THE POWER AND THE GLORY

CONTROVERSIES OF THE TIZARD MISSION, UK AND US CENTIMETRIC RADAR.

Abstract: In the September 1940 Tizard Mission, the British scientist E.G. "Taffy" Bowen took to the USA the British-developed resonant cavity magnetron, described as "the most valuable cargo to reach these shores". But British Government scientists were already at odds over centimetric military radar with Bowen and GEC, the company building Britain's magnetrons, and there were to be serious conflicts both between these scientists and the industrial concerns building centimetric radar, and between researchers in the UK and those in the USA over the development and military use of the magnetron. Where scientists and industrialists worked together, as in Royal Navy and British Army applications, and in many USA projects, or when Allies devoted proper resources to liaison, equipment was produced rapidly; where there was tension or indecision, then delays and inadequate equipment followed. This paper analyses the background to, and the personalities, course and results of, specific exemplar conflicts by reference to original sources, illustrating the tensions between scientific, industrial and military priorities in Britain, the USA and Canada during this intense period of radar development.

The paper illustrates the need when creating an effective military capability, for close and continuing liaison between Allies, and between Government research and manufacturing industry, in addition to that between research and service user – a lesson with echoes down to the present day.

THE POWER AND THE GLORY

The British development of the resonant multi-cavity magnetron (in this paper, simply "magnetron") and its subsequent transfer to the United States by the 1940 Tizard Mission is so drowned in superlatives – "the most valuable cargo ever brought to these shores"[1], "the single most important piece of electronic equipment developed during the course of the war"[2], and so on – that precise assessment of what was actually *achieved*, and why, seems almost secondary to marvel. It is the fact that in practical terms, the sought-for access to US production resources was not always capitalised upon, and scientific co-operation was sometimes limited, or led to dispute rather than benefit. This paper considers the context of the Allied application history of the magnetron and of the Tizard Mission in the context of creating military capabilities, by examination of six lesser-researched controversies:

- Even before the Tizard Mission, *the tension between British Air Ministry scientific researchers and the industrial scientists of the General Electric Company*, from whom the Government scientists wrested control of airborne centimetric research despite GEC's proven microwave achievements and manufacturing expertise ;

- following the Tizard Mission, *the speedy US development of a centimetric air interception (AI) radar as a result of the early involvement of industry, and its rejection by the same British Government researchers* despite good test results, in favour of their own equipment – equipment which would in turn be superseded within two years by further US development of its own rejected proposal. That US radar would remain the Royal Air Force's standard AI for a decade;

- *the British Army's centimetric anti-aircraft radar, initially developed rapidly by close liaison with BTH, then drastically slowed by prioritisation debates, resulting first in the deployment of a less capable Canadian equivalent to combat the German air raids of 1943/4, then in the superlative US SCR 584 being employed to defeat the V-1 cruise missile, both these developments having benefitted from close researcher/ manufacturer co-operation;*

- *The rapid development of Britain's first operational centimetric radar, by the Royal Navy with the close involvement of Allen West Ltd*;

- *Disagreements between US and UK scientists over airborne centimetric blind bombing and navigation radar*, exemplified by a 1942 US attempt to have TRE's 10 cm H2S navigation and bombing radar, H2S, cancelled as worthless, and a subsequent proposal to replace it with American 3 cm H2X;

- *Disagreement between UK scientists and operational commanders over the application of centimetric technology*, resulting in a 1944 attempt by those scientists to unseat the RAF's Commander-in-Chief, Bomber Command.

The paper concludes that the Air Ministry model of close co-operation with the fighting service, but a more distanced relationship with industry and with Allies, led to the delayed achievement of military capability contrasted with the closer industrial co-operation by the Royal Navy and British Army scientists (the latter being adversely affected by a mistaken prioritisation decision), and by US and Canadian researchers.

British Centimetric Radar before the Magnetron and the Tizard Mission.

Three nations took part in the Second World War exploitation for military purposes of a February 1940 magnetron development in Birmingham, UK. These were Great Britain itself, the United States of America, and Canada. Alone of those nations, Britain in 1940 faced an aerial onslaught from the German Air Force, the *Luftwaffe*. Britain's air defence capability hinged on the sensor of air defence radar both for early warning and for fighter control, for Britain possessed the world's first radar-based integrated air defence system[3].

