameter.[44] The limit of the sensitivity of measurement with the unaided eye and a steel rule is about 0.005 inch, yet we have seen that by 1850 the dimensions of lock parts were being held to within 0.002 inch and, by 1873, to better than 0.001 inch in routine production at works hundreds of miles from each other.[45] Such precision was possible because an artificer can determine deviation of a fraction of a thousandth of an inch by the feel of how a part fits into a gage. This was the skill that was used throughout most of the 19th century to transmit dimensional requirements and to inspect the work of artificers by gages.

The steady increase in the use of gages is shown in the records of the Springfield Armory. No gages are mentioned in Whiting's report of 1810. The first experiments with gages are said to have begun in about 1817, and Dalliba's report, widely quoted by modern writers on manufacturing technology, asserts that in 1819 the principle of making parts to gage was being perfected and that each artificer was

[42]Making gages, jigs, and fixtures required increasingly sophisticated application of planning skills on the part of the artificers who made this new equipment. This is discussed below.

[43]Roe (n. 37 above), pp. 202–13.

[44]Ordnance Office letter of July 25, 1822 quoted in C. M. Green, undated MS at the Springfield Armory Museum National Historic Site, Springfield, Mass.

[45]One commonsense reason for the continued preference of American artificers for the inch rather than the millimeter is that the inch is of a length that can be read to hundredths by eye and thousandths by vernier; the vernier on a metric caliper reads to 1/50 rather than 1/100 of a millimeter and is less convenient to use. French ideas of rationalism that inspired the interest in interchangeable manufacture also saddled practical men with impractical units of measure.

supplied with a gage for his own part.[46] This may be a statement of intention rather than a report of an accomplishment. It would have been nearly impossible to supply gages in a span of just two years even for the 118 artificers employed in bringing musket parts to final dimension at Springfield. The government requirements published in 1823 for the inspection of contract arms, which were supposed to be held to the same standards as those made at the national armories, lists only eleven gages.[47] The 1828 inspection report (see n. 31) shows that the gages used failed to detect several tumbler faults considered important by the inspector: The cock notch had not been filed perpendicular to the tumbler face in 70 percent of the examples examined, and in 25 percent the squares were described as "wrenched."

By 1850, fifty-six gages were used, fifteen for the barrel, fifteen for the lock, and twenty-six for the mountings and stock; by 1878 the number had increased to 154.[48] Although there had been a large increase in the number of gages, there was little change in the way they were made and used.[49] The National Museum of American History's complete set of gages for the M1841 rifle makes use of the following basic gage elements: (1) *patterns,* which show some aspect of the form of a part; (2) *receiving gages,* into which a part must fit (a receiving gage shows the outer boundary of a part but not an inner bound; how well the part fits once it is in the gage is a matter of judgment); (3) *groove, hole, and plug gages,* which are used to check one dimension by the goodness of fit determined by the sense of touch (most of these gages do not provide for limits, and it is left to the artificer's judgment to determine if a part is made to gage dimensions); and (4) *location gages,* which show the relative positions of different parts of the weapon, such as the position of the cone relative to the breech of the barrel. The tumbler gage from this set incorporates groove, hole, receiving, and pattern elements (see fig. 10).

Making these gage sets was a formidable task. First, a master weapon had to be made. Gages for inspection and for the use of the artificers were then designed, made, and fitted to the master parts. Consistency had to be checked by judgment of feel of fit and by eye. The level of success achieved depended on both the quality of the gages, which was determined by the artificers who made them, and the design of

[46]Smith (n. 5 above), p. 109; Whiting (n. 18 above); Dalliba (n. 19 above).

[47]Anon., *Regulations for the Inspection of Small Arms* (Washington, D.C., 1823).

[48]Anon., *Ordnance Manual* (Washington, D.C., 1850); Benet et al. (n. 17 above).

[49]No examples of the gages used before about 1840 have survived but they were probably similar in design to those used later. The method of making and using gages had changed very little even by 1917. The gages used in 1917 are described in Fred H. Colvin and E. Viall, *United States Rifles and Machine Guns* (New York, 1917).

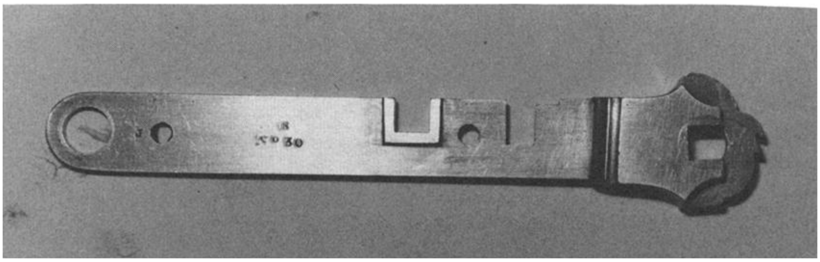

FIG. 10.—A tumbler gage for the M1841 rifle. The form of the edge of the tumbler is shown on one end of the gage; a tumbler can be inserted in the gage for comparison. The large notch in the center shows the width and length of the flats on the arbor. The smaller notches show the thickness of the tumbler and the length of the cylindrical part of the arbor. The fit of a tumbler to these slots must be judged by feel and by eye; no limits are specified. (Photographed at the National Museum of American History.)

