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► **To cite this version:**

Pierre Teissier. Modern Heating Technologies. Cyrus C. M. Mody; Joseph D. Martin. Between Making and Knowing. Tools in the History of Materials Research, World Scientific Publishing, pp.257-272, 2020, A World Scientific Encyclopedia of the Development and History of Materials Science. halshs-04478433

HAL Id: halshs-04478433

<https://shs.hal.science/halshs-04478433>

Submitted on 26 Feb 2024

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1 CHAPTER 3.1

MODERN HEATING TECHNOLOGIES

2 PIERRE TEISSIER

3
4 Fire, as Gaston Bachelard observed, haunts the psychology of modern
5 societies.² Its psychological power can be traced deep into ancient
6 mythologies. The Titan Prometheus, who stole fire from Olympus
7 and gave it to humankind, is a popular hero of European memory.
8 A broad, comparative anthropological study could link blacksmith
9 gods from Africa to Asia to Europe and demonstrate their resonance
10 with the social practices suggested by archaeological artifacts such
11 as weapons and potsherds. For the European tradition, Hephaestus
12 (or Vulcan), the Greek (or Latin) god of metalworking, fire, and
13 crafts, is an important figure in collective cultural memory. Stories
14 of his subterranean forge depict furnaces as frightening and powerful
15 tools that transform raw, unformed materials into artificial, carefully
16 shaped artifacts.

Telling Quotations

17 Comparing European and American chemical skills, a famous
chemist from Bell Labs, Francis J. Di Salvo wrote: “In the United
States, synthesis of solid-state compounds has been considered out
of date and a little dull, and few academic departments have even
one professor involved in synthesis of new solid-state compounds”
[15, p164–65]. Fifteen years later, in another context, a materials

1 scientist from Oxford University confirmed the low symbolic capital
2 of metallurgical furnaces: “The image of materials for computers,
3 aeroplanes and cars is more exciting than that of dirty blast fur-
4 naces in the steel industry.”²⁰

2 The romanticized public image of furnaces provided by classical
3 mythology was reframed by their increasing use from the Middle
4 Age onward, including in alchemy and industrialization. Medieval
5 and early modern alchemists developed high-temperature techniques
6 to produce and purify metals, glasses, and ceramics. Literary fiction
7 and visual art provided long-lasting stereotypes of alchemical prac-
8 tices.¹⁹ Such representations often drew a close association between
9 intellectual labor and material transformation, as we can see in a sev-
10 enteenth century oil painting by David Ryckaert III (Figure 3.1.1).
11 Between 1750 and 1850, the European iron industry was dramati-
12 cally transformed thanks to the adoption of several new making pro-
13 cesses [14, vol. 3, p585–614]. By replacing charcoal with coke in blast
14 furnaces, British craftsmen and engineers increased heating temper-
15 atures and produced better cast iron with less fuel. This process,
16 known as “puddling,” was gradually implemented in Europe during
17 eighteenth century, which contributed to improve the quality and the
18 quantity of manufactured engines that supported the “First Indus-
19 trial Revolution” (1750–1850), based on textile and steam engines.

20 Thinking about how different cultures have represented heating
21 technologies across millennia indicates that the history of the furnace,
22 and the way it has been used, can reveal a great deal about scientific
23 and technological imagery, the intellectual and manual labor that
24 goes into manipulating materials, and the connection between prac-
25 tical know-how and theoretical knowledge. Yet, in spite of their sci-
26 entific and economic importance in the twentieth century, furnaces
27 have received little attention from science and technology studies
28 (STS) scholars. At least five features of furnaces can be put forward
29 to explain their relative invisibility: 1) their physical appearance —
30 simple black boxes made of ceramic bricks heated by electric resis-
31 tance; 2) their low economic value — with an average price of around
32 \$10,000 for one unit; 3) their interstitial position — between science,

