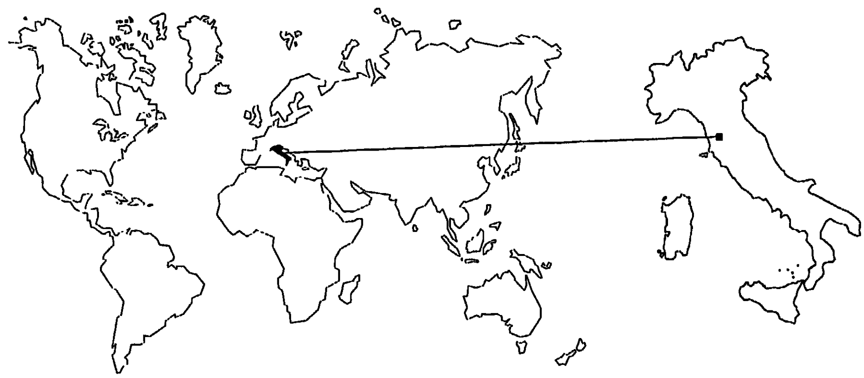

13. Historical Outline of Geothermal Technology in the Larderello Region to the Middle of the 20th Century

by
Pier Domenico Burgassi

Abstract: The chapter discusses the impact of geothermal resources on the inhabitants of the Larderello region in prehistoric, ancient, and recent times, up to 1944.

Industrial processes exploiting boric acid and other boron compounds from geothermal fluids and drilling technologies for high-temperature geothermal resources were developed at Larderello, starting in the early 19th century. An integrated drilling, chemical, and agricultural industry at Larderello paved the way in the 20th century for the birth of the world's first geothermal-electrical industry. The first successful experiments conducted between 1904 and 1910 to generate electricity using hot natural fluids are recounted, and mention is made of the geothermal power plants installed at Larderello up to the beginning of World War II.

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At the Roots of Civilization, between Prehistory and Legend

The geothermal manifestations in the region of Central Italy now known as Larderello are very young from the geological point of view: on the order of 0.5 to 1 million years old (figure 1). No one, however, can say if some of our prehistoric ancestors observed their formation and what feelings they may have had: surprise? curiosity? terror? Whatever the answer, indirect information shows that in the Upper Paleolithic, fumaroles, steam jets, hot springs, *lagoni,* and gas exhalations were already objects of attention by the first inhabitants of the Larderello region. The term *lagoni* (singular, *lagone*) refers to hot natural pools from which gas and saturated steam escape into shallow circulating waters, resulting in the formation of hydrothermal deposits at the surface, especially boron compounds.

Probably as early as the Neolithic, all these manifestations were considered signs of the existence of underground divinities, who

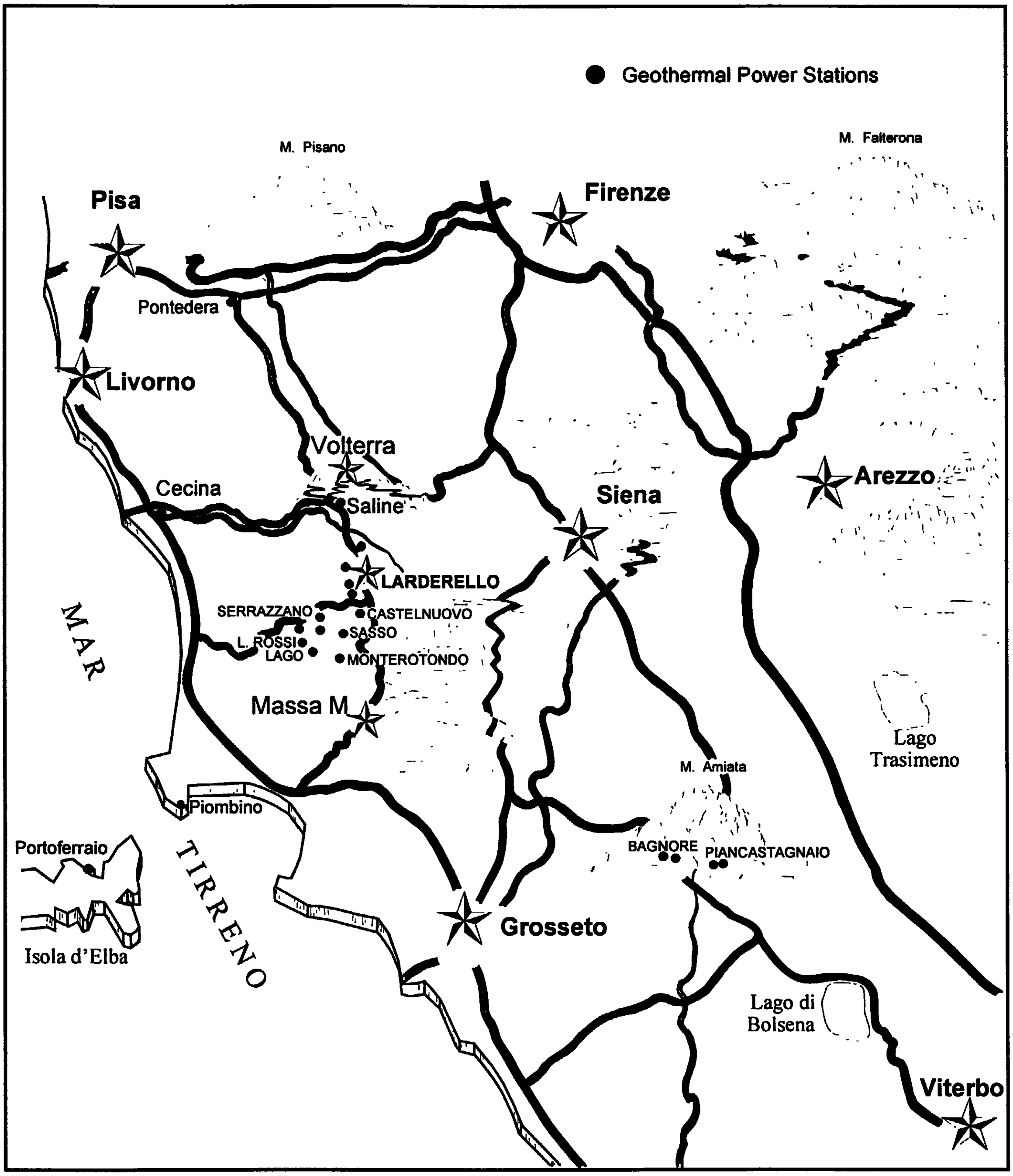

Figure 1. Location map of Larderello and the surrounding region (modified from a 19th century chorographic sketch).

occasionally rose through them up to the surface with hisses, rumbles, and subterranean noises. Perhaps then the belief began to spread in prehistoric epochs that these divinities wanted people to be aware of their intrinsic power, that they demanded signs of respect from whoever dared to tread on the roof of their abode.

Based on legends whose roots fade away into Neolithic times, some believe today that the area of manifestations was considered by the early inhabitants of the region to be the uncontested realm of infernal divinities, but this idea is not sound because the concept of hell certainly came after the Neolithic period. Instead, Neolithic people probably believed not in the devil and hell but in the existence of underground divinities, some powerful and dangerous, others gracious and benevolent. Thus people learned gradually, at their own expense, to respect the former by not arousing their wrath and to have confidence in the latter, enjoying their healing gifts. These included the heat perennially supplied by the gracious manifestations as an antidote to the cold and the therapeutic properties of certain thermal muds and waters, probably perceived as generous gifts from benign deities—certainly not from malevolent angels, as the concept of hell would suggest.