By day, Britain's metric-wavelength Chain Home early warning radar could locate *Luftwaffe* bombers over 100 miles distant, and direct Royal Air Force (RAF) fighters to within 4 miles of their position[4]. 4 miles is an easy distance for the human eye to see on a clear day, and fortunately for Britain, the 1940 summer weather was bright and clear. That summer's aerial Battle of Britain was hard-fought, but in autumn 1940 the Luftwaffe left the sky to the RAF by day, and continued their attack in the lengthening winter nights.

By night, the unaided human eye cannot see 4 miles. Due to the restricted size of aerials which could be carried in night-fighters, Britain's metric air interception (AI) radar was effectively limited in range to the height of the fighter above the ground, some 10,000 to 15,000 feet (2-3 miles)[5].

This left a gap, to which there were two practical solutions:

- place a radar intermediate between the Chain Home early warning, and air interception (AI) radar; this was Ground Control of Interception, GCI, radar, which guided the night-fighter close enough to its target to switch on its AI with a good chance of acquiring the target; ***OR***

- use shorter wavelength, *centimetric* radar, to generate a focussed beam, unaffected by ground returns, with a range of 4-miles or longer; Chain Home might then be then precise enough to guide the night-fighter, as indeed was the hope of its originator and the head of British pre-war radar, Robert Watson Watt.

After January 1940, the need for the development of Ground Control of Interception (GCI) radar, intermediate between Chain Home and AI, was championed by W.B. "Ben" Lewis[6], the incoming Deputy Superintendent of the British Air Ministry radar research centre, shortly to be titled the Telecommunications Research Establishment (TRE). This system did not enter service until November of that year, and was not truly effective until the spring of 1941; it was coupled in operation with an AI developed by Electrical and Musical Industries' (EMI's) world-class circuit genius, Alan Blumlein[7].

The alternative strategy, to research radar on centimetric wavelengths, was championed by Watson Watt and his pre-war AI team leader Edward "Taffy" Bowen. In summer 1939, Bowen had discussed the need for compact, high-power, centimetric-wavelength valves with Charles Horton of the British Royal Navy's Signals School[8], since both ships and aircraft were constrained for space for aerials, to which the use of centimetric wavelengths was one answer. The Navy had then sponsored research at Birmingham University which led to the Randall and Boot development of the British resonant cavity magnetron in February 1940[9]. Before the war, the General Electric Company (GEC) had already developed a split-anode magnetron-based communications radio for the Royal Navy[10]. Following discussions between GEC's Director of Research, Sir Clifford Paterson, and Sir Henry Tizard, then Scientific Adviser to the Chief of the Air Staff, a project had been allocated to GEC to develop a 25cm AI radar[11] at GEC's Wembley research laboratories, which were well furnished with test equipment and skilled engineers to take up this challenge. The hope was for a power of 1kW and a 5-10 mile range, which would in turn allow Chain Home adequately to position a night fighter. With Bowen acting as the Air Ministry liaison[12], GEC had concentrated on the use of the E1130 "millimicropup" valve, and on 14 March 1940 had successfully demonstrated a 25cm AI on the ground[13]. That success stimulated the Air Ministry to award a contract on 3 May to GEC for a 10cm (S-Band) AI, "AIS"[14]; in early June, GEC's 25cm set, incorporating crystal mixers, achieved ranges of 6 miles on ground targets[15]. The work of GEC had the extra merit that, as its team were used to production engineering, its equipment was being produced with blueprints ready for mass production[16]. At this time, the magnetron was not used because, until the very end of this period, it had been a massive piece of laboratory equipment, its reduction in size to a volume easily capable of fitting into an aircraft being achieved only by July - by that same GEC laboratory.

However, Bowen's wish to pursue centimetric research had broken up his own team, for his deputy, Gerald Touch, thought it essential under the pressures of the war to prioritise making metric radar operational[17], and devoted himself to this. The remainder of Bowen's small, overloaded and frequently relocated team did no major centimetric research before May 1940[18], when RAF radar research moved to Worth Matravers, Swanage. Bowen had also clashed with the head of the Government researchers, A.P. Rowe, who had received an instruction to begin centimetric research[19], and who, apparently without advising Bowen or GEC, appointed the university scientist Herbert Skinner as its head[20]; Bowen was left sidelined. In May, Skinner was joined by the energetic and disputatious Philip Dee[21], who wished to focus on centimetric research. From a previously unpublished series of file notes[22], it is apparent that Rowe had been following centimetric developments with more than passing interest, and at Rowe's bidding, from 12 June to mid-July Dee ran a series of tests to confirm that ground reflections would not be a problem at 10cm[23].