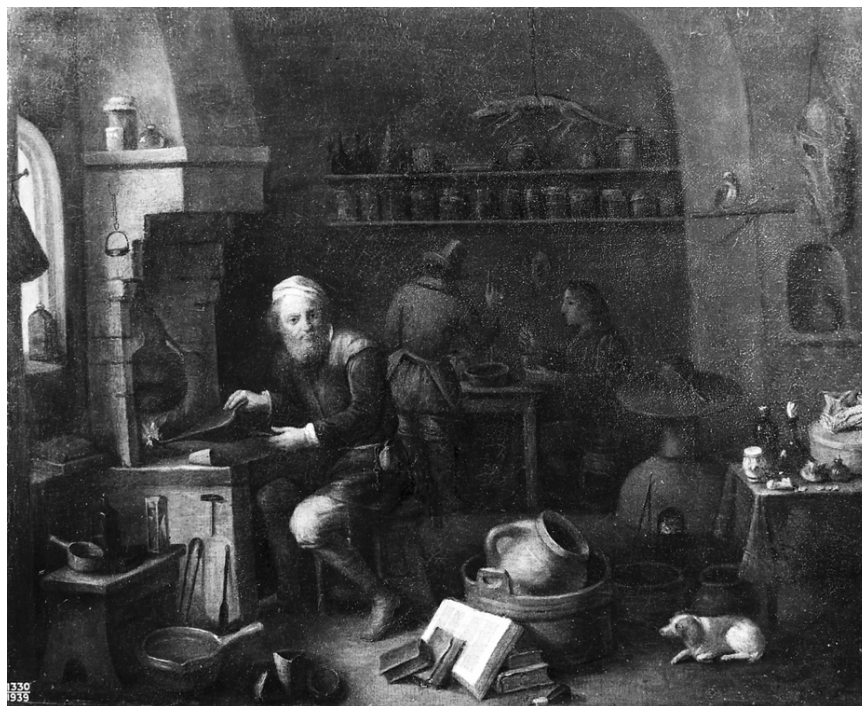


Fig. 3.1.1. David Ryckaert III, *An alchemist seated at a furnace, turning away in thought*. Credit: London: Wellcome Trust Library, Creative Commons, <https://wellcomeimages.org/indexplus/image/V0017664.html>.

1 industry, and state; 4) their low symbolic capital — due to their
2 links with empirical operations by technicians and routine syntheses
3 by chemists, usually considered as “dull” and “dirty” practices
4 [18, 22, 37, 41, p71–87,36,32]; and 5) their long-lasting tradition —
5 since medieval alchemy and early modern industry — and, thus, slow
6 apparent transformation. Furnaces thus appear as *invisible tools*
7 in the collective memory of materials. Yet, they are precisely the type
8 of “things that talk” according to Lorraine Daston’s assertion “that
9 things are simultaneously material and meaningful” [13, p17]. To
10 give voice to high-temperature devices, let us follow briefly, first,
11 some of their scientific and industrial developments during the twenty-
12 eth century and, then, the role they played in the making of the
13 US microelectronics industry in the 1950s.

1 **Historical Trends in Heating Technology**

2 To gain a historical perspective on heating technologies in materials
3 research, it is worth looking back to the “Second Industrial Revolution”
4 (ca. 1870–1920). This context was characterized by economic
5 expansion in the chemical, electrical, and mechanical industries,
6 driven by new practices of (and findings from) industrial research
7 and development (R&D). Heating technology advanced through the
8 industrial production of alloys and metals, ceramics, and glasses, as
9 well as mineral products [14, vol. 4, p493–542]. Last but not least
10 was the introduction of electric furnaces in the chemical and metal-
11 lurgical industries during the last decades of the nineteenth century.
12 Although the Siemens company had first used an electrical device
13 in 1879 for the industrial melting of iron, Henri Moissan designed a
14 more efficient “electric arc furnace” in his laboratory at the College of
15 Pharmacy in Paris (Figure 3.1.2). He aimed to synthesize refractory
16 materials, including artificial diamond (in vain) and calcium carbide
17 (with success). His laboratory prototype was quickly transferred to
18 industry and scaled up for the production of increasingly large quan-
19 tities of brand materials in the new industry of electrometallurgy.⁴⁹

20 After Moissan’s achievements, the industrial use of electric arc
21 furnaces increased for the making and study of various solid-state
22 materials such as alloys, cements, ceramics, crystals, and glasses.
23 Indeed, electric furnaces allowed a more controlled and broader range
24 of temperature (up to 3,000°C) than existing gas devices like Bun-
25 sen burners (up to a few hundreds of degrees) and welding torches
26 designed by Henri Sainte-Claire Deville (up to 1,000°C). From the
27 late nineteenth century to the 1920s, coke blast furnaces (Bessemer,
28 Martin-Siemens) had been replaced by electric arc furnaces for the
29 industrial production of steel and other materials like ceramics and
30 glasses [8, p293]. This industrial trend, known as electrothermics,
31 which has received scant historical attention, has the potential to
32 refine the classical picture of the “Second Industrial Revolution,”
33 characterized by the tripod of organic chemistry, electricity, and the
34 internal combustion engine [9, p29].



Fig. 3.1.2. Unknown author, Henri Moissan using a Moissan-Chaplet electric arc furnace. *Credit:* Wikimedia Commons.

