CHAPTER 9

MILITARIZING RADIOMETRY

Through the late summer of 1953, light was being measured on the bright Mojave desert of China Lake, California. The source was no longer a gas lamp, or incandescent bulb, or glowing pool of molten metal, or even the sun: it was a military jet, repeatedly approaching, banking and sweeping past[1].

There had been a side-step in this relocation. The quantification of intensity no longer seemed quite so important, but *detection* now mattered critically. And a shift in sponsors brought a shift in wavelength. By the end of the Second World War, photometry had largely stabilized in terms of standards, technology, institutional management and social specialization. Colorimetry, too, had attained several of the attributes of a stable subject. But the third specialism of this newly identified triumvirate—radiometry—was expanding disproportionately. Light measurement had broached a military dimension.

9.1. THE MYSTIQUE OF THE INVISIBLE

Until the early 20th century, radiometry had been the facet of light measurement least tarnished by the mundane, and the most imbued with an aura of exciting scientific discovery and mystery. This was due in no small part to the invisibility of the radiations detected. As discussed in chapter 2, the study of radiant heat had distinct historical origins and was, for some time, devoid of any compelling application. Nor was a connection between this elusive entity, affecting thermometers and other heat-measuring instruments, commonly connected with visible light[2]. Such factors tended to isolate the subject from the workaday concerns of photometry and colorimetry during the 19th century. Blondlot's investigations of n-rays, impelled by the turn-of-the-century scientific excitement at the discoveries of new and exotic radiations, were unusual in bringing photometric techniques to bear. But the vacillating methodology of Blondlot and his co-workers suggests just how tentatively invisible radiation was labelled as 'optical'.

Most investigators maintained a clear distinction between their research on invisible radiations and those of photometrists. Boundaries of several types existed: *occupational*, because radiometry developed in the exclusive domain of the physicist whereas photometry and colorimetry, as we have seen, had mixed parentage[3]; *workplace related*, because radiometric research was to be centred for a time at universities, the home of academic physicists; *application oriented*, because, as outlined earlier, it was divorced from practical utility; and in technical practice. Foremost in maintaining such distinctions of practice was the implicit rejection of direct human-centred observations. The complicated responses of the human eye were never an issue for radiometrists. Instead, they focused on investigating and developing physical detectors of radiation, and applying them either to discover more about the radiations themselves or in devising instruments to exploit the radiations. By unproblematically avoiding this perennial difficulty at the centre of photometry and colorimetry, specialists in radiometry had no difficulty in associating themselves with mainstream physical science. Nevertheless, the late 19th-century distinctions that set radiometry apart were to be reconstructed with the appearance of new sponsors and technologies.

9.2. MILITARY CONNECTIONS

The device-centred nature of this alluring research was eventually responsible for attracting an attentive sponsor: the military. The new sponsored research was, from the beginning, decidedly application oriented and new uses multiplied rapidly. The applications were bound up with the covert and clandestine—which unavoidably produces a patchy and unevenly weighted historiography. Military interest centred initially on the generation and detection of invisible radiation for signalling.

During the First World War, Theodore W Case in America found that sulphide salts were photoconductive (that is, altering in electrical conductivity according to the intensity of light falling upon them), and developed thallous sulphide (Tl_2S) cells. Their sensitivity, in fact, was principally to infrared rather than to visible radiation. Supported by the US Army between 1917 and 1918, Case adapted these relatively unreliable detectors for use as sensors in an infrared signalling device (and eventually patenting his 'Thalofide' cells in 1919). The prototype signalling system, consisting of a 60 inch diameter searchlight as the source of radiation (which would be alternately blocked and uncovered to send messages, akin to smoke signals or early optical telegraphs) and a thallous sulphide detector at the focus of a 24 inch diameter paraboloid mirror, sent messages 18 miles through what was described as 'smoky atmosphere' in 1917. The smokiness was not merely a passing observation: it was a strong selling point. A longstanding belief—largely unsubstantiated—about communicating and imaging with infrared radiation was that it was little affected by cloud, fog and smoke. This notion, widely repeated to and by the military for decades, promoted the technology's acceptance[4].

Nevertheless, Case's apparatus was not a success: the detectors were too irregular in performance to support even such a non-quantitative application. Their electrical response to radiation varied from cell to cell, and was proportional neither to the intensity of radiation nor to the applied voltage. Like visible light, invisible radiation was difficult to quantify. Work was discontinued in 1918; communication by the detection of infrared radiation appeared distinctly unpromising.

9.2.1. British research

Unlike their American counterparts, the interest of the British military centred on the detection of small aircraft by the heat they emitted[5]. Such an idea had been proposed by F A Lindemann (later Lord Cherwell) as early as 1916 but not taken up, and an investigation in 1926 by A B Wood of the Admiralty also looked unpromising. In 1935, R V Jones was developing infrared detectors at the Clarendon laboratory at Oxford under Lindemann's guidance. He was occasionally diverted from this work—intended for observations of the sun—to produce detectors for a retired American Navy inventor, Commander Paul H MacNeil, who was promoting his own version of an infrared detector of aircraft. While the MacNeil device was also unsuccessful, it reinforced interest at the Air Ministry, which in January of that year had set up a Committee for the Scientific Survey of Air Defence. Jones and an NPL scientist, J S Anderson, performed their own trials late in 1935, again with poor results. Detecting the radiation from hot engine surfaces appeared difficult.