Satisfied that centimetric research had a future, on 16 July Rowe wrote a "Secret and Personal" letter[24] to GEC's Director of Research, Clifford Paterson, from which it is worth quoting at length (*italics mine*):

> "I want ... to tell you what I feel about the A.I.S. situation and to appeal to you once again for help, which I feel sure will be forthcoming. It remains true that the A.I. problem is about the most important work in the country. ... The limitations of the present A.I. are well-known to you, and *we have awaited some favourable discontinuity in technical progress to start an intensive effort on A.I.S., using 10cm or less. This discontinuity is now being produced by you in the form of several kW from sealed off magnetrons operating at about 10cms.* My personal view is that we must stop at nothing to push on with this work, and I have asked that it be given high priority here.
>
> 2. In this connection you can once again be of the very greatest help to us. It has become of the very greatest urgency for us to have samples of the new magnetrons for the short-wave developments here and I am wondering how we can most quickly obtain the development of specimen tubes to this establishment. ....
>
> 3. As you know, I have no authority whatever to ask you to spend money on behalf of the Air Ministry..... I am appealing to you personally simply because I am fearful of the delays involved in going through the normal channels, but having stated our desperate need, I am leaving it to you to decide how far you can help us. I may be going outside the limits of even your goodwill, but I most earnestly hope that this is not so. "

This letter is breath-taking. Rowe is advising Paterson that Rowe's small group of scientists, with neither test facilities nor expertise, had simply been awaiting an excuse to take over centimetric AI research, even though GEC had extensive laboratory and production facilities and a track record in military centimetrics, and though Paterson had demonstrated a working and production engineered AI; that GEC had provided that excuse by their work on packaging the magnetron, so that it could now be used in AI; and that since Rowe had no magnetrons, would GEC please send some urgently, at their own cost, so that Rowe's scientists could carry out the research thus taken over.

Paterson's reply of 18 July has, interestingly, been taken out of the file[25]. What remains is a 21 July file comment by Rowe[26] that "...we are up against a basic difficulty. Dr Paterson thinks he is developing the whole of 10cm AI whereas we feel firms should be doing specific parts. All this has been said to the Air Ministry and we are waiting for a reply. Our reply to Dr Paterson will therefore need to be rather non-committal".

In fact, Rowe's firm stand, that his people were to have charge of all centimetric developments and that GEC had to pass its work across to them, had already been confirmed by a directive of 19 July. Professor Burns, in an excellent paper which deserves to be better-known, has well summarised GEC feelings[27] in their subsequent series of meetings with Dee and Skinner; from Paterson's perspective, TRE had no radio engineering knowledge, no test equipment, no expertise, no team-working capability nor any articulate idea on the subject. Paterson viewed Dee as "seriously intolerant and entirely satisfied with his own ideas, which are often narrow and unsound", while Skinner, Paterson felt, "has no conscience in appropriating credit to himself and Swanage which should go to Wembley", so that in summary "I hope Rowe will manage to keep his wild men from doing too much harm" and "our academic ridden radio effort is poisoned with intrigue, jealousy and uncharitableness. Industrial and commercial life seems clean in comparison..... Truly the Professor type needs to learn how to give honour where honour is due". These quotations are some of many which cover a period of months, and which illustrate the depth of ill-feeling created between Government researcher and industrial manufacturer

It will be recalled that at this time Bowen, until April the head of British AI research and the liaison with GEC, had been sidelined, and Tizard's insistence on Bowen travelling to the USA as a member of the Tizard Mission probably came as some relief to all parties. During the period that Bowen was unfolding the secrets of the magnetron in America, GEC carried on its work on AI, in particular on a common transmit and receive antenna system. But the effect of the two groups competing against one another throughout July and August was negative – the urgent research seemed now to be slowing down; Burns reports[28] F S Barton, a Farnborough scientist, commenting that the "new arrangement seemed to have the only effect of slowing Wembley down to the pace of Swanage", while Batt[29] recounts the depression of the Government scientists after seeing how advanced the work of GEC was, and their elation when their own ideas showed results.