1 In the early 1920s, researchers and industrialists perceived high-
2 temperature devices as “modern tools.” Development of these tools
3 was nurtured by several institutions around the world: the Faraday
4 Society (London), the Franklin Institute (Philadelphia), the Inter-
5 national Union of Pure and Applied Chemistry (Zurich), the Elec-
6 trochemical Society (Pennington, NJ), and others.⁴⁸ At a Franklin
7 Institute meeting in March 1923, Edwin F. Northrup, a former
8 Princeton University physics professor, surveyed six categories of
9 furnaces for high-temperature research: “Apparatus which focuses
10 radiation from the sun, hot flames, the electric arc, and the elec-
11 tric resistance furnace, vacuum bulbs which heat a surface by elec-
12 tron impact, and the high-frequency induction furnace” [38, p676].
13 The four last categories were “electric furnaces” characterized by
14 different heating means: arc, resistance, electrons, and induction.

1 Some alternative classifications could be found around this time.
2 A collective book by French physicists and chemists identified one
3 additional category — that of spark and gas electric furnace —
4 without considering the electronic furnace.²⁷ In addition, their cat-
5 egories were refined according to components (metallic or carbon
6 resistance), conditions of uses (high or low frequency), and gaseous
7 atmospheres (vacuum or high pressure). But Northrup’s categoriza-
8 tion was nonetheless influential.

9 According to Northrup, the “high-frequency induction furnace”
10 (Figure 3.1.3) was “the final and ideal method” for research since it
11 provided a uniform volume of heating with no contamination from
12 wire coils (no contact) and a continuous range of temperature that
13 was only limited by the temperature of fusion of the walls. Besides the
14 method of crystallization in a crucible, high-temperature physicists
15 and chemists were excited by two novel techniques for growing crys-
16 tals from melt: the flame-fusion “Verneuil process” (ca. 1891) to syn-
17 thesize artificial ruby and the Czochralski method for pulling metallic
18 single crystals (ca. 1916).³⁷ Strong financial interest drove the indus-
19 trial production of artificial gems at high temperature and pressure.²³
20 Most industrial domains sought to benefit from the increasing ther-
21 mal and material efficiency of furnaces. (The energy intensity, which
22 is the energy required to make a given mass of materials, was actu-
23 ally divided by twofold between 1880 and 1940 for the production of
24 pig iron in the United States) [18, p6].

25 Interwar France offers an interesting entry point for exhibiting
26 the multiple actors involved in high-temperature R&D across scien-
27 tific, industrial, and political spheres. In the context of early national
28 industry policy, the minister of trade and industry (1915–1919),
29 Étienne Clémentel, promoted a four-tier organization of industry
30 going from iron at the bottom to cast iron and steel, mechanics and
31 engines, and, finally, textiles and chemistry at the top [28, p189].
32 Both coke blast furnaces and electric furnaces were identified as key
33 actors for the production of cast iron and steel. This national pol-
34 icy echoed the establishment in 1921 of a private Foundation for
35 the Development of Scientific Research by Edmond de Rothschild.
36 The Rothschild Foundation had the dual goal of providing grants for