The Committee nevertheless asked Jones to continue with full-time development, even if it was recognized to be a peripheral line of investigation. Unlike the concurrent radar research, which 'had a large research team... devoted to it', Jones 'for much of the time, had only [him]self'[6]. He devised equipment based on infrared detectors coupled to a small telescope, with signals amplified by a four-stage valve amplifier and indicated on a galvanometer—an arrangement employed tentatively in spectroscopy laboratories since the 1920s[7]. With various versions of the system developed over two years, it proved possible to detect single-engined aircraft from the ground at a distance of up to two miles, or about a half-mile air-to-air. Compared to radar, though, this radiometric equipment was incapable of detecting the range (distance) of aircraft. And experience belied myth: the detection was not effective through clouds. In March 1938, the small project was ended in favour of radar. A year later, however, Jones briefly joined a new Infra-Red Group, 'Group E', at the Admiralty Research Laboratory (ARL). E G Hill, its head, had earlier explored infrared signalling at HM Signal School in Portsmouth, and the group focused on such applications[8]. Infrared 'light' could be detected in some circumstances, to be sure—especially when emitted by cooperative targets—but appeared too weak to be measured for the planned military applications.

9.2.2. American developments during the Second World War

Aircraft detection initially excited little interest in America but, early in 1940, Theodore Case's idea was revived for a ground-based signalling system to be used during times of radio blackout. Several such projects were sponsored by the American government, which organized directed research for military applications. Through the war, this military sponsorship became wide-ranging and pervasive. In 1940, the National Defense Research Committee (NDRC) was formed to coordinate the funding of research for military purposes. One of its original four Divisions was 'Detection, Controls and Instruments'; within it, two of the four sections were 'Instruments' and 'Infrared Devices'[9]. The following year, after complaints that the NDRC was responsible only for researching and prototyping, and not for developing instruments to a manufacturable stage, the wider-ranging Office of Scientific Research and Development (OSRD) was set up, making NDRC a sub-section within it[10]. An Optics Division and Physics Division were formed with George R Harrison, formerly director of the Instruments Section, as Chief and Deputy Chief, respectively.

The NDRC drew upon some of the most prominent American optical scientists for its membership, bringing together physicists, colour scientists and psychologists for some projects. It also intermixed these specialisms and imposed a military impetus unseen in the previous war. Harrison led a 13-man team for 17 months as Chairman of the Instruments Section of the original NDRC. Of the three other Sections in the Detection, Controls and Instruments Division at that time, a Section alternately labelled 'Infrared Devices' or 'Heat Radiation' Section was chaired by A C Bemis and included infrared spectroscopist J D Strong with five other members and consultants. From December 1942 until the war's end, Harrison was Chief of the Optics and Camouflage Division, and Deputy Chief of the closely associated Physics Division. Optics included a five-member Infrared Section, a 13-member Illumination & Vision Section which included W E Forsythe and spectroscopists A H Pfund and H E White, and a Camouflage Section which included colour scientists and psychologists such as A C Hardy, L A Jones and E G Boring[11]. Significantly for the cognitive unity and management of these sections, Harrison had made his name in the inter-war years for his refinement of photographic photometry[12].

Even so, radiometry seemed to be a technology in search of an application. While the NDRC was the central organization in America responsible for wartime military-directed research, the Optics and Physics Divisions tackled miscellaneous problems, 'which had no particular relationship to each other and defied ready classification'. Indeed, reports the official history,

> except for a few instances, their work was almost entirely lacking in continuity... their primary goal was to create or improve any physical instrument which was needed by the Army or Navy which did not fall into one of the specialized, major fields of investigation.[13]

Nevertheless, among the wide range of sponsored wartime projects, the collective radiometry research and development were significant—'a program which ranks with radar as a prime example of the application of theoretical science to the practical problems of war'—and were to influence American post-war developments[14]. The work of Robert J Cashman, a physicist at Northwestern University in Illinois, was a fertile seed. Cashman had been extending Case's work on photoconductive thallous sulphide detectors since 1935. His efforts to develop a stable detector with reproducible characteristics in production were spurred by the knowledge that Case had seen such detectors in Germany in the early 1930s[15]. Cashman consequently received one of the first contracts from the NDRC—from among some 126 granted in December 1940—to make a systematic study of Thalofide cells, and his work was supported throughout the war[16]. The NDRC organized American military research on a new model which was to become the template for post-war funding: rather than requiring scientists and technologists to accept a military commission and to work at a government facility under military command procedures, as had been the practice in the previous war, the NDRC preferred to channel money via short-term contracts to existing groups at large institutions[17]. Through them, Cashman's research led to reliable production procedures for detectors. Further fundamental research on the cells started at MIT in 1943, and in 1944 the NDRC contracted General Electric at West Lynn, Massachusetts, to manufacture the cells. Within 11 months some 6800 had been produced with a reported 90% yield[18]. Other successful programmes included an infrared-guided bomb which used a bolometer as sensor, and heat-sensitive phosphors for sniperscopes and scanning systems used for the detection of heat-radiating targets. Several NDRC contracts directly benefited from, and publicized, such detector and infrared systems research, which led to 'nearly a score of infrared systems for a variety of highly specialized military applications'[19]. Few of these projects entered full-scale production during the war, but there was a hint that perhaps radiometry could be as applicable as photometry after all.