The parties were brought together on 3 September in a "Committee on 10 cm wave AI"[30], with Dr Walmsley of the Ministry of Aircraft Production (MAP) as chair – MAP were now the Government body allocating contracts for the RAF, as well as running research. This Committee included EMI, the Birmingham researchers, and RAF Fighter Command in addition to GEC and TRE. At the first meeting[31], GEC emphasised that their equipments were "drawn up and blueprinted", while Dee argued that Swanage should "formulate the technical character of the complete AI system". GEC roundly replied that Swanage had "only recently been in the position to make any real contribution towards the solution of the AI centimetric problem". Walmsley, as Chairman, pointed out that supervision and control was in his Ministry's hands, and in the meeting of 28 September[32] reported that Paterson had agreed not to press the point, but "would like the idea of reciprocity to obtain as far as possible". An interesting point is that Walmsley inquired why it was necessary for Swanage to build copies of GEC-designed equipment[33], as GEC could presumably provide these more easily; Swanage would in time go on to set up an entire Research Prototype Unit (RPU)[34], despite having no background in the production engineering techniques required. This Unit from its inception was often misleadingly titled the Rapid Production Unit or Radar Production Unit, and used, as Rowe tries to defend, for volume production.

Rowe hammered home his view. A file note of 16 October[35] to Lewis, his deputy,, referring to Walmsley's Committee, says that " the minutes ... give me no evidence that we are running the 10cm AIS. The arrangement promised ... whereby Dr Dee (and presumably his deputy) should give instructions to GEC and EMI does not seem to be working. ... I would like you to tell me whether we should again go into battle on this subject". At this time, Rowe was facing a strong user challenge. Air Marshal Joubert, Assistant Chief of Air Staff for radar, visited Swanage on 16 September[36] to emphasise that metric AI, now improved by EMI's Blumlein and with GCI radar now being built, was all that was needed. Dowding, Commander-in-Chief of Fighter Command, reinforced the point powerfully to TRE two days later[37]. Joubert, as we shall see below, recommended TRE to focus centimetric radar on anti-aircraft gunnery[38], and Walmsley, in opening the meeting to which Rowe refers, mentioned GL as a likely application[39]. By the time of his October note, Rowe was engaged in trying to take over all Army centimetric anti-aircraft gunnery research[40], whose head, Cockroft, was out of the country as part of the Tizard Mission. Lewis replied that "Dee had now returned (from sick leave with pneumonia) and will soon be resuming his authority in the matter"[41]. The draft minutes of the meeting of the 26 November meeting are very heavily amended by Dee[42], and are indicative of a difficult working relationship; the vast majority of actions are laid upon GEC.

As we shall see below, parallel developments were subsequently carried out on centimetric AI by GEC; by Swanage; and by the Americans, using the knowledge gained from the Tizard mission. Here it is sufficient briefly to record the facts that GEC continued to work more or less unhappily with TRE, providing the silicon for the AI system's receiver crystal mixers in September[43]; the helical scanner in December; flight trials in February 1941; and refining and improving their offering until the winter of that year. It is sufficient here to point out that the way in which Rowe's scientists had gained control of centimetric research had led to poor relationships with GEC and a slowing of the work; it will be seen below that this would develop into something of a pattern.

We turn now to consider the Tizard Mission itself, in terms of the immediate practical development of an Air Interception (AI) radar parallel to the UK developments discussed.

The Tizard Mission and US Centimetric Air Interception (AI) Radar.

The Tizard Mission itself is an oft-told tale, most comprehensively by Professor Zimmerman[44], but most relevantly for the present paper also as personal reminiscence by "Taffy" Bowen[45], then the UK's prime researcher on AI radar and specifically the earliest military researcher who had foreseen the need for, and advantages of, centimetric radar.

The original aim of the British in mounting a mission to the USA to interchange military/ scientific information had been to secure specific items of technology – in particular, the Norden bombsight[46], perceived, pre-war and early-war, as the key to accurate day bombing. As the US refused to discuss this, and as the British also were inhibited in what they revealed for fear of "leakage" to the Germans, early missions such as that of A V Hill[47] did not achieve their hoped-for results, despite such senior US scientists as Ernest Lawrence having written to Oliphant at Birmingham offering to share US progress on microwaves[48]. But British day bomber losses (ironically a result of German radar) quickly forced the RAF to change to night bombing, so that the Norden bombsight became of far less importance; and the deteriorating situation after the fall of France stimulated much greater

British openness and a change of aim, the desire now being both to avail Britain of the full resources of US electronics production capacity, and to create a favourable climate towards Britain in the US, now seen as a potential military ally. Churchill himself, at this time only at the start of his wartime premiership, fluctuated from day to day on the Mission and its prospects[49]; the antagonism between his personal scientific adviser, Frederick Lindemann (later Lord Cherwell) and Tizard did not aid consistency. This personal antagonism had already led to Tizard resigning his position in the Air Ministry once Churchill, and hence Lindemann, had come to power[50]. At the time of his Mission to the USA, Tizard held no senior Government position.