Whichever interpretation one places on the first relationships that prehistoric people established with geothermal manifestations in the Larderello area, whether these were exclusively functional or included a religious aspect, as I believe, the fact remains that the first contacts of the region's early inhabitants with geothermal manifestations have faded away from the roots of civilization into the night of time.

From the Etruscans to the End of the First Millennium

From the Paleolithic through the Neolithic, the development of civilization was long and slow, a fact reflected in the evolving relationships between prehistoric peoples and the natural manifestations of Central Tuscany. Etruscan settlements in this region around 1300 B.C. and their flourishing growth for over a millennium brought something new to the harnessing of geothermal energy and its by-products—the use of thermo-mineral waters and muds for therapeutic purposes, and the exploitation of hydrothermal minerals deposited near the edges of the *lagoni*.

Numerous vestiges and handmade objects found in Tuscany's Metalliferous Hills—the hilly, low mountainous region between Florence to the east and Grosseto and Pisa to the west—attest to widespread therapeutic use among the Etruscans of the hot springs and muds in the Larderello area. Moreover, traces of boron compounds found in the glazes of Etruscan plates and crockery show how these people, many centuries before Christ, had developed a high degree of expertise in grinding and processing borates, mixing these products with other ingredients to manufacture fine pottery.

As time passed, the fame of the therapeutic properties of the thermo-mineral waters and muds of the Larderello area extended to other regions in the Mediterranean basin. The Greek poet Lycophron in the 3rd century B.C. wrote in his poem "Alexandra" (or "Cassandra") that "the river Lynceum, running through the territory of the Etruscans, originates in an area with special manifestations...whose waters are used to treat numerous diseases of the eyes...." The river Lynceum was identified later as the present-day river Cornia, originating near Larderello. Its catchment basin covers a large part of the area with high-temperature manifestations.

The glazes of the *vasa sigillata*, dating from the 1st century B.C. and conserved in the archaeological museum of Arezzo, offer another proof of the ancient use of boron compounds associated with the Larderello manifestations. *Vasa sigillata* means "seal-bearing vases," and this red-glazed pottery often had designs in relief resembling seals, perhaps a sort of trademark for the vases. The glazes for this pottery are a mixture of iron oxides and boron compounds, both found near the manifestations of Monterotondo, a few kilometers south of Larderello. Other origins of these compounds can be ruled out, since the only important deposits of boron minerals in Italy are associated with thermal manifestations in the Larderello region.

The fact that such products were used during the 1st century B.C. is not surprising if one considers that the Etruscans until the 3rd century B.C., and the Romans after them, knew and mined all the mineral resources of Central Italy for more than a millennium. These include hydrothermal deposits in the Larderello area and the rich metal ores of the Metalliferous Hills and the island of Elba, such as copper, iron, zinc, lead, and silver. After the 1st century B.C., many Latin poets and writers, such as Tibullus, Strabo, Pliny the Elder, and Vitruvius, mentioned these uses of hydrothermal minerals and metals along with the balneologic and therapeutic uses of hot springs and muds from Central Italy to the south of Pisa.

The *palle da cani* probably date from the beginning of the Christian era. These were small balls of mud gathered from the edges of natural hot pools, then dried and sold to treat skin diseases. The term itself means "balls for dogs," most probably because the mud balls were tried on the sores of dogs before they were used on people.

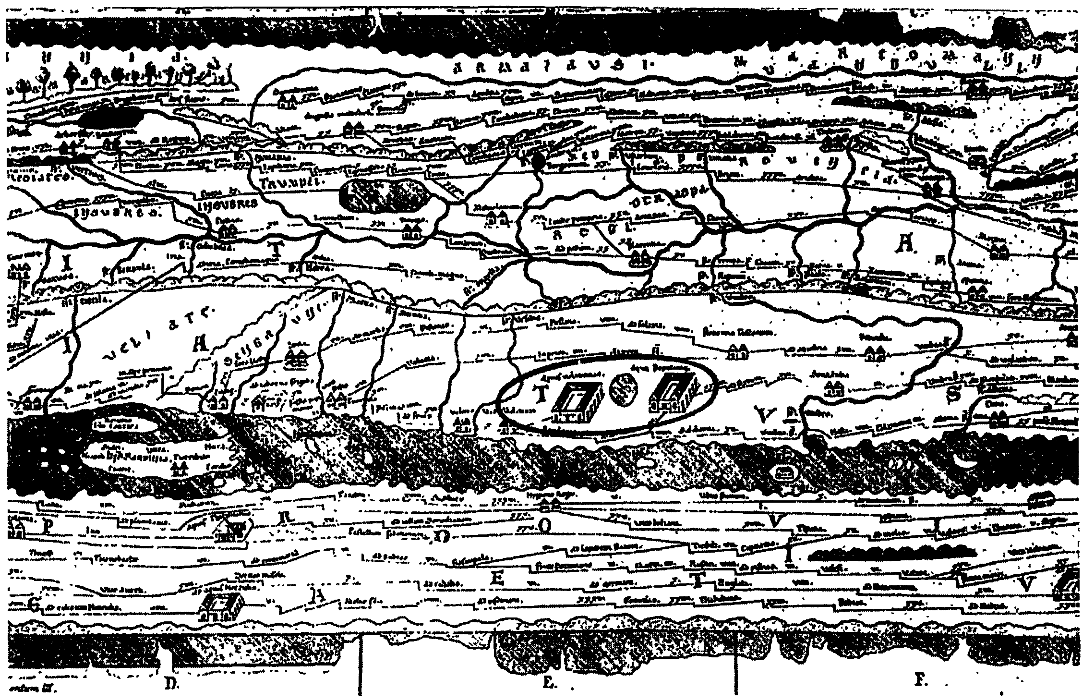

Figure 2. Detail of the *Tabula Itineraria Peutingeriana*, showing the location of Aquae Volaternae and Aquae Populaniae.

The first cartographic document recording two spas near Larderello (Aquae Volaternae and Aquae Populaniae) is the *Tabula Itineraria Peutingeriana* (figure 2). This document, dating from the late 3rd or early 4th century A.D., is a map of the main routes and military roads of the Roman Empire. The fact that these two spas, among the many existing in Central Italy, were singled out in the portion of the map shown in figure 2 means that they had long since reached a stage of advanced development and fame.

Most likely not only were thermal waters and muds used for therapeutic purposes, but hydrothermal minerals associated with natural manifestations were traded since Etruscan times. This trade was well established before the Christian era began and flourished for several centuries in Roman times. This exploitation of hydrothermal products slowed toward the end of the 4th century when the Roman Empire began to decline. The place names of localities such as Montecerboli (from the Latin *Mons Cerberi*), "Devil's Mountain," and *Valle dell'Inferno*, "Hell Valley," probably originated between 800 and 1000, clear indications of people's belief that thermal manifestations had an infernal origin.

In Italy, as in most of Southern Europe, the last two to three centuries of the first millennium were a period of low economic and social growth, generated mainly by historical causes and subordinately by the widespread conviction that the world would come to an end in the year 1000. All these factors strongly reduced balneotherapeutic practices as well as exploitation and use of hydrothermal products in that period.

From 1000 A.D. to the Discovery of Boric Acid

With the beginning of the second millennium, when the expectation of the end of the world had passed, a far-reaching cultural reawakening over all Italy led to relaunching many old enterprises and beginning many new ones. This occurred in all commercial and mining activities, including the exploitation of hydrothermal minerals in the Larderello region. The first contracts between the bishops of Volterra, who had jurisdiction over the region in the name of the Holy Roman Empire, and the lessees entrusted with mining the *lumaie* date from the middle 11th century. The term *lumaie* comes from the Latin word *lumen.* The word may mean "bright spot," alluding to whitish mineral deposits at the surface caused by condensation of thermal fluids, or *lumen* may refer to localities with alum deposits.