July 13, 1954

J. B. LITTLE ET AL
PRODUCTION OF GERMANIUM RODS HAVING
LONGITUDINAL CRYSTAL BOUNDARIES

2,683,676

Filed Jan. 13, 1950

2 Sheets-Sheet 1

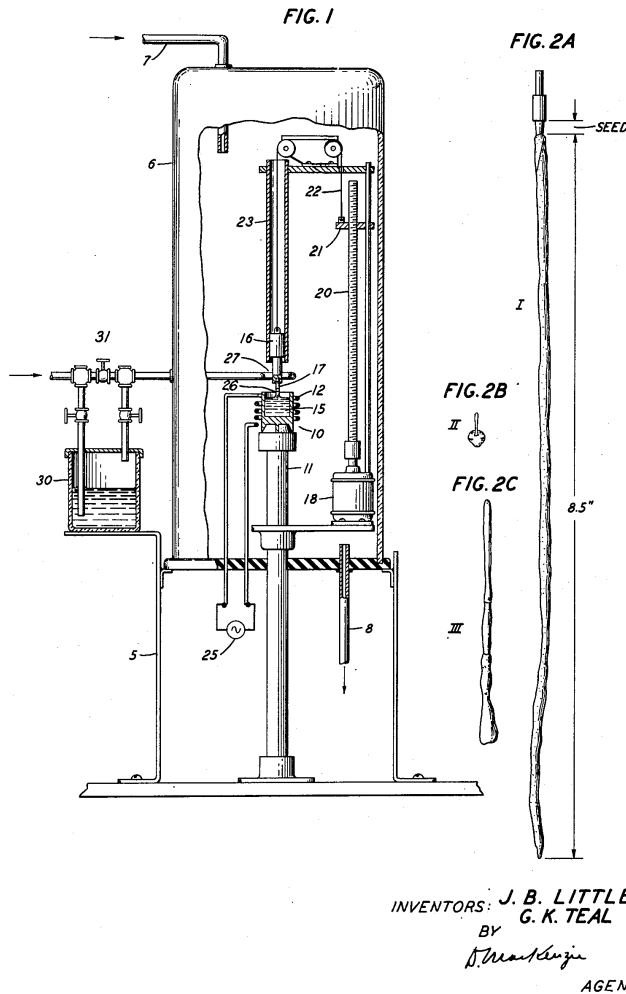


Fig. 3.1.3. A convenient form of high-frequency induction furnace [39, p682].

1 "an elite of scholars" and orienting scientists toward "the applications
2 of science" so as to favor "the economic forces of the nation."²⁹ The
3 first committee to be set up, that same year, was for hightemperature
4 research, under the leadership of an heir of Moissan, Paul Lebeau.

1 Its editorial activity and research aroused the interest of metallurgists
2 like Henry Le Chatelier, Georges Charpy, and Léon Guillet, who had
3 managed the *Revue de métallurgie* since its foundation in 1902.^{11,31}
4 Both engineering schools (Centrale, CNAM, Mines) and universities
5 were involved in the dynamics of high temperature R&D. In 1926, the
6 Gas Company of Paris funded a chair at the University of Paris enti-
7 tled “fuel chemistry” that would become that of “high temperature”
8 in 1932.¹⁰ In addition, the French Ministry of Aeronautics funded
9 PhD grants in several laboratories to develop light materials with
10 good mechanical properties. All this disciplinary research, infused by
11 private and public funds, contributed to a blossoming French com-
12 munity of chemists, engineers, metallurgists, and physicists involved
13 in the production and measurement of high temperatures both for
14 research and applications for gases and solids. This was typical of an
15 “instrumental research community” shaped by the material nexus of
16 furnaces under the umbrella of technoscience [24, p1–13].

17 This nationwide focus had international ramifications. The French
18 community contributed to the field of high temperature research
19 that was structured after World War II by the context of Cold
20 War. From 1956 onward, three successive international symposia
21 on high-temperature technology were organized by the Stanford
22 Research Institute in California.^{44–46} Discussions were divided into
23 methods, materials, and processes. They gathered between five-
24 and eight-hundred participants from around the Western (that is,
25 non-communist) bloc of the Cold War: academic and industrial
26 researchers with administrative experts and financial entrepreneurs.
27 The main sponsors of the events were US military, nuclear, and space
28 agencies. By this time, refractory compounds with good mechanical
29 properties had become strategic materials for the design of reactors,
30 rockets, and shields. A large consensus supported the craft design
31 of new apparatus to produce still higher temperatures and develop
32 still cleaner processes.³ Different techniques were supposed to find
33 their places in different spheres: “plasma furnaces” as promising
34 industrial devices because of their high electricity–heat conversion
35 rate; “image furnaces” as high-technology research tools; and “solar
36 furnaces” as cheap tools for developing countries.¹⁶ The influential

1 culture of microelectronics R&D pushed a general trend toward the
2 ultra-purification of materials, including metals.¹

3 The 1960s can be understood as a golden age for high-temperature
4 R&D. Since then, several trends related to changing research on
5 materials have modified the landscape: 1) Standardization of com-
6 mercial furnaces (as opposed to tailor-made apparatus built in-
7 house), driven by an industrial demand for control [9, p27–28], has
8 transformed most high-temperature apparatus into humdrum black-
9 boxes;³⁵ 2) The relative dominance of high-temperature “dry routes”
10 was gradually challenged by alternative methods: epitaxy, electro-
11 chemical processes (deposition, intercalation), hydrothermal synthe-
12 ses (wet chemistry), and sol-gel (soft chemistry) [47, p271–87]; 3) The
13 increasing precision of characterization instruments and the diversi-
14 fication of synthetic methods moved interest from 3D crystals to a
15 larger range of morphologies — which would lead to nanoscience and
16 technology in the 2000s — used in new commercial compounds —
17 advanced glasses, gels, films, liquid crystals, and others.^{5,33}