9.2.3. German experiences

Despite post-war claims by the NDRC that 'American scientists won by a wide margin in their race to be the first to make practical use of infrared light'[20], German work clearly surpassed it in pursuing new technical directions and concepts. A novel variety of infrared detector, the lead sulphide (PbS) photoconductive detector, had been developed in Germany from 1932 when Edgar W Kutzscher at the University of Berlin began to study them[21]. Like his British and American contemporaries, within a year he obtained military sponsorship—from the German Army, in this case. Kutzscher was Director of Infrared Research and Development of the Electracustic Company in Kiel during the war, where he and his teams developed the new detectors and infrared systems based on them[22]. Compared to British and American work, German infrared research was wide-ranging, theoretically based and innovative. Indeed, according to a 1944 report to the German Air Ministry, infrared homing devices were a more promising technology for missile guidance, owing to simplicity and technical advancement, than either radar or acoustic methods[23].

The breadth of development is suggested by the variety of wartime actors involved. A decade after the war, Kutzscher listed seven collaborators within his own company with whom he had studied the basic physics of detectors, materials and the atmosphere, as well as production techniques and applied systems engineering for infrared detection. Other techniques of fabricating infrared detectors were also developed by Bernhard Gudden[24] from the 1920s, Dr Gorlich at the laboratories of Zeiss-Ikon in Dresden, and others. The most successful wartime development was the 'Kiel IV', an airborne infrared system that—unlike Jones' English prototypes—had excellent range, and which was produced at Carl Zeiss in Jena under Werner K Weihe[25].

Developing such detection systems demanded a mixture of optics, electronics and materials science. German advances were made in materials that transmit infrared radiation (as glass transmits visible light). 'KRS5', a mixture of thallium iodide and thallium bromide, was developed by the Zeiss firm; infrared-transmitting 'Duran' glass was fabricated by Schott Glassworks. Other aspects of infrared systems were developed at German firms such as AEG, Kepka and Rheinmetall-Borsig. Yet Kutzscher stated that the design of efficient systems mated to their most important recognized potential application, the guidance of missiles, 'was not accomplished at the end of the war'[26]. Like the other combatants, the German military deployed only limited production runs of some infrared devices during the war, for example using the radiation reflected from targets such as tanks to direct guns and the *lichtsprecher* or optical telephone[27].

9.2.4. Post-war perspectives

These extensive German developments remained largely unknown to the Allies until after the war. While identified as a useful and potentially fertile wartime expedient, radiometry never received American funding remotely comparable to the technologies of radar, the proximity fuse, solid-fuel rockets or the atomic bomb; in Britain, its limited funding was a pre-war casualty. The 'night scopes' employed by US riflemen were credited with being responsible for 30% of the Japanese casualties in the early stages of the battle for Okinawa[28], but the technology of infrared measurement in both countries remained both technically and organizationally marginalized.

The sponsorship of this American wartime research appeared equally ephemeral. Its chief architect, Vannevar Bush, saw the NDRC as a temporary organization purely to deal with the requirements of the wartime emergency; it was already being dismantled in the final year of the war. In mid-1945, the Office of Scientific Research and Development was effectively replaced by the creation of a new body, the Research Board for National Security (RBNS). This was a joint board consisting of Army, Navy and civilian representatives to organize post-war research for military purposes. At about the same time, an Office of Naval Research (ONR) was formed by the Navy to provide continuity to maintain the wartime research impetus while other organizations still awaited approval, and to gain a central role in military research and development[29]. The ONR proved to be a liberal source of funding for civilian science, and became the principal contractor for fundamental research at universities in the post-war years.

The end of the war rapidly brought new information but just as rapidly closed off certain avenues for unclassified research. Cashman extended his studies in the early post-war years and discovered other lead salts that showed promise as detectors of infrared radiation[30]. But the wide-ranging German successes, newly uncovered by the Allies, did more than flesh out these findings: they redirected the thrust of research and development. The German trajectory of research was essentially the direction continued in the USA and Britain under military sponsorship after the war. From 1946, detector technology was rapidly disseminated to firms such as Mullard Ltd in Southampton, UK, as part of war reparations, and sometimes was accompanied by the valuable tacit knowledge of technical experts. E W Kutzscher, for example, was flown to Britain from Kiel after the war, and subsequently had an important influence on American developments when he joined Lockheed Aircraft Co in Burbank, California as Research Scientist[31].

Some aspects of this information were recognized as having considerable post-war potential and were classified. Where information about 'Metascopes', or night-vision devices based on infrared phosphors, was widely publicized as an example of American wartime ingenuity[32], information about 'heat detectors' became as invisible as the radiation itself. The 1948 history of the NDRC Optics Division reports tersely that 'the details of the actual adaptation of heat-detection principles to military needs are still locked in the files of the War Department'[33]. At a NATO conference discussing wartime German infrared homing devices a decade later, Kutzscher—now representing the Americans—spoke in intentionally vague terms of the physics of detection and deflected detailed questions with the statement that 'results of recent measurements are classified'[34].