The main products extracted and marketed from the *lumaie* are listed below:

- Yellow sulfur, commonly used to prepare pharmaceuticals, such as ointments and salves, and bleaching agents for the wool industry

- Cyprian (green) and Roman (blue) vitriol (heptahydrated ferrous sulfates: $FeSO_4 \cdot 7H_2O$), used by pharmacies to prepare disinfectant and anti-hemorrhagic agents, and in the textile industry to dye wool. It should be pointed out, however, that green vitriol was also produced artificially in the Larderello area by the reaction in sulfurous waters of pyrites and/or bits of iron

- Alum, $KAl(SO_4) \cdot 12H_2O$, a product then indispensable for the wool industry

- *Nitro volterrano,* "nitre from Volterra," a product whose chemical formula is unknown, but on the basis of two 16th century manuscripts known as *Ricetti* ("Books of Medical Prescriptions") of the towns of Florence and Siena (*Ricettario Fiorentino* and *Ricettario Senese*) is thought to be boric acid. We learn from the manuscripts that *nitro volterrano* was prescribed for curing certain eye diseases. Mercati wrote about this product in 1717: *"nitrum nativum scissile ex quo venetis borax conflatur"* ("processed native nitre from which Venetians obtain borax").

These products were of great commercial importance in the Middle Ages. Consequently, bitter disputes and even wars broke out among some Tuscan communes over who would own the areas with *lumaie* in the Boraciferous region. A war between the towns of Florence and Volterra ended with victory for the Florentines; therefore, in 1472 ownership of the *lumaie* passed from Volterra to the Florentine craft guild for wool, known as *Arte della Lana.*

The geothermal manifestations in the region continued to be used for therapeutic purposes as they were commercially exploited for hydrothermal products. Many treatises on natural history and medicine from the Late Middle Ages, the Renaissance, and the Modern Age deal with the beneficial effects that thermal waters, muds, and gaseous exhalations had for treating all kinds of internal and external disorders. The authors who described the uses include Ristoro d'Arezzo (1282), Ugolino da Montecatini (1420), Savonarola (1460), Agricola (1546 and 1556), Fallopio (1560), Merula (1605), Cluverius (1624), and Targioni Tozzetti (1769).

During a period of grave economic crisis that befell Tuscany in the second half of the 18th century, the Grand Duke of Tuscany, Pietro Leopoldo, decided to inventory all of the natural resources in his territory. He asked a number of specialists to make on-site area surveys, with descriptions of the situation, sample collection, and analyses of minerals, thermal and fresh waters, gas, hydrothermal compounds, natural resources, and products of every kind. Targioni Tozzetti in 1769, while describing the situation at Larderello, pointed out the state of obsolescence into which the vitriol production plants, the alum quarries, and the spas had fallen since the end of the 17th century. He recommended that a number of specific analyses be undertaken. It was in analyzing the waters of *lagoni* at Monterotondo and at Castelnuovo in 1777 that Hoefer, director of the grand-ducal pharmacies, identified boric acid, then called "Homberg's sedative salt."

In 1779 Mascagni, noted anatomist, physiologist, and chemist, proved that boric acid was a component characteristic to all thermal fluids in the Larderello region. In one of his papers, Mascagni discussed the possibility of using natural heat to evaporate waters from the *lagoni* by burying metal boilers close to thermal manifestations. In a following paper, Mascagni published further analyses of thermal waters in the area, adding a detailed description for a method he had patented to exploit natural heat with boilers buried near fumarolic manifestations. Each boiler actually amounted to a heat exchanger, and it was the first equipment in the world used to obtain evaporative heat from geothermal fluids.

The Technology of Chemical Production between the End of the 18th Century and the Mid-19th Century

The discovery of boric acid, the studies by Hoefer and Mascagni on this compound and Mascagni's ideas—ingenious for his time—on using heat exchangers, mark the beginning of a period of strong growth for producing chemicals from geothermal fluids.

In the 18th century, the boric acid market was extremely important all over Europe and boric acid was obtained by processing a boron compound (tincal) imported from Persia. Just the cost of transporting tincal from such a distant country makes it easy to understand the worth of boric acid in those days. At that time, all of Europe was characterized by revolutions, national independence movements, and wars; therefore, the situation was poorly suited for launching a new product obtained from the hydrothermal manifestations of the Larderello area, and—perhaps more importantly—bringing a local product into the market would clash with established and powerful business interests that had grown in Europe around boric acid.

Nonetheless, a company was formed in 1812 to attempt industrial exploitation of boron compounds deposited around some manifestations in the Larderello area with the methods proposed by Mascagni. The venture failed for organizational and economic reasons. In 1815-1816, a new company was set up to develop the evaporation process for boric waters. However, instead of using Mascagni's heat exchanger to supply evaporation heat, the process was based on burning wood taken from the thick forests in the area. This time the initiative was successful and in just ten months (June 15, 1817, to April 14, 1818) some 36 tons of boric acid were produced and immediately found a receptive market in France. This explains the interest aroused in that country by boric acid produced in Tuscany.

In 1818, the company Chemin-Prat-La Motte-Larderel was formed and incorporated in Leghorn, where the charter members, all French, were living in exile. The company leased the *lagoni* of Montecerboli for a period of six years, with an option to renew, and named one of the partners, Francesco Larderel, as the executive manager for technical activities. The evaporation process used the same technology just described (evaporating the waters of the *lagoni* in metal boilers heated with wood fires) and immediately yielded very positive results. Indeed, thanks to the exploitation both of natural *lagoni* and artificial *lagoni* dug next to some “dry” manifestations, an average of about 50 tons per year of boric acid was produced for about 10 years.

However, as time passed, the increased use of firewood began depleting the forests. The resulting wood shortage slashed the company’s profits and pointed out the precariousness of the technology used to evaporate the boric waters. Thus the French company came into trouble, but Francesco Larderel refused to abandon the project. He became a naturalized citizen of the Grand Duchy of Tuscany, bought out his three partners, and in 1827 began to apply some innovative ideas derived from his past experiences.

Above each artificial *lagone,* he had a brick dome built with a riveted metal pipe inserted at the top to redirect the steam accumulating inside. This construction, called a *lagone coperto* (“covered lagoon”), enabled a substantial amount of steam to be gathered and used to evaporate boron-bearing waters drawn off at the bottom of the dome (figure 3, center). The *lagone coperto* was essentially a low-pressure separator, while the steam collection pipes and the boilers they fed constituted a refined version of Mascagni’s heat exchanger. Both Mascagni’s

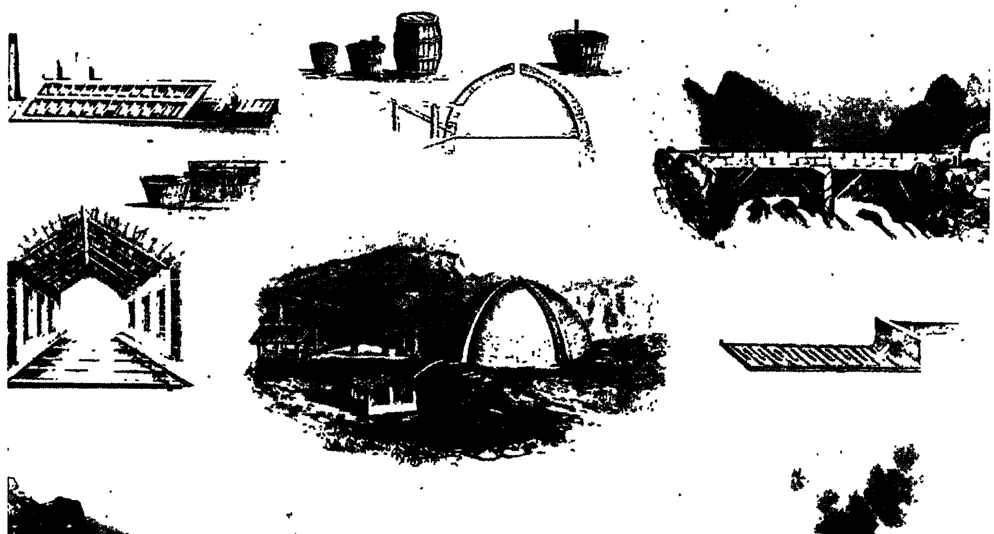

Figure 3. Lithograph of the 19th century showing a “covered lagoon” in the center and the related facilities, as seen around 1860.

boiler and Francesco Larderel's *lagone coperto* were inventions embodying remarkably advanced technology for their times.