the gages—their capacity to measure all critical dimensions and avoid requiring unnecessary precision where not needed.[50] Examination of the gages for the M1841 rifle shows that, except for holes and cylindrical surfaces, they were made entirely by hand filing. The scribed lines used for layout are still visible on some of them. The gages used at Springfield are described by Dalliba as made of hardened steel, and Roswell Lee proposed that gages be case-hardened. But these gages appear not to have been hardened (except for the barrel-plug gages) and so would be subject to loss of accuracy through wear in use.[51] The increased reliance on gages placed new demands on the judgment skills of the artificers who used them; making gages called for the highest standards of workmanship in all of the components of mechanical skill. Gage making and maintenance was an important task at the national armories, and the practitioners of this special art were the progenitors of the toolmakers of the 20th century.

Only one gage in the set for the M1841 rifle is described in the Ordnance Manual as a limit gage. It is a plug gage for the bore of the barrel and is 0.009 inches larger than the standard plug gage. The gages that were used to control the absolute accuracy of lock parts to better than 0.004 inch by 1850 were not limit gages; they depended entirely on the artificer's judgment of the fit of the part he was making to the dimension set by the gage.

[50]A critical study of the design of the gages for the M1841 rifle has not been made yet but it appears that precision was called for in many places where it was not needed. This would be a critical concern in determining the utility of armory practice in commercial manufacturing.

[51]Dalliba (n. 19 above); G. S. Cesari, "American Arms-Making Machine Tool Development" (Ph.D. diss., University of Pennsylvania, 1970).

So, as manufacturing methods developed through the 19th century there was less call for planning skills but heavier demands on the artificer's dexterity and judgment. Superior mechanical skills were developed and disseminated among a growing number of artificers. The mechanical requirements and the methods of attaining them were established early in the century, and after that there was little change in the basic methods of making parts for lock mechanisms other than increased use of machine tools for the heavy labor of roughing cuts, which allowed filers to concentrate on the final, precise shaping of parts to gage. There was a continuing improvement in the quality of work done with hand tools. The rate of progress in the attainment of interchangeable manufacture in the first two-thirds of the 19th century may have been limited as much by the rate of learning and transmission of the requisite mechanical skills among artificers as by the rate of invention of mechanical appliances to aid their work.

Economic History of the Springfield Armory

The Springfield Armory was not required to be commercially profitable, but did have to be able to demonstrate that its production of small arms was economical in order to serve its function as a "yardstick" against which the prices charged by the private armories could be evaluated and to deflect attempts by private contractors to capture its business.[52] One method of investigating whether decisions about manufacturing technology at the armory were made in response to economic considerations is econometric analysis of the aggregated data on expenditure and output of arms. Such analysis is framed in terms of *production functions,* which relate quantity of arms produced to *factors of production,* such as expenditure on labor and equipment.

In a 1968 article Edward Ames and Nathan Rosenberg addressed the problem of devising production functions that reflect technological change and that could be used to explain why small-arms producers made more use of specialized machinery in the United States than in England.[53] In order to describe the consequences of using

[52]The division of small- arms procurement between government armories and private contractors was in dispute throughout the 19th century. The best organized and most determined attempt to capture all of the government small arms business was made by the Association of Manufacturers of Arms, Ammunition, and Equipments of the United States in the late 1870s. The association's efforts were deflected with the aid of data on the cost of arms production at the Springfield Armory developed by Superintendent J. G. Benton. C. Meade Patterson, "Springfield on Trial," *Gun Report,* July 1963, pp. 15–23, 44; August 1963, pp. 14–17; September 1963, pp. 10–13.

[53]Edward Ames and Nathan Rosenberg, "The Enfield Arsenal in Theory and History," *Economic Journal* 78 (1968): 827–42.

specialized production machinery, they asserted that machine-made arms are interchangeable while craft-made arms are not. (More accurately, the assertion is that interchangeability could be attained at reasonable cost by using production machinery but not by craft methods.) This led them to describe, for example, gunstocks made after 1820 as interchangeable (because they were made with specialized machinery) and to state that a higher degree of interchangeability was attained through the use of milling machines than through hand filing with jigs. This formulation of technological change in small-arms manufacture is contrary to the material evidence discussed above. A better identification of the factors of production with the physical processes actually used is needed if econometric analysis is to define how decisions on technology may have been based on costs of production.

A step in this direction was made by Paul Uselding in an analysis intended to test the importance of including materials as well as labor and capital in the production function for arms making.[54] He showed that the growth of labor efficiency at the Springfield Armory was particularly great between 1840 and 1850; during this time there was no marked increase in the ratio of wage rate to rental of capital, which argues against the labor-scarcity hypothesis that has been suggested to explain the preference of American armories for specialized machine tools. Instead, Uselding finds evidence of improvement in labor quality at the armory. Since the analysis is based on aggregated data, this generalization cannot be identified with actual physical processes, but Uselding's results appear to be in accord with the material evidence that shows a marked improvement in the quality of the mechanical work done by armory artificers in the first two-thirds of the 19th century.