Although infrared devices had seen only limited deployment by the Germans and Americans during the war, they appeared to show promise. How was a strong post-war development programme, supported almost entirely by military funding, justified? Four factors were prominent. First, the new military aircraft and missiles developed at the end of the war proved ideal targets for infrared sensors. Kutzscher's teams had studied infrared detection of reciprocating engines in aircraft, for which the hot exposed exhaust pipes were the principal source of infrared radiation. As the British had long realized, such heat sources could easily be shielded by engine shrouds[35]. The NDRC history of the American developments, in fact, fatalistically omitted any mention of such targets, describing its infrared systems as being 'instruments that could guide missiles toward the hot smokestacks of ships and factories', and reported that post-war investigations had found a similar Japanese heat-seeking bomb intended for 'the hot innards of ships in the invasion fleet'[36]. But the new jet aircraft and rocket motors, by contrast, produced more concentrated and hotter plumes of exhaust gases that were radiometrically bright and hence much more easily detectable by infrared detectors. Nevertheless, development programmes strongly encouraged fundamental research because improvements in the sensitivity of detectors translated directly into longer-range detection of these much faster-moving targets.

The second factor in favour of infrared technology was its ability to be used 'passively', i.e. by measuring the radiation emitted by warm bodies, rather than having to illuminate the targets with another source. This made infrared detection more covert than radar. Third, there was the German (and limited American) evidence that sensitive infrared detectors could be produced in volume and employed successfully in military contexts. And fourth, theoretical research was suggesting that considerable improvements in such detectors should be possible. Thus a newly ripe application, combined with manufacturing confidence and theoretical potential, created a new military market. Nevertheless, a fifth factor outweighed the others: these technical factors merely facilitated the general military pressure for tactical post-war advantage. The extension of radiometry was fuelled primarily by the political context of Cold War.

9.2.5. New research: beyond the n-ray

The military engagement with radiometry bore striking parallels with Blondlot's study of n-rays a half-century earlier. The very properties of their radiations were unclear, intriguing and communicated by hearsay. Both were concerned with *detection* rather than quantification. The radiation they sought was perpetually at the limit of detectability. Infrared detection systems, like Blondlot's laboratory assistants, merely signalled 'presence' or 'absence' of the elusive signal. And military designers shared Blondlot's philosophy of observation. There was little need to measure the size of the signal; what was important was to extend the threshold of detectability as far as possible.

An awareness of a greater potential for the technology emerged from spectroscopy. The spectroscopy community was eager to extend observations to ever-longer wavelengths (and correspondingly weak energy sources) of infrared radiation and to more difficult (e.g. thicker, more absorbing or more scattering specimens)[37]. But unlike the military, spectroscopists had a more central need to quantify their measurements. The co-evolution of commercial infrared spectroscopy for applications such as organic and analytical chemistry was another active research area immediately after the war, and was responsible for most of the published research at that time[38]. Research focused as much on instruments as on experiment, including several new types of infrared detector and studies of the ultimate sensitivity of such detectors[39]. While this work placed limits on the feasibility of infrared detection, it also demonstrated the gulf between practical systems and their theoretical potential.

9.2.6. New technology

Into the early 1950s, detectors developed in Germany included the thallous sulphide and lead sulphide (PbS); Americans added the lead selenide (PbSe), lead telluride (PbTe) and indium antimonide (InSb) detectors. British workers introduced mercury–cadmium–telluride (HgCdTe) infrared detectors. These developments were largely a product of military funding, but were available (if often expensive) to academic spectroscopists.

These devices rapidly found military applications. A guided aircraft rocket (the GAR-2) was in production from 1956; the similar infrared-guided Sidewinder missile was first used militarily against Chinese aircraft in 1958 (figure 9.1).

Figure 9.1. GAR-2A infrared Guided Aircraft Rocket (left) developed by US Air Force, beside James J O'Reilly, engineering test pilot for the Hughes Aircraft Company. In production from 1956, some 16 000 of the original design were produced. Reproduced with permission of HRL Laboratories, Malibu, CA.

By the early 1960s, the American military had missile guidance systems, fire control systems, bomber-defence devices, thermal reconnaissance equipment and others, all employing infrared measurement devices[40]. Despite such apparently rapid deployments and funding on a scale hitherto unknown by the scientific community, infrared research and development remained a rather secondary technology for the American military in the first post-war decade. As one early compendium on the technology reported,

> Infrared engineering, like radar engineering, has evolved under cover of military security. Many current applications are still highly classified, and details cannot be divulged... unlike radar, which received a monumental development effort during World War II, operational infrared has evolved rather slowly, on a limited-budget

> basis. With the advancement of military strategy into environments which are more favorable to the infrared technique, such as high altitude and space, infrared devices are receiving more serious attention.[41]

Indeed the American space programme, and particularly military projects for communications systems and the remote sensing of information by infrared radiation, maintained the momentum throughout the 1960s and 70s. In an environment free of atmospheric absorption and unhindered by earlier restrictions in project budgets, infrared radiometry research attained unearthly levels.