Another innovative technology, introduced by Larderel as a follow-up of an idea conceived by his then technical advisor, the French chemist Payen, was to connect several natural and artificial *lagoni* in cascade (figure 4). In this configuration, the boric waters, which had at the source a boron content of 5 to 10 g/l, could be enriched gradually by natural evaporation before they were channeled into decantation tanks and evaporation boilers, where they became boric brines.

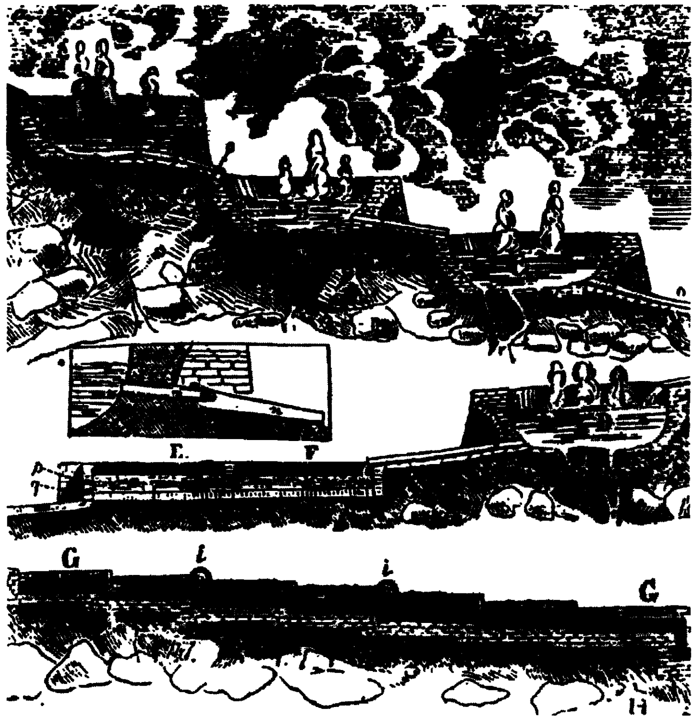
Figure 4. Print from 1841, showing a system of cascading lagoons (*lagoni*). *From Payen, 1841*

For the drying process, Larderel drew off part of the steam collected at the top of the covered lagoons and circulated it through a network of brick conduits beneath the floor of the processing plants. This operation concluded the multiple use cycle of the geothermal fluids: production of chemicals, evaporation, and drying. With these technological innovations in place, no less than 125 tons of boric acid were produced in 1829 and sold across Europe.

The ready availability in Western Europe of boric acid from Larderello had a great impact on the market, which had been dominated by English and Dutch companies importing *tincal* from Persia and other Middle Eastern countries. One offered to buy Larderel's company, but he had the farsightedness to refuse.

From 1840 on, Larderel's sons began collaborating in the company: Federigo eventually succeeded his father as the general manager and Adriano later became technical director. Both prepared for their jobs by studying industrial chemistry at the University of Pisa. They first improved the processing cycle—the drainage of boric waters, vaporization, crystallization, and drying—with newly invented equipment. For the vaporization process, a new type of boiler was designed, named the *caldaia adriana* ("adrian boiler") after its inventor and designer, Adriano Larderel. This boiler consisted of a series of brick conduits internally lined with lead (figure 5). Boron-rich waters were circulated above the conduits in counterflow to the steam stream. In this way, the heat content of the steam was fully exploited, achieving a much higher efficiency than the previous boilers at considerably lower operating costs. It will not go unnoticed that the *caldaia adriana* is a forerunner of modern counterflow heat exchangers. Thanks to this advanced process cycle and because of increased availability of boric waters from new drilling technologies discussed below, boric acid production rose from 125 tons in 1829 to over 1,000 (!) tons in 1850.

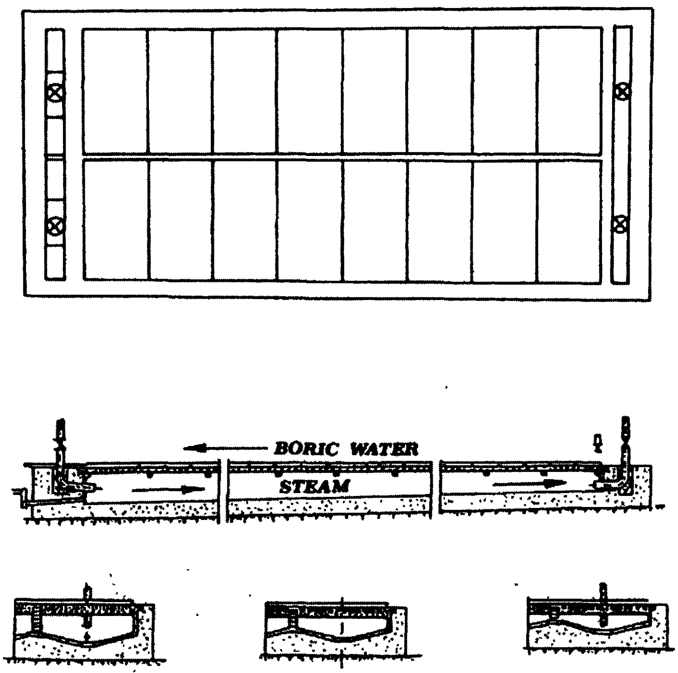

Figure 5. Layout (top), longitudinal section (middle), and cross section (bottom) of the *caldaia adriana* ("adrian boiler").

Another innovation, introduced in 1845 by Federigo and Adriano Larderel, was the use of steam to heat workshops, plants, and civil buildings. At first, simple copper tubes were used, but later, lead-surface heat exchangers were adopted, increasing the heat output.

Geothermal Drilling Technology in the 19th Century

Until the end of the 18th century, the exploitation of geothermal fluids and the extraction of boron minerals were based on simple holes, hand-dug to shallow depths (4 to 5 meters). The first geothermal wells, ordered by Francesco Larderel in 1832, were drilled with hand-operated drills in the immediate vicinity of fumaroles and natural hot pools. Although the wells had small diameters (about 10 centimeters) and were very shallow (6 to 8 meters), in most cases they produced fluids in greater amounts and at higher temperatures, pressures, and boron concentrations than fluids obtained directly at the surface from natural or artificial lagoons. However, after the first experiments were made, technical adviser Payen convinced Larderel to suspend all attempts to drill wells because of the possibility of uncontrolled blowouts.