18 **Heating Technology in 1950s US Microelectronics**

19 A survey of materials research and industry in the United States
20 shows that furnaces were routine devices in the two decades after
21 World War II. They paved the way for the dominant crystal syn-
22 thesis technique, known as “dry chemistry” (as opposed to “wet
23 chemistry” in liquid solutions). High-temperature synthesis had two
24 stages: first, inorganic powders were melted at high temperature in
25 a crucible, then the liquid crystallized as it gradually cooled. Since
26 crystal growth is essential to understanding the structural and phys-
27 ical properties of solids, many solid state physicists could hardly
28 work without a furnace in the early 1950s.²² As the physicist John
29 B. Goodenough put it: “Physicists wanted single crystals. . . . The
30 ceramics laboratory that I inherited at Lincoln Laboratory had high-
31 temperature furnaces, a hand press, a hood, a powder x-ray diffrac-
32 tometer, and chemical benches. . . . At Oxford, there was little money
33 for equipment in the Inorganic Chemistry Laboratory. . . . I acquired
34 furnaces for my own synthesis needs.”¹⁷

1 Furnaces were also used to purify materials, to modify their mor-
2 phology (defects, grains, interfaces, and other features), to test their
3 thermal resistance, and to observe their behavior in various ther-
4 mal conditions. This is, for example, the case of “solid oxide fuel
5 cells” (SOFC), the behavior of which was (and is still) analyzed at
6 high temperature and high pressure in a laboratory furnace to sim-
7 ulate their conditions of operation.²⁵ Characterization of materials
8 was another common application. It became usual in the second half
9 of the twentieth century to analyze structural and physical prop-
10 erties of crystals at high temperatures with standardized furnaces
11 coupled with X-ray diffraction machines or microscopes. Other high-
12 temperature techniques, such as thermal differential analysis (TDA),
13 were used to measure glass transition temperatures of amorphous
14 materials (glasses and polymers). Their multiplicity of uses turned
15 furnaces into a nexus of interaction among chemists, engineers, met-
16 allurgists, physicists, and technicians. In the late 1950s, US policy-
17 makers considered these cheap tools to be essential characterization
18 instruments for the formation of materials science and engineering
19 (MSE). A memo prepared by the staff of the US President’s Science
20 Advisory Committee in March 1958 stated: “In various universities
21 one finds the faculties engaged in planning interdepartmental efforts
22 to establish a new materials science and engineering. One of their
23 problems is the lack of buildings and equipment. There are many
24 research tools such as electron microscopes, electron diffraction units,
25 high temperature furnaces, and x-ray diffraction units, each of which
26 represents a cost of approximately \$20,000” [40, p23–24].

27 The ability of furnaces to bring about new connections among
28 researchers was amplified by architectural strategies in the design of
29 research buildings, as shown by the materials research laboratory of
30 the University of Pennsylvania.¹² Indeed, the building, which dated
31 from about 1960, was designed around ten “central facilities” — well-
32 equipped, specialized experimental rooms — to which all researchers
33 and students of the laboratory had access. One can imagine that
34 many casual discussions started in front of the closed doors of the
35 operating furnaces of the “materials processing facility.” (See Brit
36 Shields’s contribution to this volume.)

1 High-temperature tools and processes also helped to transfer
2 research materials into commercial devices. This was the case for
3 the early development of the microelectronics industry, as shown by
4 the examination of several “institutional locations.”³⁰ At AT&T’s
5 Bell Laboratories, ca. 1948–1952, the chemist Gordon Teal and the
6 engineer John Little adapted earlier metallurgical methods devel-
7 oped by Jan Czochralski to design a “crystal puller,” patented in
8 1950 (Figure 3.1.4), for growing, from melt, single crystals of germa-
9 nium, and then silicon. As stressed by historian of electronics David
10 Brock, this “was a key milestone on the road to a silicon junction
11 transistor” [7, p12]. The chemist William Pfann, from the Metallurgy
12 Research Department of Bell Labs, carried on their effort by invent-
13 ing “zone melting,” a high-temperature process to purify solid-state
14 compounds, including semiconductor materials.³⁹ High-temperature
15 purification and crystal growth of semiconductor materials enabled
16 solid state physicists to make and understand junction transistors
17 [27, p26–30]. Interdisciplinary R&D has been characteristic of Bell
18 Labs since the 1930s.²¹

19 Then, around 1952–1954, Texas Instruments, under Teal’s lead-
20 ership, scaled up Bell Labs’ high-temperature synthetic methods
21 to become “the first firm to commercialize the silicon transistor”
22 [30, p310]. Around 1958–1960, at Fairchild Semiconductor, Sheldon
23 Roberts and his co-workers designed robust, simple, practical heating
24 apparatus and crystal pullers that “enabled the firm to be the first to
25 develop and market two major electronic devices — the double dif-
26 fused planar transistor and the integrated circuit” [30, p314]. Thus,
27 a quick look at materials R&D in the United States during the 1950s
28 and 1960s shows that furnaces and high-temperature techniques were
29 essential for making advanced materials and microelectronics devices
30 through the networked interaction of laboratories, factories, and mar-
31 kets. This contributed to “the expansion of both military technology
32 and consumer culture across the Cold War” [30, p316]. Investigat-
33 ing the role of furnaces in the US semiconductor industry therefore
34 permits us to endorse the dominant historiography of “research on
35 materials” focused on MSE and the electronics industry in the United
36 States during the Cold War.⁴