9.3. NEW CENTRES

Given the relatively large scale of American funding compared to its pre-war levels, it is not surprising that new loci of expertise in radiometry sprang up in the post-war years, mainly at military contractors. The government and private laboratories of the first decades of the century were joined by something different in scale and practice. The new laboratories operated by research and development contracts, and proliferated in proportion to military expenditure. For the writing of the 1965 text *Handbook of Military Infrared Technology*, some of the institutions and companies providing technical information were the Raytheon Co; Minneapolis-Honeywell Regulator Co; Westinghouse Electric Corp; Garrett Corp; Naval Ordnance Test Station; Barnes Engineering Co; Servo Corporation of America; Eastman Kodak Co; Air Force Cambridge Research Laboratories; Malakar Laboratories, Librascope Division; General Precision Co; A D Little Co; The RAND Corp; Texas Instruments Inc; Leesona Moos Corp; Infrared Detector Department of Radiation Electronics Inc; Engelhard Industries, Inc; National Bureau of Standards; Fish Schurman Corp[42]. Firms providing entire chapters for the text included Sylvania Electronic Systems; Infrared Industries Inc; Itek Corporation; Grumman Aircraft Engineering Corp and Mithras Inc. Many of these firms were located near the institutions that had benefited from wartime NDRC contracts such as MIT, and contributed to a growing belt of technology firms in the north-east USA.

In Britain, the principal government-directed research centre was the Radar Research Establishment (RRE) at Malvern (later the Royal Signals and Radar Establishment)[43]. Several British firms had research and development departments devoted to infrared work from the early 1950s, including de Havilland Propellers and EMI. Owing to the Official Secrets Act and government policy, their work was kept substantially separate.

Yet government-sponsored bodies organized interactions. Replacing the former word-of-mouth communication between academic physicists were new, more formal, structures. Organizations such as IRIS (Infrared Information Symposia) and IRIA (Infrared Information and Analysis Center) existed by 1961 to collate information from the large number of development projects. The following year the US Department of Defense further coordinated efforts by establishing the Joint Services Infrared Sensitive Element Testing Program

(JSIRSETP) at the Naval Ordnance Laboratory in Corona, California (later moved to the Naval Electronics Laboratory Center, San Diego). A sifting out of the firms participating in the original research projects eventually occurred. The major detector firm by the late 1960s was the Santa Barbara Research Center (SBRC), a subsidiary of the Hughes Aircraft Company[44]. Thus, apart from the University of Michigan, itself a major beneficiary of military contracts, the bulk of radiometric research was being undertaken by private firms. Previously centred in universities, radiometry had been redirected by the war to join photometry as a shadowy specialism outside the mainstream of academic science.

9.4. NEW COMMUNITIES

As the discipline was translated, so were its specialists. They increased in number, and the centre of mass was displaced from physicists to a new breed of appropriating specialist.

From a small group of researchers in the early 1950s, infrared meetings drew 500 to 1000 participants by 1965[45]. The collective biographies of these communities mutated as they expanded. The special status of physicists in the American and British military began to be eroded by the mid 1950s. By that time, although they were still valued for the development of novel instruments, their role as generalists—juggling information of markets, engineering, production expertise and strategy—had been grasped by electrical engineers[46]. The new catch-all subject of 'electro-optics' was becoming a more useful description. The *Handbook of Military Infrared Technology* mirrored this new concoction, acknowledging publications mainly of the IEEE (*Proc. IEEE*, *Proc. Inst of Radio Engineers*), the OSA (*Applied Optics*, *JOSA*), and, in Britain, the Institute of Physics (*J. Sci. Instr., Physics in Technology*). The editors categorized infrared detectors as a sub-category of 'modern optics' entwined 'intimately with the contemporary field of solid-state physics'.

Physicists continued to lose ground within this new specialism. The Society of Photo-Optical Instrumentation Engineers (SPIE, and renamed 'The International Society for Optical Engineering' in the 1980s), a small organization bringing together technologists primarily in the photographic and motion-picture industries in the post-war years, was transformed by an influx of researchers benefiting from military contracts. The initial connection was for specialized cameras and tracking devices to monitor missile launches. Gradually, however, these new 'electro-optical engineers', versed in mechanical, optical and electronic design to varying degrees, began to work with radiometric systems. The military component was so significant that some SPIE meetings were restricted to American citizens during the 1970s and 1980s.

Thus, unlike photometry and colorimetry, radiometry by the 1960s arguably *did* succeed in attracting its own appropriating specialist community—the electro-optical engineers. While sub-fields became concerned with the specialism, optical engineers had the strongest claim to control it—from theory, to design, installation and operation of its technology. That electro-optical engineers took over this role can be attributed to the dominance of bountiful sponsors and controlling applications—governments funding military usages.

9.5. NEW UNITS, NEW STANDARDS

The specialism of radiometry adapted to its new sponsorship not only by shifting its occupational locus, but by altering its language and technical guideposts: its measurement units and standards.

To some—who were developing an infrared version of what had previously been optical technology, such as optical telegraphs and optical telephones—a connection with photometry had seemed natural, if implicit. The US Navy specified the sensitivity threshold of Metascopes in terms of specified sensitivity in terms of ungainly 'nautical-mile-candles'. During Cashman's wartime work on thallous sulphide cells, infrared sources were calibrated in terms of *visual* response, sometimes in Hefners or foot-candles. As one chronicler states, an NDRC contractor 'chose to adopt a system of *photometry* for the infrared', constructing 'analogies to photometric concepts. . . such as the "holocandle" and "infrawatt"'. By the late 1960s such quantities were derided as 'cumbersome concepts' long discarded in favour of direct, energy-related units[47].