Within the USA, the National Defence Research Committee (NDRC) was formed in June 1940[51], with membership from Army, Navy, the National Academy of Science, universities, and crucially industry, under the chairmanship of Vannevar Bush. One of its subcommittees, chaired by the millionaire financier and gentleman scientist Alfred Loomis[52], carried out work on microwaves, and specifically on a 10cm klystron-based radar. It was apparent that greater power was needed, and research was focussed on developing the klystron.

During July and August, the British assembled almost the total of their military secrets – the Tizard Mission is remembered primarily for the magnetron and microwave radar, but in fact covered a huge sweep of technologies from atomic energy to sonar – and the relevant papers were packed into a solicitor's deed box, the "black box" of legend. The human details of the Mission – Bowen's hiding the box under his Cumberland hotel bed as the hotel safe was too small; his taxi dash across London with the "black box" of military secrets strapped to the cab roof; his rail journey to Liverpool in a closed compartment with a silent Secret Service protector; the voyage across the Atlantic in the "Duchess of Richmond" liner; the terror when the box almost went astray between Halifax, Canada and Washington - are wonderful tales well told by Bowen[53]. Somewhat forgotten is the fact that he also took GEC's micropup and millimicropup valves[54], no doubt as insurance!

Louis Brown offers an insightful analysis[55] of the groups who met the Tizard Mission in the USA. Broadly, there were three – first, the Army's Signals Corps and Navy's Research Laboratory researchers, who considered that Britain would probably lose the war, and were in any event positive only about Britain's Chain Home Low and Air to Surface Vessel (ASV) radars; second, the US civilian scientists, such as Alfred Loomis, who supported Britain's fight against Nazism, and were impressed by the promise of the magnetron; and third, the US Army Air Corps, who were greatly enamoured of the British operational radars, and wanted some as soon as possible.

The Mission began cautiously, with Tizard arriving first and conducting preliminary high level discussions, including with President Roosevelt[56], both sides talking around what could be revealed and what could not. When the total Mission was assembled for the first time in the USA on 9 September, the British were able to tour the Army Signal Corps and Naval Research laboratories[57], and that of Loomis, building trust. They quickly found that their operational mastery of radar was unique, but that some American hosts were less than impressed with both Chain Home and with the Army GL radar[58]; given the US already possessed the SCR-268 and SCR-270 metric radars, it was less Britain's technology than its operational experience which the Americans appreciated. The exceptions were airborne radar and the magnetron, for neither of which the USA had any counterpart. It had been Tizard's intent to demonstrate both British metric ASV radar and the cavity magnetron; but the ASV did not arrive on time, and its replacement ASV II did not arrive until October[59], so it was fortunate that Bowen had the cavity magnetron. The magnetron itself was merely discussed verbally for almost three weeks; it was physically revealed only on 29 September, when, to quote a US team member[60], "All we could do was sit in admiration and gasp". Arrangements were promptly set in place with Bell's Whippany laboratories for a practical demonstration of the magnetron; and Loomis promised that if it lived up to expectations, a contract for production by Bell Laboratories would immediately follow.

Bowen visited Bell with the magnetron and drawings on 3rd October[61]; tested on the 6th, the magnetron produced 15kW of power at 9.8 cm; X-rays next day[62] revealed, to Bowen's horror, that he had inadvertently been given an 8-cavity magnetron to demonstrate to the USA, but manufacturing drawings for the 6-cavity version, but the crisis of confidence passed and all in the end was well. Loomis, meanwhile, had smoothed the way ahead by his contacts with the US Secretary of State for War, Henry Stimson, and Karl Compton of MIT[63].