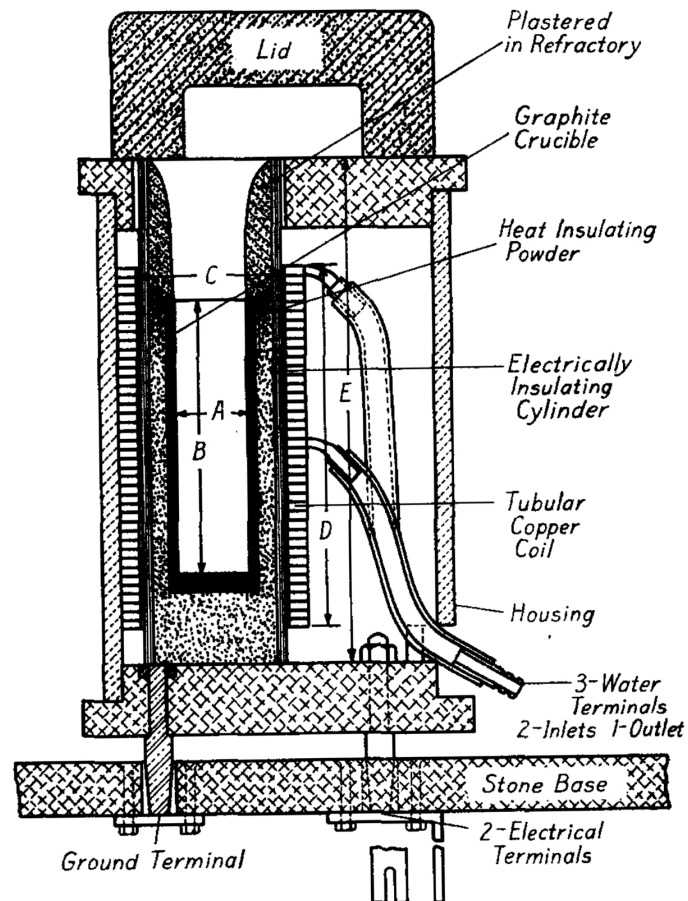


Fig. 3.1.4. Little John B, Teal Gordon K, Production of germanium rods having longitudinal crystal boundaries. *Source:* US Patent 2683676 A, Submitted 13 January 1950, Published 13 July 1954, Assignee Bell Telephone Labor Inc.

1 Conclusion

- 2 A more careful study of heating technology during the twentieth
- 3 century may give several fresh perspectives to science and tech-
- 4 nology studies as well as history of science and technology. At
- 5 least four types of questions could be investigated. First, the topic
- 6 would provide an original probe to compare national specificities.

1 For example, although France and Germany were comparable in
2 solid-state research as a whole, their high-temperature science and
3 technology were quite different: the French interwar community was
4 reinforced by nuclear and space policy after 1945, whereas the lack of
5 a nuclear or space industry in Germany hindered high-temperature
6 research, both in industry itself and in academic institutions
7 [34, p272, 6, p32].

8 Second, the field of high temperature can be considered as a case
9 of “American hegemony,” in which the United States used its larger
10 volume of science and technology to implement policies regarding
11 US allies during the Cold War.²⁶ The long-term history of high-
12 temperature technologies would strengthen the Cold War model of
13 American hegemony and show how technological devices could be
14 shaped to become political tools. A comparison with other mod-
15 els of techno-scientific politics could thus be fruitful.⁴³ Third, high-
16 temperature R&D constitutes a fresh ground to test different models
17 of the interaction among science, industry, military, and state. It
18 could lead to a reappraisal of the role of heavy industry with regards
19 to aerospace, microelectronics, and nuclear industry in the making
20 of military-industrial complexes in the post–World War II context.
21 Last, but not least, the focus on customers and communities, compa-
22 nies and institutions, instruments and practices, or systems and ter-
23 ritories, involved in the blossoming field of high temperature would
24 provide stimulating and surprising historical alternatives to the main-
25 stream narrative on research materials largely molded by the US Cold
26 War lens of MSE and the microelectronics industry.⁴²

27 **References**

- 28 1. American Society for Metals. Ultra-high-purity metals. Papers presented at a
29 seminar of the American Society for Metals, October 21 and 22, 1961. Metals
30 Park, Ohio; 1962.
- 31 2. Bachelard G. The psychoanalysis of fire. Beacon Press; 1987. 1st ed. in French
32 1938.
- 33 3. Bensaude-Vincent B, Teissier P. Robert Collongues (1924–1998). In
34 Koertge N, editor. New dictionary of scientific biography. Detroit: Charles
35 Scribner’s Sons; 2008;2:159–164.