The very notion of a reference standard was also problematic. As turn-of-the-century photometrists at national laboratories had found, a good standard of brightness had to be very similar to what was being evaluated. Gas lamps had to be compared with flames; electric light bulbs needed to be compared with other glowing metal filaments of similar temperature. The distribution of radiation also generated its own 'standard units': gas lamps were amenably described by 'horizontal candlepower', while incandescent electric lamps were more suited to 'spherical candlepower'. So it was with military aircraft. But the nature of aircraft as sources of light is complex. The leading surfaces of a jet aeroplane or missile are heated by aerodynamic friction, and emit infrared light something like a blackbody source. Jet and rocket nozzles are much hotter. And the exhaust gases themselves are often a combination of blackbody radiation and 'emission' lines (strong radiation of isolated wavelengths due to chemical species in the burning fuel). Indeed, the spectral distribution of radiation could serve as an accurate 'signature' of the airborne body unique to it. In such circumstances, the inter-comparison of instruments was difficult. 'Traceability of instrument performance to the National Bureau of Standards is more and more a real question', noted William Wolfe, editor of the *Handbook of Military Infrared Technology*[48]. Calibration of the detection equipment was therefore a fraught process involving a combination of crude laboratory comparisons, theoretical estimates and expensive field trials.

The very form of the units also changed to suit new circumstances. The new light sources of interest did not remain at rest on a laboratory optical bench; aircraft and rockets, soldiers and tanks changed distance, angle, orientation and apparent shape. Consequently the units of radiometry ceased to be adequate. Why should investigators be concerned with the *total* power (the 'radiant flux', in watts) emitted by a light source or the power emitted from its *surface* ('the radiant emittance' or 'exitance', W/m^2), when its size and even distance might be unknown? When 'sources' became uncooperative 'targets', new measurement philosophies and units gained relevance. All were based on what could be measured by the detector rather than on how the light source could be manipulated. The power falling on the detector ('irradiance', W/m^2), the power radiated into a solid angle ('radiant intensity', W/sr) and, given the luxury of knowledge of the target size, the power radiated into a solid angle per area of the source ('radiance', W/sr m^2) became the new values of interest[49]. This shifting of consideration from source to detector has parallels with illuminating engineering, which had moved from the characterization of sources to that of reflective surfaces (roads, walls and windows) some 50 years earlier.

9.6. COMMERCIALIZATION OF CONFIDENTIAL EXPERTISE

9.6.1. New public knowledge

By the early 1960s, the large number of firms and technologists connected with infrared technology demanded a wide distribution of information. Civilian applications were also sufficiently widespread to promote popular articles and texts. The major source of information, however, was the *Handbook of Military Infrared Technology* sponsored by the US Office of Naval Research, and contracted by the Advanced Research Projects Agency (ARPA) of the American military. ARPA had contracted the University of Michigan to supervise the writing of the book[50]. Given the military background to this work, it is unsurprising that many of the sources of information were connected with the analysis of targets. Among the sources of information and acronyms were: BAMIRAC, the Ballistic Missile Radiation Analysis Center; TABSAC, the Target and Backgrounds Signature Analysis Center; BAC, the Background Analysis Centre [all at the Institute of Science and Technology, University of Michigan]; RACIC, the Remote Areas Conflict Information Center, the Battelle Memorial Institute in Columbus, Ohio; CINFAC, the Counterinsurgency Information Analysis Center, American University, Washington, DC. Radiometry, the central subject of the book, was extended to the meteorology of clouds, properties of the atmosphere, vegetation and ground covers, tracking system design, linear systems engineering, thermal coatings and optical materials.

This compendium was updated as the ostensibly civilian *Infrared Handbook* in 1978[51]. In it, military connections with radiometry were distinctly downplayed. Chapters on 'Targets' and 'Backgrounds' were subsumed into 'Artificial Sources' and 'Natural Sources'. The technology was recast as less aggressive: descriptions of 'Control Systems' gave way to 'Warning Systems'. The sponsor remained, however, the Infrared Information and Analysis Center—a 'Defense Logistics Agency administered Department of Defense Information Analysis Center' and supported by American defence contracts. Similar research and development programmes were instituted in the Soviet Union, and produced similar technical compendia, both overtly and covertly military in origin[52].

Only from the 1990s, with the end of the Cold War and the search for new markets, did firms transfer their energies frankly to civilian applications of radiometry.

9.7. A NEW BALANCE: RADIOMETRY AS THE 'SENIOR' SPECIALISM

While having distinct origins from those of both photometry and colorimetry, radiometry began to subsume the other two specialisms as it mushroomed after the war. The sources of this coalescence were threefold:

(1) the general acceptance of visible and invisible radiation as electromagnetic, and analysable by conventional physics in terms of energy and wavelength;
(2) the strong unifying effect of measurement standards and
(3) the existence of an integrating sponsor.