A few years later in 1838, the Florentine scientist and engineer Gazzeri wrote an article discussing the possibility of increasing boric acid production by drilling "deep wells." Gazzeri did not specify the depth of the wells, but considering the drilling technology then available, he probably was thinking of initial depths on the order of 12 to 15 meters. In the same article, the author contended that fluids containing boric acid did not exist in small accumulations found only at the bottom of each surface manifestation but were supplied, instead, by a single deep, and presumably large, deposit: "The most elementary notions of geology persuade us that the mineral, whose decomposition gives off the boric acid contained in the ardent vapor of the steam jets, is not distributed in isolated masses at the base of each steam jet or *lagone*, but forms a single and huge deposit, the extent of which is unknown. If we were able to reach the deposit by means of drilling, a spontaneous blowout of natural fluids should follow, similar to that occurring in artesian wells. Alternatively [if a spontaneous blowout does not occur], we could obtain a stimulated production [of the well] by judicious injection of [fresh] water or by other methods...." Thus, Gazzeri believed that it was necessary to reach the deep reservoir by drilling, not only to tap the larger amount of fluid produced spontaneously by the wells, but also to pump fresh water through the wells into the reservoir for more sustained leaching of boric acid.

In another paper in 1841, Gazzeri developed these concepts further and announced that the engineer Manteri, stimulated by the theory and operative suggestions presented in Gazzeri's article of 1838, had built new drilling equipment that could be used without a winch and could drill holes about four inches in diameter. Using his drill, Manteri had bored three wells 6 to 7 meters deep that he sited over 100 meters away from natural manifestations at Lago.

The production from these three wells, located for those days at such great distances from the manifestations, seemed to prove Gazzeri's theory—and for some aspects concerning the large size of the geothermal reservoir, it actually did. Gazzeri's hypotheses on the size of the geothermal reservoir and on drilling wells far from manifestations were important contributions to geothermal knowledge and development technology.

Also in 1841, a small company (not Larderel's) successfully drilled a few "deep" geothermal wells using a rig called the *verga artesiana* ("artesian bar"), illustrated by A in figure 6.

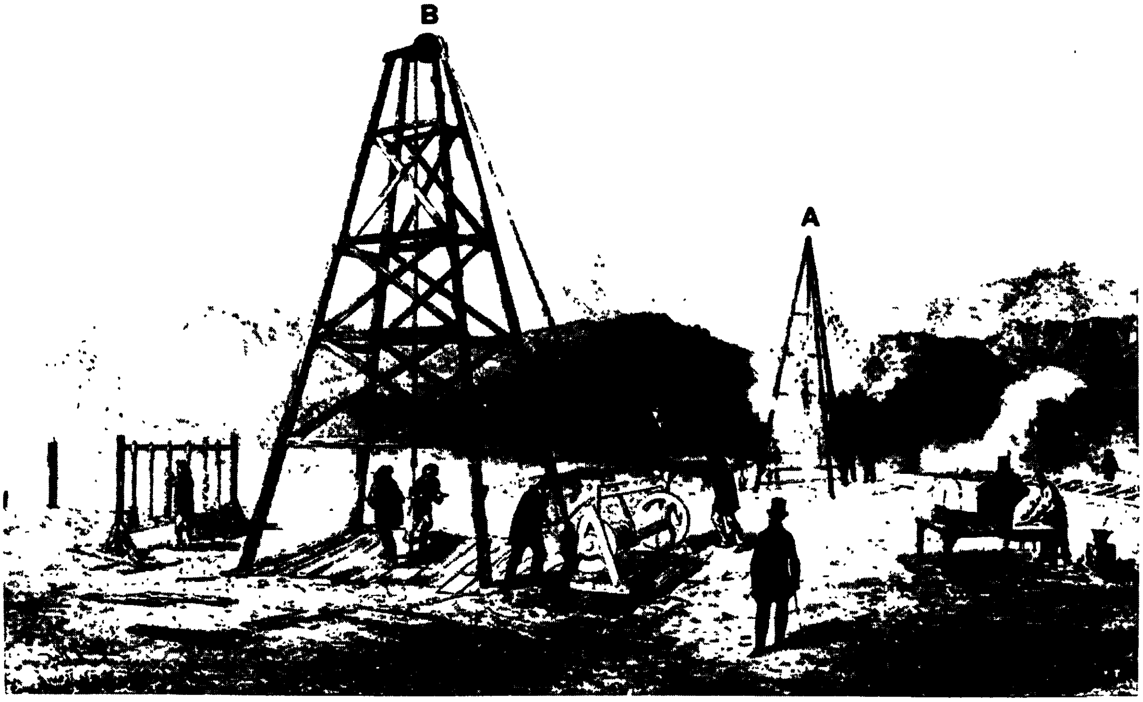

Figure 6. Old print showing (A) the *verga artesiana* ("artesian bar") and (B) a square-based drilling rig with winch.

Therefore, in consideration of the encouraging results by this company and by Manteri, and having noted that wells could be kept under control without risking the blowouts Payen had predicted, Larderel and his sons decided to resume drilling wells using the *verga artesiana.*

In a few years, the boost to drilling by the Larderels brought considerable technological improvement: four-legged drilling rigs (B in figure 6), a winch to enhance percussion efficiency, various types of drilling bits (some with a flat cross section, others with a helicoidal shape), and bucket-type tools, called bailers, to remove cuttings from the well bottom. Furthermore, to obtain a hole with a round cross section, a method of manually rotating the drill stem was developed that allowed lining the first 6 to 8 meters of the hole with an anchor pipe (surface casing) of riveted metal plate.

By 1842, all these technological improvements enabled drilling wells at a depth of 25 to 30 meters. Moreover, between 1841 and 1855, a large pit (5 to 6 meters deep) was usually dug at the well site and drilling actually began at the bottom of the pit. In this way, well depths in the order of 30 to 35 meters were reached around the mid-19th century. However, the function of this pit was not so much to increase the well depth but to hold the liquid fraction of the steam-water mixture produced by the well. In this manner, an artificial *lagone* was created at each drilling site. The pit was covered with the characteristic brick dome (described earlier and illustrated in figure 3), resulting in an artificially covered lagoon.

The year 1856 marked the beginning of a new stage in geothermal drilling technology, one that in a few years would enable depths to be reached of between 150 and 200 meters. Innovations from 1856 to 1870 were the first rig with an elevated working floor (2 meters high), walking beams to operate the drill stem and increase the percussion efficiency of the bit, a protective shield for winch operators, and a wellhead with a side outlet called a *gomito* ("elbow"), which constituted the first blowout control device ("blowout preventer") for geothermal wells. The device had two main parts, the *chiusino* ("lead plug") and the *bisesta* ("arm with keyhole"). See figure 7.

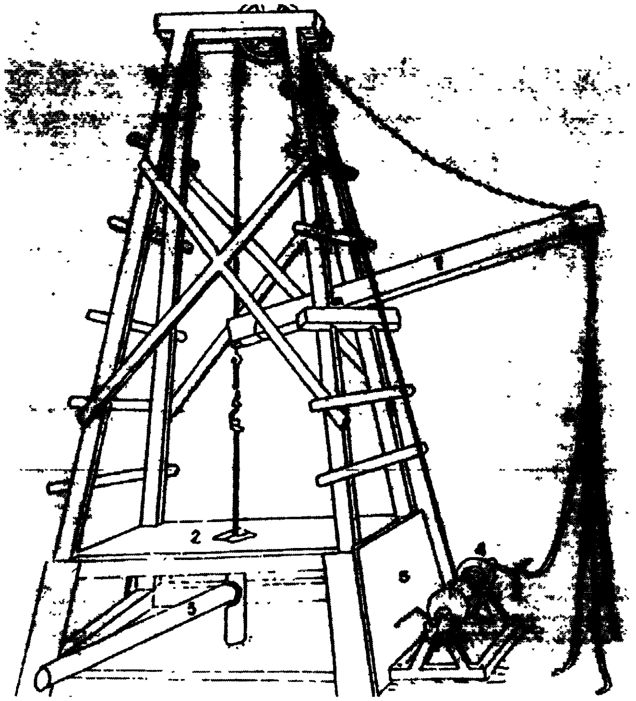

Figure 7. Sketch of a drilling rig in 1862, showing (1) walking beam; (2) work floor; (3) *gomito* ("elbow"); (4) winch; (5) protective shield; (6) ropes for percussion drilling.