The Tizard Mission discussed with their American hosts the tasks most needed by Britain at Loomis' estate, Tuxedo Park, on the weekend of 12/13 October[64], defining these as a 10cm airborne radar (AI being Britain's highest priority); a 10cm anti-aircraft gunnery radar; and a long-range navigation system, which would eventually crystallise as LORAN. Bowen wrote the specification for the AI radar[65]; and the group sketched "on scratch pads and envelopes...the block diagram of a typical system right there, with a modulator, a transmitter incorporating the magnetron, a receiver and indicator and appropriate power supplies". What is of great significance here is that the next morning, Monday at 11am, Loomis held a meeting[66] with prospective manufacturers, demanding tenders within a week and delivered equipment 30 days after that. Bell would provide the magnetron, GE the magnet, RCA modulator/ power supplies/ CRT, and Sperry the paraboloid scanner. By Friday, a progress meeting had Bell, GE and Sperry commitment to delivery in 30 days, and Westinghouse producing a modulator and RCA display tubes in the same time; RCA wanted a little longer for the receivers. Within a month, therefore, a laboratory system would be possible, and would form the basis for rapid development.

In parallel, Loomis, using his position as head of the NDRC Microwaves subcommittee, set in place the steps to create a microwave research laboratory modelled on the British TRE – this would blossom as the famous MIT Radiation Laboratory, "RadLab"[67]. Lee DuBridge was identified as Director by 16th October, and the Laboratory itself, with test facilities on the roof of MIT, was operational within weeks. The university scientists who moved to work there made this truly a powerhouse of centimetric research, with their contribution fully documented and published for the benefit of US industry as the renowned "six-foot shelf" of 28 detailed volumes of microwave technique[68].

The US Army Air Corps assigned a B-18 to air-test the AI equipment, and the first flight took place on 10 March 1941[69]. Aircraft, surface vessel and submarine targets were successfully plotted on 27 March, and on 29 April a demonstration flight in the B-18 was given to Air Chief Marshal "Stuffy" Dowding[70]. He was sufficiently impressed by this that the British Ministry of Aircraft Production placed an order with Western Electric for the delivery of an immediate 10 and a subsequent 200 of an engineered version of this set.

The subsequent history of this order is revealing. Bowen quotes[71] the “great pressure on getting a working model over to Britain at an early date”, and describes an improved version installed in a Boeing 247D (loaned by the Canadian Government) urgently shipped to the UK in June, to be joined there by Bowen himself for a series of test flights at the RAF’s Fighter Interception Unit (FIU), just ten months after the Tizard Mission had left Liverpool in August 1940.

The US equipment performed extremely well, but the reception it received was underwhelming. “The TRE group”, Bowen comments[72], “were lukewarm about the whole thing”, and the RAF night fighter crews – who had, it will be remembered, just finished dealing with the Blitz, where their metric AI Mk IV linked with ground GCI had finally started to perform well - were “light-hearted; FIU tested (the US equipment) extensively (and was) full of approval, but I could not detect an urgent demand for production”. By contrast, RAF and Ministry of Aircraft Production top levels had a reaction that “could not have been better”, for these commanders saw that the RAF already depended heavily on US equipment; while at the technical level, TRE’s Skinner showed by tests that the US transmitter outshone the British, though the British receivers performed better. The order for 200 American sets, the SCR-520, was eventually cancelled in 1942[73], on the grounds of its excessive bulk, weight and power consumption. In the US, the SCR 520 was modified to ASV use, and over 2,000 would be delivered during the war.

It is important here to observe that the TRE team, with the exception of Skinner, seem to have reacted in a manner consistent with their treatment of GEC; a potential compromise for the speediest production of a powerful AI might have been for the US to manufacture the transmitter and the UK the receiver, but this did not happen. We now examine what historically took place.

In parallel with the American SCR-520 development, the TRE team under Dee and Skinner, had continued to develop British AI. The first flight of their “AIS 1” (later to be titled AI Mk VII) took place on 10 March 1941[74], coincidentally the same date as the US equipment’s first flight, and 70 flights followed over the next five months; the design was based around a magnetron/ reflex klystron/ silicon crystal mixer/ helical scanner configuration. GEC, already of course fully if ill-temperedly involved, would be the prime contractor on the electronics. A modest number only were built, the intention being that AI Mk VIII – the Mk VII enhanced with radar beacon and IFF facilities – would quickly become the production version[75]. The first 500 Mk VIIIs would be hand-built by GEC; then the plan was for the Stage 2 batch of 1,000, incorporating a higher-powered magnetron, to be manufactured by E.K. Cole (Ekco), for “GEC were still smarting over the 25cm equipment”[76].