- 1 4. Bertrand E, Bensaude-Vincent B. Materials research in France: a short-lived
2 national initiative (1982–1994). *Minerva*. 2011;49:191–214.
- 3 5. Boilot J-P. Interview (French) with Bensaude-Vincent B. Palaiseau,
4 Polytechnique. December 12, 2000. [https://www.sho.espci.fr/spip.php?](https://www.sho.espci.fr/spip.php?article121)
5 [article121](https://www.sho.espci.fr/spip.php?article121).
- 6 6. Brauer G, Riley RF. *Handbook of preparative inorganic chemistry*, vol 1.
7 Academic Press; 1963.
- 8 7. Brock DC. The backdrop to Moore’s Law: developments in semiconduc-
9 tor electronics to 1965. In Brock DC, editor. *Understanding Moore’s Law.*
10 *four decades of innovation*. Philadelphia, PA: Chemical Heritage Foundation;
11 2006. Chapter 2.
- 12 8. Cardwell D. *The Fontana history of technology*. London: Fontana Press; 1994.
- 13 9. Caro P. Interview (French) with Teissier P. Paris: French Academy of Science.
14 May 3, 2005.
- 15 10. Charle C, Telkes E. *Les professeurs du Collège de France. Dictionnaire*
16 *biographique 1901–1939*. Paris: CNRS; 1988.
- 17 11. Chezeau N. *De la forge au laboratoire: naissance de la métallurgie physique*
18 *(1860–1914)*. Rennes: Presses universitaires de Rennes; 2004.
- 19 12. Choi H, Shields B. A place for materials science: laboratory buildings
20 and interdisciplinary research at the University of Pennsylvania. *Minerva*
21 2015;53(1):1–42.
- 22 13. Daston L, editor. *Things that talk: object lessons from art and science*. New
23 York: Zone Books; 2008.
- 24 14. Daumas M, editor. *Histoire générale des techniques*. 5 vols. Paris: Presses
25 universitaires de France; 1979.
- 26 15. Di Salvo F. New and artificially structured electronic and magnetic materi-
27 als. In Psaras P. A., Langford H. D., editors. *Advancing materials research*.
28 Washington, DC: National Academy Press; 1987: 161–75.
- 29 16. Foëx M. *Compte-rendu sur le “Symposium des hautes températures”*
30 *d’Asilomar (1959)*. *Bulletin de la Société chimique de France*. 1961;28:117–23.
- 31 17. Goodenough JB. Interview with Bensaude-Vincent B., Hessenbruch A.
32 Austin: University of Texas. May 2001. [https://sho.spip.espci.fr/spip.php?](https://sho.spip.espci.fr/spip.php?article28)
33 [article28](https://sho.spip.espci.fr/spip.php?article28).
- 34 18. Gutowski TG, Sahni S, Allwood JM, Ashby MF, Worrell E. The energy
35 required to produce materials: constraints on energy-intensity improvements,
36 parameters of demand. *Philosophical Transactions: Mathematical, Physical*
37 *and Engineering Sciences*. 2013;317(1986):1–14.
- 38 19. Haynes R. The alchemist in fiction: the master narrative. In Schummer J,
39 Bensaude-Vincent B, Van Tiggelen B, editors. *The public image of chemistry*.
40 Singapore: World Scientific; 2007.
- 41 20. Hirsch P. Interview with Bensaude-Vincent B. Oxford, Oxford University.
42 December 12, 2002. <https://sho.spip.espci.fr/spip.php?article126>.
- 43 21. Hoddesson L. The roots of solid-state research at Bell Labs. *Physics Today*.
44 1977;30(3):23–30.