The practice of casing wells as drilling proceeds comes from this period. This was done with pipe joints of riveted plate in standard two-meter lengths. The bottom joint was equipped with a toothed ring of hardened metal that reamed and enlarged the wellbore. The joints were coupled every two meters with a riveted metal band, and the casing string was given a jerky, rotating motion so that the toothed ring on the bottom joint acted as a hole reamer. In this manner, drilling could proceed under reasonably safe conditions.

Another drilling technique developed at Larderello between 1856 and 1870 was the stimulation of well production. Since wells were gradually increasing in depth (up to 200 meters), they often encountered shallow, cold aquifers that in many cases prevented them from producing spontaneously because of the cooling and hydrostatic pressure by fresh water on the reservoir fluid. The Larderels and their drilling personnel understood the importance of this phenomenon and managed to find a way to lighten the hydrostatic load on the producing layers. For this, a special tool was devised, a series of coupled metal disks with a slightly smaller diameter than the casing.

Sandwiched between the two disks of each couple were hemp or rags, and lengths of chain were used to connect the various couples of disks, one below the other. For its length (some 10 meters) and flexibility, the tool was called a "serpent." With the help of a lead weight, it was lowered into the well—25 to 30 meters below water level—to piston out the water. To do this, a team of workmen manually extracted the serpent from the well as fast as possible, which lowered the water level in the well, making it produce. Sometimes the operation was repeated several times before stable production was achieved.

By the end of the 19th century, the combination of all these new drilling techniques and the new equipment, mostly developed autonomously at Larderello and continuously refined over the years, made it possible to drill wells 250 to 300 meters in depth.

Before concluding this outline of drilling technology at Larderello, it is interesting to recall a few organizational aspects of this work toward the end of the 19th century. As rig capacity increased, clear-cut rules for drilling were laid down by the Larderels: each rig was equipped with a metal winch when the well depth was greater than 130 meters, and with two winches when the well was expected to exceed this depth. The work was carried out in one 10-hour shift, with two teams alternating every 10 minutes to rest. The number of workmen on each team was five down to 30 meters, six from 30 to 50 meters, and one additional worker for every 10 meters of depth thereafter. The gradually increasing well depths also required standardization of equipment, allowing for interchangeability between drilling rigs operated simultaneously at different sites.

This, along with the fact that Larderello was far from other towns and had to develop as an autonomous community, made it necessary to set up workshops to build and maintain all equipment, tools, and materials (figure 8). The shops not only supported the drilling activity but provided services for the chemical production plants and for every other need of the chemical industry.

The First Modernization Period: 1860 to 1900

As the number and depth of the wells, and therefore the fluid production, increased over the second half of the 19th century, rapid technological improvement continued to occur in systems for gathering fluid and processing boron compounds. These improvements

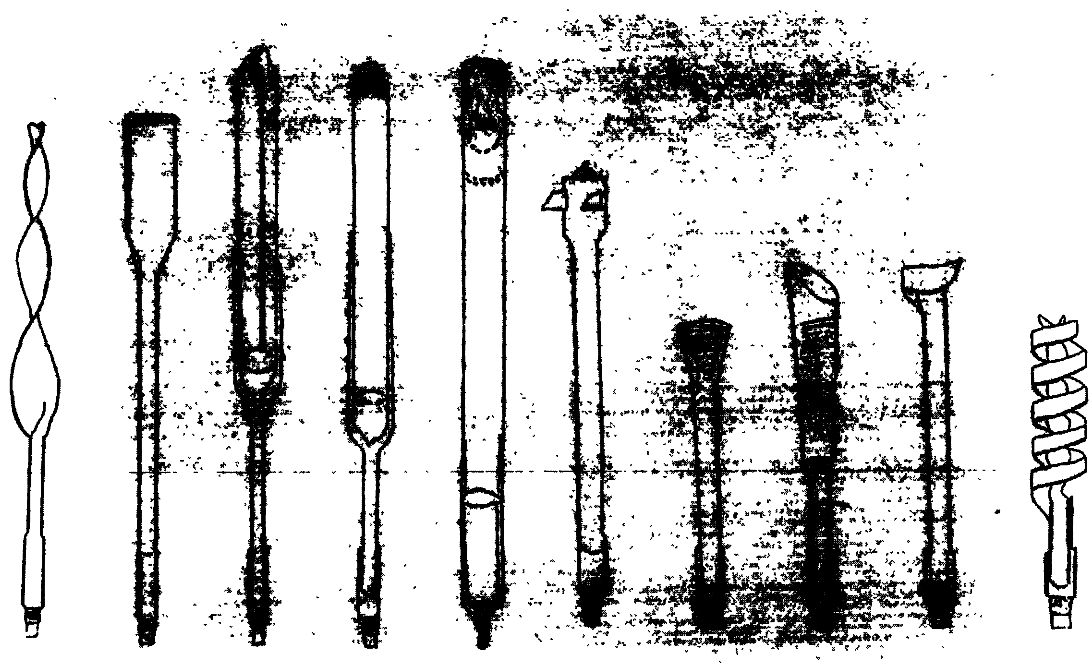

Figure 8. Sketch of various types of percussion bits (a and b), shell augers (c, d, and e), and recovery tools (f, g, h, i, and j) made and used at Larderello from 1860 to 1900.

resulted in increased boric acid production, which rose from 1,000 tons in 1850 to 2,000 (!) in 1860. For the next 10 to 15 years, Larderello's boric acid production grew so fast in the European market that it became a near monopoly.

However, in about 1875, when boric acid produced from borates of sedimentary origin, such as ulexite, colemanite, and rasorite, began penetrating the market, especially those from the United States, Larderello's chemical industry suffered a sudden setback that threatened to nullify its technological achievements and experience in the use of geothermal fluids for chemical production. The owners and workers of Larderello reacted by fostering further technological innovations, introducing organizational improvements in geothermal fluid extraction and processing, and diversifying chemical production as much as possible. This resulted in the production of a wide range of borate compounds and the development of a philosophy for geothermal fluid utilization that we today call "multiple use." Among the technological innovations made in this period, the following are worth mentioning:

- Development of steam-driven pumps and their systematic use for well stimulation and for pumping borate solutions to processing plants (actually, the first experiments on using the mechanical energy of natural steam to drive pumps date back to 1859. However, owing to the rather low pressure of the steam produced by the wells between 1850 and 1870, this use remained at the experimental stage until 1875)

- Modernization of the gathering system for steam and boric brine solutions. This was obtained by replacing the old wooden or brick channels with riveted pipes, insulated to reduce heat dissipation

- Use of multi-tubular boilers as heat exchangers in all production processes requiring pure steam or hot water of nongeothermal origin

As to the diversification of chemical products, the principal achievements of the period 1880 to 1900 were threefold: production of refined, highly pure boric acid, use of ammonia present in residual boric brines for the production of ammonium sulfate, and production of borax by the reaction between boric acid and sodium carbonate.