The problems that this introduced were twofold[77] – first, a rivalry immediately broke out between GEC and E K Cole over engineering standards, for each wished to build to its own while the RAF naturally wanted a common equipment; and second, E K Cole itself was in the middle of a move to rural Malmesbury[78], where no skilled workforce existed, and the consequence was a predictable multitude of faults. The first GEC sets arrived in July 1942, and after flying trials in August, scored their first kill in January 1943; the production E K Cole sets began to arrive only in May 1943, with a first kill in September. It is difficult to say other than that, had relationships with GEC been handled more sympathetically, the problems of the involvement of Ekco might have been avoided.

By contrast, in the USA during this same period, Western Electric worked to miniaturise the SCR-520 into a "small package" variant, the SCR-720[80], whose success in displacing its British counterpart is now detailed. In November 1942, the RAF stated a formal requirement for an AI with a 10 mile range and an automatic follow facility[81]; this, christened the AI Mk IX, had already been the subject of extensive research. On 23 December, 1942, the AI IX prototype with Downing, then head of UK AI research, was shot down into the North Sea[82] on an air test in a tragic case of mistaken identity. The first American SCR-720, received just before that accident, was installed in a Wellington for tests, and in early January 1943 immediately displayed good anti-Window (chaff) performance, and an improved range[83]; this the British AI VIII – *whose production sets E K Cole were still some months from delivering* - could not match. Subsequent trials from January to April in a Mosquito were "highly successful" and in June Western Electric were confirmed in an order for 2,900 sets, 250 being needed by the year-end, the aim being to refit the whole of the British installed AI VIIIs[84]. This speed of production meant that modifications desired by TRE could not be incorporated during manufacture, and had to be retro-fitted in the UK. Despite this, the first operational SCR 720s, incorporating those changes, came into service in January 1944, the first "kill" being claimed in February. SCR 720 became the UK's standard AI radar for the next decade[85]. British AI IX research was continued, but on a low priority, and by late 1944 was capable of operating against Window and of blind-firing. However Fighter Command found it to suffer from excessive ground returns, and though 500 had been ordered, it was never of significant operational use in WW2.

The effective demise of British AI development is usually ascribed to the loss of Downing in the tragic case of mistaken identity described above. But as we shall see below, in the development of the H2S centimetric bombing radar, the loss of EMI's world-class circuitry genius Alan Blumlein in an air crash did not halt the development; others took his place and work continued. The British AI IX was an inferior system for the air war now being fought with the use of such counter-measures as Window (Chaff), and better liaison with the USA might have identified that fact at an earlier stage with a consequent economy in resources.

Anti-Aircraft Radar: British and American

The second project upon which the MIT RadLab was working was a 10cm gun-laying radar[86]. Here, the British story is one the rapid development of a design into prototype and manufacturer's studies by close liaison with a contractor, even though a totally inexperienced one; but initial wrangles over where the research should be performed, compounded later by inter-service dispute over design priorities and scarce resources, and lack of liaison with allies, compounded by lack of appreciation of production issues almost left Britain unprotected in the field of anti-aircraft gunnery. As will be seen, Britain has cause to be grateful both to Canada and to the USA for their developments during 1940 - 1944.

The British Army War Office at the time of the Tizard Mission already had work in hand on a 50cm gun-laying radar, with a detachment under Oliphant at Birmingham, and a complete experimental set had been produced by July 1940[87]. Nonetheless, on 22 September 1940 Air Chief Marshal Joubert, Assistant Chief of Air Staff (Radio), presumably knowing nothing of Army work, visited the Air Ministry's Research Establishment at Swanage and ruled that the RAF considered its existing metric AI to be acceptable for air defence, and that the centimetric researchers under Dee and

Skinner should concentrate instead on anti-aircraft gun laying (GL) radar[88]. Dee, head of the Swanage centimetric group, was ill with pneumonia from 11 September to 21 October 1940, and returned to discover that "Rowe was seizing this opportunity to try and filch the GL problem from (the Army research scientists)"[89]. D.M. Robinson, the luckless scientist placed in charge by Rowe, managed to get a set of equipment together by 6 November together, but challenge of producing a working GL set in the timescales he had been given were too great[90].