- 1 22. Hoddeson L, Braun E, Teichmann J, Weart S, editors. *Out of the crystal*
2 maze: chapters from the history of solid-state physics. New York: Oxford
3 University Press; 1992.
- 4 23. Jayaraman A. A brief overview of gem materials: natural and synthetic.
5 *Current Science*. 2000;79(11):1555–65.
- 6 24. Joerges B, Shinn T. *Instrumentation between science, state and industry*.
7 Dordrecht: Kluwer Academic Publishers; 2001.
- 8 25. Joubert O. Interview (French) with Teissier P. Nantes, University of Nantes.
9 May 2, 2017.
- 10 26. Krige J. *American hegemony and the postwar reconstruction of science in*
11 *Europe*. Cambridge, MA: MIT Press; 2006.
- 12 27. Lassman TC. *From materials research to materials science: the industrial*
13 *origins of an academic discipline*. Baltimore, MD: Master of Arts; 1996.
- 14 28. Lebeau P, editor. *Fours électriques et chimie*. Paris: Presses universitaires de
15 France; 1924.
- 16 29. Lebeau P, Meyer A. *Cérémonie en l'honneur du XXVe anniversaire de*
17 *l'Institut de Biologie physico-chimique*. 2^e Fondation Edmond de Rothschild
18 pour le développement de la Recherche scientifique. Paris: Hermann; 1953.
- 19 30. Lécuyer C, Brock D. *The materiality of microelectronics*. *History and Tech-*
20 *nology*. 2006;22(3):301–25.
- 21 31. Letté M. *Henry Le Chatelier (1850–1936) ou La science appliquée à*
22 *l'industrie*. Rennes: Presses universitaires de Rennes; 2004.
- 23 32. Letté M. *Le rapport d'Étienne Clémentel (1919). L'avènement administratif*
24 *des technocrates et de la rationalisation*. *Documents pour l'histoire des tech-*
25 *niques*. 2011;20:167–95.
- 26 33. Livage J. Interview with Bensaude-Vincent B. Paris, University of Paris.
27 4 January 2001. <https://www.sho.espci.fr/spip.php?article122>.
- 28 34. Lochte-Holtgreven W. *High temperature research activity in germany*. In
29 *Stanford Research Institute, editors. Proceedings of an International Sympo-*
30 *sium on High Temperature Technology, held at Asilomar, California, October*
31 *6–9, 1959*. New York: McGraw-Hill; 1960.
- 32 35. Lucas J. Interview with Teissier P. Paris, Quartier latin. May 9, 2005.
- 33 36. Mody C. *A little dirt never hurt anyone: knowledge-making and contamina-*
34 *tion in materials science*. *Social Studies of Science*. 2001;31(1):7–36.
- 35 37. Nassau K. Dr. A. V. L. Verneuil: The man and the method. *Journal of Crystal*
36 *Growth*. 1972;13–14:12–18.
- 37 38. Northrup EF. *High temperature investigation*. *Journal of the Franklin Insti-*
38 *tute*. 1923;195(1169–46):665–86.
- 39 39. Pfann WG. *How zone melting was invented*. *Progress in Crystal Growth and*
40 *Characterization*. 1983;6:iii–iv.
- 41 40. Psaras PA, Langford HD, editors. *Advancing materials research*. Washington,
42 DC: National Academy Press; 1987.
- 43 41. Riordan M, Hoddeson L. *Crystal fire: the birth of the information age*. New
44 York: Norton; 1997.

- 1 42. Sabel S, Zeitlin J. Historical alternatives to mass production: politics,
2 markets and technology in nineteenth-century industrialization. *Past and*
3 *Present*. 1985;108:133–76.
- 4 43. Sismondo S. Science and technology studies and an engaged program. In
5 Hackett E, Amsterdamska O, Lynch M, Wajcman, editors. *The handbook of*
6 *science and technology studies*. Cambridge, MA: MIT Press; 2008.
- 7 44. Stanford Research Institute, editor. *Proceedings of the symposium on “High*
8 *Temperature — a Tool for the Future,”* Berkeley, California, June 25–27,
9 1956. Menlo Park, CA: Stanford Research Institute; 1957.
- 10 45. Stanford Research Institute, editor. *Proceedings of an International Sympo-*
11 *sium on High Temperature Technology, held at Asilomar, California, October*
12 *6–9, 1959.* New York: McGraw-Hill; 1960.
- 13 46. Stanford Research Institute, editor. *Proceedings of an International Sympo-*
14 *sium on High Temperature Technology, held at Asilomar, California, 8–11*
15 *September, 1963.* London: Butterworths; 1964.
- 16 47. Teissier P. *Une histoire de la chimie du solide contemporaine. Synthèses,*
17 *formes, identités.* Paris: Hermann; 2014.
- 18 48. Trumbore FA, Turner DR, *The Electrochemical Society, 1902–2002: a cen-*
19 *tennial history.* Pennington: The Electrochemical Society; 2002.
- 20 49. Viel C. *Henri Moissan, pharmacien, premier Français prix Nobel de chimie,*
21 *1852–1907.* Paris: Pharmathèmes; 2006.