Organizational aspects and scientific advances in the second half of the 19th century included the following:

- Establishment in 1854, and expansion in 1880, of a chemical laboratory at Larderello to monitor the characteristics of geothermal fluids and optimize the quality of chemical products

- Execution of many geoscientific studies aimed at better understanding the conditions of the Larderello geothermal system. As a result of all these studies, toward the beginning of the 20th century, an eminent geologist, Bernardino Lotti, formulated the "theory on the juvenile origin of endogenous steam"

- Execution of lab analyses and on-site experiments in a continuous modernization of the chemical processing cycles. Among other achievements in this field, in 1895 a group of scientists from the Universities of Pisa and Padua, headed by the renowned chemist Nasini, discovered helium and argon in the gas contained in the steam at Larderello. This discovery was followed in a few years by the detection of radon and the quantitative assessment of the radioactivity of geothermal fluid

THE START OF GEOTHERMAL POWER PRODUCTION: 1904 TO 1913

NEAR THE BEGINNING OF THE 19TH CENTURY, THE LARDERELLO CHEMICAL INDUSTRY CAME under the direction of Prince Piero Ginori Conti, son-in-law of Florestano Larderel. The most outstanding achievements of Ginori Conti's commitment to innovation are the studies and experiments on the use of geothermal steam as an energy source for electrical generation. This work was carried out at a fast pace, and in only a couple of years it was rewarded with success: on July 15, 1904, the first five light bulbs were lighted at Larderello using geothermal power. The success of the experiment is immortalized in a picture familiar to geothermal specialists the world over (figure 9).

Figure 9. Photo showing the first experiment in the world of electrical generation from geothermal steam, carried out by P. Ginori Conti at Larderello in 1904.

This experiment used a piston engine coupled with a 10 kilowatt dynamo; the engine was driven by pure steam produced in a small heat exchanger fed with wet steam from a well near Larderello. Therefore, the first use of geothermal steam for power generation was carried out with a transformation cycle that we today call an "indirect cycle." Although Ginori Conti and his technical staff had also studied the possibility of feeding the piston engine directly with natural steam, the indirect cycle was chosen because, aiming to relaunch his chemical company, Ginori

Conti wanted to lay the technological basis for the simultaneous use of geothermal fluids for power generation and chemical production.

The encouraging results of this experiment quickly led to the first prototype of a geothermal power plant, which went into operation in 1905. The plant was formed by a Cail reciprocating engine connected to a 20 kilowatt dynamo. This first small power station, along with another installed in 1908 composed of a Neville reciprocating engine coupled to a second 20 kilowatt dynamo, enabled electrification of Larderello's most important industrial plants and the main residential buildings.

In 1913, after absorbing all the small local firms that produced boric acid with obsolete technology, Ginori Conti's company assured itself of the possibility of extending exploitation of geothermal fluids to the whole Boraciferous region, an area of several hundred square kilometers. In the same year, the first commercial geothermal power plant went into operation. The energy it produced was fed into a network serving all the chemical production plants and the main buildings of Larderello and the other villages of the region. This power plant, named Larderello 1, was equipped with a turbine generating 250 kilowatts of electricity. It was designed and built by the Tosi Electromechanical Company to operate with wellhead fluid pressures of up to three atmospheres. The turbine was driven with pure steam obtained from a heat exchanger supplied by two wells.

Achievements from 1900 to 1944

Although Ginori Conti initiated a further step in modernizing the chemical plants in 1903, it was not until 1908 (when electricity from geothermal power stations became available) that he was able to start a radical renewal of almost all activities of his company and launch new initiatives. From the beginning of this century to the end of World War II, the principal achievements can be summarized as follows:

Chemical processing of geothermal fluids. The processes were further expanded to obtain new products, such as sodium perborate, ammonium carbonate, carbonic acid, talcum powder, and other compounds widely used in the pharmaceutical industry. Very wide multiple use of geothermal fluids for chemical production was thus achieved.

Drilling. The activities were organized as a completely autonomous service sector of the company. Its main operational characteristics were

- 1906: the use of mechanical winches driven by geothermal steam. These were replaced with electrically-powered winches in 1914

- 1907: oxyacetylene welding, enabling radical change in well casing configurations

- 1923: drilling partly converted from the percussion to the rotary system. The new "H" and "BCF" rigs, built by Termomeccanica Co., were equipped with water circulation systems. The rotary system was only used to drill impermeable formations. Once the first producing fracture was encountered (usually at the top of the carbonate formations forming the principal reservoir), the rotary rig was replaced with a percussion rig until it reached the main producing layers. Using two different rigs to drill a single well, however, was abandoned after a few years when more versatile drilling equipment became available

- 1929: introduction of Trauzl rigs, equipped with high-powered pumps suitable for both rotary and percussion drilling

- 1938-1940: percussion techniques abandoned definitively in favor of rotary drilling

Scientific achievements. A few words will suffice to emphasize the intensity and advanced nature of the scientific effort that accompanied geothermal development at Larderello during this period: geologic and structural surveys, hydrogeologic investigations, paleontological analyses, chemical and physical analyses in company and university laboratories, geoelectric prospecting, well logging, seismic recording in special stations to single out possible relationships between well production rates and earthquakes, measurements of production characteristics and reservoir studies, lab tests and field experiments with pilot plants to improve chemical processing cycles of geothermal by-products, and studies on thermodynamic cycles for power generation. The results of all studies carried out until about 1928 are included in a voluminous monograph published by Nasini in 1930, prepared in collaboration with several other Italian scientists and top technical staff of the Larderello company. The monograph described the situation up to the publication date, but commitment to science and technology actively continued in the following decade, before the outbreak of World War II.

In particular, based on results of the geoscientific nature, the criteria for selecting drilling sites were gradually improved after 1925 and wells were located at ever greater distances away from localities where natural manifestations were seen. Although it would be incorrect to say that Lotti's "theory on the juvenile origin of endogenous steam" was outdated after 1925, it is worth mentioning that the technical archives at Larderello contain unpublished data and reports from the period that discuss the limits of this theory and hypothesize on the meteoric origin of geothermal steam. A special contribution came from the results of the well Soffionissimo 1 ("a very powerful well"), shown in figure 10, that initially produced 230 t/h of steam at 4.5 abs. atm. and 205° C.

Figure 10. The well "Soffionissimo 1" during the initial stage of production in 1931.

Space heating. This use was introduced around 1845, but it was not until 1910 that it began systematically taking root. By 1940, all establishments, plants, facilities, workshops, and residential buildings, plus a number of greenhouses and agricultural installations created by the Larderello company—not only in the main village but also in many other localities of the Boraciferous region—were warmed with the residual heat of low-pressure steam.

Electrical generation. This is the most significant achievement of geothermal development at Larderello in this period. The first 250 kW_e commercial power plant, dating from 1913, was followed in 1916 by two 3.5 MW_e turboalternator units manufactured by Tosi Co. These units used the indirect cycle for power generation and were supplied with pure steam obtained in heat exchangers. The size of these two units, although very small by today's standards, equaled that of most of the world's installed hydroelectric and thermal power plants of the time.

The first pilot turbine fed directly with natural steam produced by the wells ("direct cycle") had a capacity of 23 kW_e and was installed at Serrazzano in 1923. It remained in operation without any significant problems for about two years, when it was assigned for use in training technical personnel at the Larderello company school. After this pilot turbine, other direct cycle turbines were installed at Castelnuovo (a 600 kW_e unit in 1926 and an 800 kW_e unit in 1927) and Larderello (a 3.5 MW_e unit in 1930). This raised the total installed capacity in the Boraciferous region, as of December 1930, to 12,150 kW_e, of which 7,250 used the indirect cycle and 4,900 the direct cycle.

The first large geothermal power plant, called Larderello 2, was completed in 1939 and included six 10 MW_e units fed with pure steam in an indirect cycle. Adoption of this cycle was dictated by the need to use most of the natural steam produced by the wells at Larderello to extract valuable chemical by-products.