Traditional methods of armory work established early in the 19th century persisted well into the 20th. This was a subject of criticism when the methods used at the Springfield Armory were viewed by observers experienced with the production methods used in other industries in 1917. Colvin and Viall found that a great many of the gage requirements for the M1903 Springfield rifle were unnecessarily tight and that it made little sense to make a part like the trigger guard by machining and filing away a forging that initially weighed $3\frac{1}{2}$ pounds to less than $\frac{1}{2}$ pound; a stamping would have served as well.[55] The design of the gages used in 1917 had changed little from those used

[54]Paul J. Uselding, "Technical Progress at the Springfield Armory, 1820–1850," *Explorations in Economic History* 9 (1972): 291–316. This paper is discussed by V. Kerry Smith, "The Ames-Rosenberg Hypothesis and the Role of Natural Resources in the Production Technology," *Explorations in Economic History* 15 (1978): 257–68.

[55]Colvin and Viall (n. 49 above), p. 155.

in 1850, and the last step in many of the sequences of operations for the rifle parts was still filing to gage. (One reason for the continued use of the file may have been the antiquity of much of the machinery at the armory, however.) Clearly, leadership in manufacturing technology had passed from the armories to other industries sometime in the last third of the 19th century.

Conclusions

A large reduction in the physical labor of shaping wood and metal parts was achieved by the armories in the 19th century by use of power-driven machine tools. Yet what made possible the attainment of interchangeable manufacture was the remarkable growth in the skills of the artificers who brought the machined parts to final dimensions with hand tools. This has been demonstrated by study of the tumblers of the lock mechanisms of military small arms, but examination of the other lock parts and of the stocks of the weapons studied shows that the same conclusions apply to these.[56]

Manufacture of arms for the government is not subject to the economic constraints that apply to products that must be sold on commercial markets; hence, results obtained from a study of developments at the armories making military arms are not necessarily applicable to other branches of manufacturing. Once the technical capacity to manufacture to certain standards exists, the decision on the degree to which this capacity is used in making any given product is an economic one.[57] The very wide variation in the quality of the mechanisms in commercial arms made in the 19th century shows that not all manufacturers found the federal armory standards of quality economically useful. However, the skills developed in small-arms making by the armory artificers were available when required in other industries. Study of artifacts other than small arms will be required to show how much these skills were drawn on in other branches of American manufacturing. I anticipate that they will be found to have been fully exploited by midcentury in making both machine tools and measuring equipment. Thus, the superior quality of the machinery

[56]In view of the claims made on behalf of John Hall's machinery, it would be of particular interest to apply the archaeological methods of examination to surviving samples of Hall rifles. I think it likely that such examination will show results not appreciably different from those found for the products of the other armories.

[57]E. Buckingham, *Principles of Interchangeable Manufacture*, 2d ed. (New York, 1941). On the lack of incentive to use interchangeable manufacture in the nonmilitary small arms industry, see R. A. Howard, "Interchangeable Parts Reexamined: The Private Sector of the American Arms Industry on the Eve of the Civil War," *Technology and Culture* 19 (1978): 633–49.

sent to the Enfield Armoury by Robbins & Lawrence and the Ames Manufacturing Company in the 1850s, some of which remained serviceable for over 100 years, is as much due to the skills of American mechanical artificers as to the design capabilities of American mechanicians. And, once manufacture of vernier and micrometer calipers began in the United States, dependence on imported instruments for factory use was quickly eliminated, and the cost of accurate tools was reduced enough so that each artificer could have his own.

The new levels of skill attained in the armories were not economical in cases where a more crudely made mechanism was serviceable to most customers, as with agricultural and sewing machinery throughout much of the 19th century. Nevertheless, the availability of skilled artificers and accepted methods of working to close tolerances, together with new machinery such as the cylindrical and centerless grinders, made possible the production of new products, such as bicycles, steam turbines, and, early in the 20th century, aircraft engines, in which precision manufacturing was required for success. It was only in the 1920s that precision filing began to become unnecessary in training programs for apprentice toolmakers; the introduction of more rigid machine tools with better bearings and of high-speed cutting tools finally made machine work more accurate than the handwork of even the most skilled mechanical artificers.

A mechanical ideal was indeed achieved in 19th-century American manufacturing, but it was not the one proposed by Fitch. It was the superior standards of workmanship and mechanical skill of American artificers.[58]

[58]Since this paper was written in 1985, examination of the Hall pattern rifles and carbines in the collection of the Springfield Armory Museum has shown that, while some surfaces in the lock mechanisms that are neither mating nor bearing carry milling marks, all surfaces where a fit to another part is required have been filed to their final dimensions.