The combination of a cognitive viewpoint with government-directed applications was a common feature of post-war science. Having an affluent sponsor moulded the measurement of light and colour. It promoted the majority of research and applications for two decades, supported the integration of research at disparate companies and institutions and controlled the communication and publication of such research. Strong ties were irresistible. Government sponsorship transcended boundaries: it broke down the occupational boundaries by mixing specialists; removed workplace-related boundaries by encouraging new research environments in well funded private laboratories; promoted novel applications and equally new technological collaborations and lowered technical boundaries by supporting novel solutions.

Thus the story of radiometry between 1930 and 1970 can be summarized as being impelled by military funding and actioned by a plethora of firms in Germany, America, Britain and elsewhere. The post-war subject was based on the theoretical trajectory launched by German wartime studies and the NDRC organizational/funding model. As much as late 19th century photometry and early 20th century colorimetry, radiometry from mid-century was the product of formal organizations acting in a particular social and cultural context.

NOTES

1 The China Lake Naval Ordnance Test Station, used for tests of the US Navy's Sidewinder air-to-air missile, was one of several sites used for post-war radiometric observations. Other important locations were the White Sands Proving Ground in New Mexico, the Redstone Arsenal Complex (US Army) in Alabama and the salt flats of Utah.

2 I will avoid the term 'electromagnetic radiation' (a connection first mooted by James Clerk Maxwell's work), which suggests an anachronistic identification between visible light and invisible radiations that was seldom pressed by non-physicists before the First World War.

3 The close connection between 'pure' and 'applied' physics for combined photometric and radiometric research at the PTR is a national and temporal exception to this occupational separation.

4 More careful atmospheric research later showed the limitations, as for other forms of radiation, caused by absorption and scattering by atmospheric molecules.
5 Jones R V 1961 'Infrared detection in British air defence, 1935–38' *Infr. Phys.* **1** 153–62; Jones R V 1979 *Most Secret War: British Scientific Intelligence 1939–45* (London) especially ch 4.
6 *Ibid.*, p 161.
7 In America, the technique of infrared spectroscopy spread substantially from two centres: the National Bureau of Standards at Washington, DC, and The Johns Hopkins University some 50 miles away. William Coblentz at the NBS had been measuring infrared absorption spectra of materials since the turn of the century. At Johns Hopkins, the research group of Harrison Randall concentrated on developing instrumentation and extending measurements to ever-longer wavelengths. The group also devoted considerable effort to improving methods of detecting radiation. The thermocouples they used were conceptually the same as those used in the previous century. Randall's group developed schemes for discounting the effects of changing temperature (which caused the thermocouple voltage to drift). This perturbation from outside disturbances was the major limitation in measuring infrared intensity. Just as importantly for acceptance of the techniques, Randall's collaborators developed recording spectrometers. These early systems had to be proven to give results as accurate and repeatable as manual measurements. For an account of this crucial American work, see Randall H M 1954 'Infrared spectroscopy at the University of Michigan' *JOSA* **44** 97–103.
8 Jones *op. cit.* note 5, pp 46–50.
9 Stephenson H K and Jones E L with Harrison G R (ed) 1948 'OPTICS: a History of Divisions 16 and 17, NDRC' in *Science in World War II: Applied Physics* (Boston).
10 Leslie S W 1993 *The Cold War and American Science: The Military–Industrial–Academic Complex at MIT and Stanford* (New York).
11 Stephenson *et al op. cit.* note 9.
12 See chapter 6 note 37.
13 Stephenson *et al op. cit.* note 9, p 196.
14 *Ibid.*, p 199.
15 Lovell D J 1971 'Cashman thallous sulfide cell' *Appl. Opt.* **10** 1003–8.
16 Kevles D J 1978 *The Physicists: a History of a Scientific Community in Modern America* (New York). On the NDRC, see pp 297–303.
17 Zachary G P 1999 *Endless Frontier: Vannevar Bush, Engineer of the American Century* (Chicago).
18 Stephenson *et al op. cit.* note 9, pp 232–5.
19 For example H E White at the University of California under NDRC contract developed a portable infrared optical telephone; other projects were carried out at RCA Indianapolis; Baird Associates, Cambridge, Massachusetts; and a Navy speech/communications system was developed at Northwestern University. Lovell *op. cit.* note 15; Stephenson *et al op. cit.* note 9.
20 Stephenson *et al op. cit.* note 9, p 227.
21 Significantly, British research neglected photoconductive detectors. Jones [*op. cit.* note 5, p 160] claims that this was a consequence of long research at a 'Government Establishment' which showed them to have poor sensitivity for hot targets, and because the detectors would have required cooling to be effective.
22 Kutzscher E W 1956 'The physical and technical development of infrared homing devices', in Benecke T and Quicke A W (eds) *History of German Guided Missiles*

Development (Brunswick, Germany) pp 202–17.

23 *Ibid.*, p 201. Acoustic methods relied on detecting aircraft range and direction from the sounds of their engines.

24 For his pre-war work, see Gudden B 1928 *Lichtelektrische Erscheinungen* (Berlin).

25 Kruse P W, McGlauchlin L D and McQuistan R B 1962 *Elements of Infrared Technology: Generation, Transmission and Detection* (New York) pp 6–7.

26 Kutzscher *op. cit.* note 22. This may have been disingenuous, given Kutzscher's post-war employment by an American military contractor with an interest in continued development, and the predominance of Electroacustic's technological solutions in American infrared compedia through the 1960s.