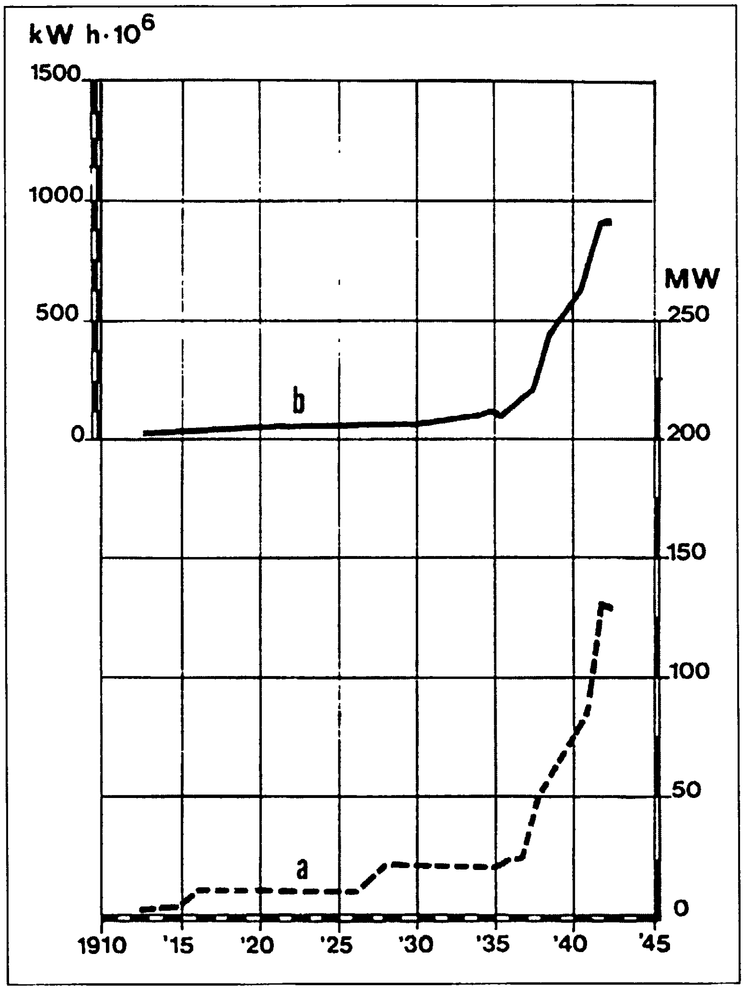

Figure 11. Installed capacity (a) and electricity generated (b) at Larderello from 1913 to 1943.

Between 1940 and mid-1943, other units went into operation: four 10 MW_e units at Castelnuovo (similar to those at Larderello), one 3.5 MW_e direct cycle unit at Sasso Pisano, and two units for a total of 8.5 MW_e at Serrazzano, again based on the direct cycle.

At the end of 1943, the total installed capacity in the

Boraciferous region was 132 MW_e, of which 107 MW_e was fed by pure steam, the indirect cycle (figure 11). The others were exhausting-to-atmosphere units, the direct cycle.

At the start of 1944, the Larderello region was dramatically involved in the events of World War II. The Larderello power plants were strategically important because they were fed from an indigenous energy source and were supplying electricity to the whole railway network of Central Italy. In the spring of 1944, not far from Larderello, the retreating armies then in Italy organized the "Gothic Line." This was the strategic line separating the belligerent armies of the two opposing forces.

All the geothermal power stations and chemical plants in the zone were heavily bombed and destroyed, and almost all the production wells were blown up by charges placed at the base of the master valve. A desolate scene of noise and ruin spread over the region. Thus, the modern phase of geothermal development in Italy ended tragically in early 1944.

Among the ruins of war, miraculously still intact, was the 23 kW_e exhausting-to-atmosphere turbine used at the company school to train technical personnel since 1925 (figure 12). Thanks to it and to the determination of the people of Larderello, the curtain rose in the summer 1944 on the present act of Italian geothermal history.

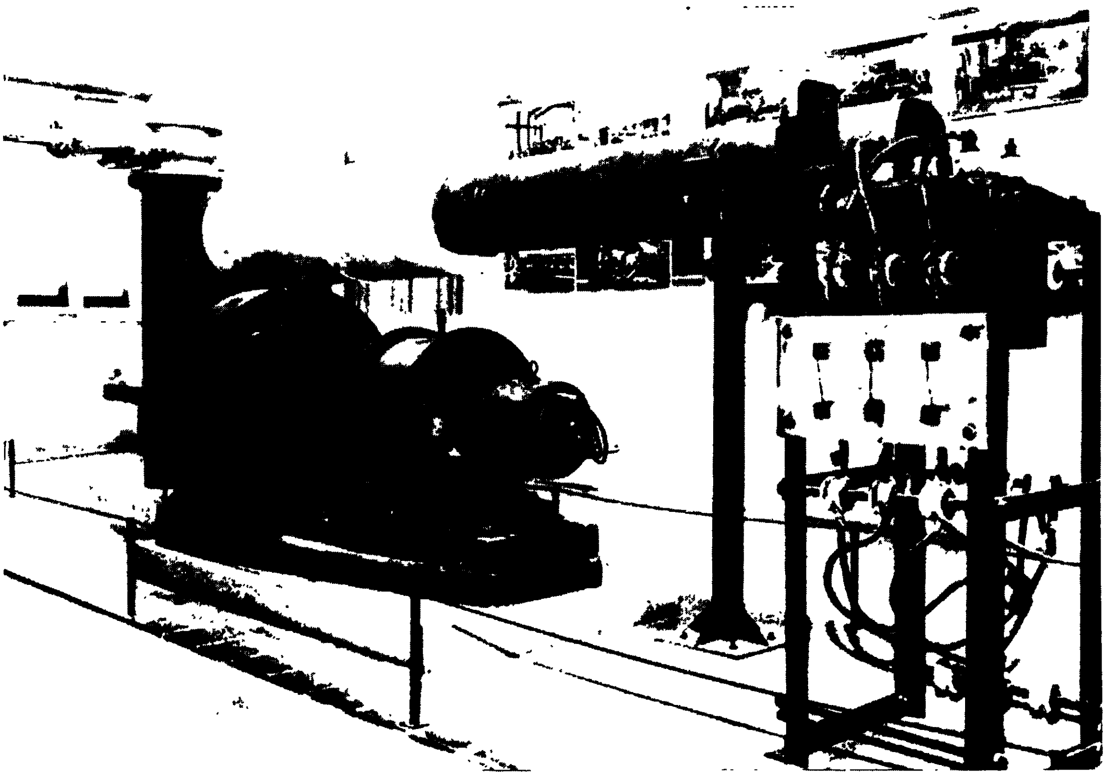

Figure 12. First exhausting-to-atmosphere geothermal turbine (23 kW_e), installed at Serrazzano in 1923.

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Extracting boron compounds by evaporating and concentrating boron-rich geothermal waters from natural boiling pools (*lagoni*) near Larderello, about 1540. A: natural boiling pool (*lagone*) lined with wooden boards and bricks; B: pots; C: ladles; D: wooden boxes and iron pans; E: tongs. Earthenware pots were placed in the *lagoni* and ladles of hot saline water were added, filling the pots half full. The water was evaporated from the pots until a thickened brine remained. Then the pots were clasped with tongs and the brine was poured into iron pans standing on four heavy legs near the borders of the *lagoni*. As nearly boiling hot water flowed freely around the pans, the saline brines condensed even further until the last of the water was evaporated. The mixture of boron salts was then shoveled out of the pans and the process begun anew. From *De re metallica* by Agricola, Italian translation by M. F. Fiorentino, H. Frobenio, and N. Episcopo. Basilea, 1563. ***Courtesy of ENEL SpA/Geothermal Department***