27 Jamieson J A, McFee R H, Plass G N, Grube R H and Richards R G 1963 *Infrared Physics and Engineering* (New York).

28 Stephenson *et al op. cit.* note 9, p 243.

29 Schweber S S 1988 'The mutual embrace of science and the military: ONR and the growth of physics in the United States after World War II', in E Mendelsohn, M R Smith and P Weingart (eds) *Science, Technology and the Military* (Dordrecht) pp 3–45; Sapolsky H M 1990 *Science and the Navy: the History of the Office of Naval Research* (Princeton).

30 Cashman R J 1946 'New photoconductive cells' *JOSA* **36** 356.

31 Bower T 1987 *The Paperclip Conspiracy: the Battle for Spoils and Secrets of Nazi Germany* (London) p 149; Kutzscher *op. cit.* note 22. On the same subject see also Judt M and Ciesla B (eds) 1996 *Technology Transfer Out of Germany After 1945* (Amsterdam).

32 The Metascope was, in fact, a development of an ultraviolet-radiation imaging device developed by university physicists, and not an innovation of wartime research.

33 Stephenson *et al op. cit.* note 9, p 245.

34 Kutzscher *op. cit.* note 22, p 217.

35 Jones *op. cit.* note 5, p 154.

36 Stephenson *et al op. cit.* note 9, p 200.

37 See, for example, Perfect D S 1924 'Some instruments for detecting infrared radiation' *J. Sci. Instr.* **1** 312–29, 353–3. Randall H M 1954 'Infrared spectroscopy at the University of Michigan' *J. Opt. Sci. Am.* **44** 97–103. Palik E D 1977 'History of far-infrared research I. The Rubens era' *J. Opt. Sci. Am.* **67** 857–64; Ginsburg N 1977 'History of far-infrared research II. The grating era, 1925–1960' *J. Opt. Sci. Am.* **67** 865–71.

38 Ballard S S 1951 'Spectrophotometry in the United States', in *Proc. London Conference on Optical Instruments* (London) ch 13; Randall *op. cit.* note 37; Edlen B 1966 'Frontiers in spectroscopy' *JOSA* **56** 1285.

39 See, in particular, Golay M E 1947 'A pneumatic infra-red detector' *RSI* **18** 357; Golay 1949 'The theoretical and practical sensitivity of the pneumatic infra-red detector' *RSI* **20** 816; Hornig D F and O'Keefe B J 1947 'The design of fast thermopiles and the ultimate sensitivity of thermal detectors' *JOSA* **37** 474–82; Jones R C 1947 'The ultimate sensitivity of radiation detectors' *JOSA* **37** 879–90; Fellgett P B 1949 'On the ultimate sensitivity and practical performance of radiation detectors' *JOSA* **39** 970–6; Smith R E, Jones F E and Chasmar R P 1957 *Detection and Measurement of Infrared Radiation* (Oxford).

40 Jamieson *op. cit.* note 27, pp 4–5.

41 *Ibid.*, p 1.

42 Wolfe W L 1965 *Handbook of Military Infrared Technology* (Washington).

43 Gummett P 1988 ‘The government of military R&D in Britain’ in Mendelsohn *et al* *op. cit.* note 29, pp 481–506.
44 Hudson R D Jr and Hudson J W (eds) 1975 *Infrared Detectors* (Stroudsburg).
45 Wolfe *op. cit.* note 42.
46 Schweber *op. cit.* note 29, pp 5, 35–6.
47 Lovell *op. cit.* note 15.
48 Wolfe *op. cit.* note 42, p v.
49 American National Standard Institute 1986 *Nomenclature and Definitions for Illumination Engineering* (ANSI Report); Rea M S (ed) 1993 *The Illumination Engineering Society Lighting Handbook* (New York, 8th edn).
50 Wolfe *op. cit.* note 42. The idea of publishing unclassified information was conceived in 1961, and information was collated between 1962 and 1963.
51 Wolfe W L and Zissis G J (eds) 1978 *The Infrared Handbook* (Washington, DC). The introduction [pp vi–vii] hints at the cultural differences between communities: ‘Nomenclature uniformity was…difficult to obtain. Our first rule, of course, was to define the terms as they are used. The most troublesome technical word was “intensity”. Most astronomers use “intensity” or “specific intensity” as a term referring to the distribution of flux (or radiant power) with respect to area and solid angle. We use “radiance” for this. Workers in the fields of electromagnetic theory often use “intensity” when they refer to the distribution of flux with respect to area alone. We use “irradiance” or “exitance” for this. We use “intensity” only for referring to the distribution of flux with respect to solid angle.’ The ‘we’ behind the revised *Handbook* continued to be American electro-optical technologists supported by US military contracts.
52 For example Kriksunov L Z and Usoltsev I F 1963 *Infrakrasnyye Ustroystva Samonavedeniya Upravlyayemykh Snaryadov [Infrared Equipment for Missile Homing]* (Moscow); Margolin I A and Rumyanstev N P 1957 *Fundamentals of Infrared Technology* (Moscow, 2nd edn); Bramson M A 1968 *Infrared Radiation: A Handbook for Applications*, transl. by B Rodman (Plenum). The latter two texts are devoid of any mention of military applications.