During that month, the War Office/ Ministry of Supply revised the GL specification to concentrate on the 10cm magnetron and reflex klystron combination, and by January 1941 a team under the senior Army scientist Pollard, joined by 2 RAF scientists from Swanage, relocated to British Thompson-Houston (BTH) at Rugby[91]. Despite the fact that BTH had no background whatever in this field, by April they demonstrated their ""A" Model 0" centimetric GL radar[92]. Employing a 5kW magnetron and 2 separate dipoles for transmit/ receive, on a searchlight trailer chassis, this received an Army order for just 3 trial models - but an RAF order for 17, with larger parabolae, to be used for accurate height-finding for their metric Ground Control of Interception radar. It should be emphasised that BTH had no experience whatever of radar, microwaves, receivers or pulse modulators, but thanks to working closely with the Army scientists, they had made a superlative effort in this compressed timescale. They followed up with a study for a production engineered "B" model, which they "mocked up" in wood on a single four-wheel trailer, and in June-July, the Army cancelled its "A" model order in favour of that "B" model, of which it now ordered 28 handmade sets and a production run of 900[93], later increased to 1,500 – 500 each from STC, Ferranti/Metropolitan-Vickers, and BTH/Gramophone Company. However, the RAF refused to cancel its "A" model order[94], and by so doing considerably delayed the small design team – never more than 20 Army and 25 BTH and EMI staff – in reaching their final design; it remains only to add that the A model eventually proved useless for RAF purposes.

At this point Lord Cherwell, Churchill's scientist *eminence grise* again enters the history. Early in 1943, the War Cabinet Radio Board was asked to resolve the huge gap foreseen between the 32 million radio valves which could be produced in, or imported by, Britain and the 52.2 million demand for them[95]. Radar sets consumed many valves; Cherwell, who favoured bombing and derided anti-aircraft gunnery, performed his own calculations to show that more German aircraft would be destroyed in German factories by British bombers using centimetric bombing radar than would be shot down over the UK by centimetric radars directing AA guns. He made a general statement to that Board on 15 April, and later that day circulated a paper proposing that all British manufacture of the GL3B centimetric radar should cease[96], and that a promised Canadian centimetric radar, described below, suffice. Students of "Meeting management" may note that Cherwell did not table his paper at that Radio Board meeting, and that, once the Army's barely-contained rejoinder had been circulated, he absented himself from the following meeting where the matter was to be discussed. The debate dragged on for some time, further delaying the production of the British GL3; as Cockroft, then in charge of Army radar research, comments[97], "the programme was constantly in danger of being cancelled or cut, and finally, in the autumn of 1943, it was dramatically reduced by half, the Metro-Vick production being completely cancelled". In fact, a part of the order was transferred to BTH, who eventually made 876.

The Tizard Mission, as is often forgotten, had visited Canada as well as the USA. Relevant to our story, it had devised a specification for a centimetric gunnery radar on which the Canadian National Research Council could work[98]. Unfortunately, little liaison followed between British and Canadian radar scientists over detailed design and development; and the Canadian electronics industry had to be created almost from scratch, with the formation of Research Enterprises Limited (REL) as late as 16 July 1940[99] – there was no experience of large-scale production engineering of complex electronics in that country at the time.

The Canadians, in a magnificent effort, produced through REL their first radar, known as GL3C (C for Canadian), by January of 1942. Primarily for UK use – Britain took 600 of the 670 produced[100] – it was mounted in two trailers, and consisted of a metric Zone Position Indicator (ZPI) radar for target acquisition, and an Accurate Position Finder (APF) radar for gun direction. Regrettably, the first set was provided directly to AA Command, and then moved to the Canadian Army, rather than being assessed and modified by British Army scientists[101], who did not receive one until March 1943. The result was that modifications took longer to specify and incorporate. This was a problem as GL3C's rotating cabin caused a number of injuries to its crews, and breakdowns due to damp resulted from exposed high-voltage wiring and the positioning of the magnetron directly behind the roof-mounted transmitter aerial[102]; GL3C's display, by meters rather than by cathode-ray tube, was also novel to, and perhaps hence disliked by, British operators. Necessary modifications were, in consequence, carried out in parallel by the Canadians and by a British Army "black market modification unit" [103](Cockroft's words), with not a little confusion resulting. Nonetheless, since the British GL3B was not available, for the reasons explained above, the supply of the Canadian GL3C provided London with its AA defence during 1943/4, where, in the words of the Official History, "they contributed materially"[104].

1944 would bring the advent of the V-1 cruise missile, and the need for automatic gun-laying to be combined into the air defence radar. At this point, the USA provided one of its greatest benefits. After the Tizard Mission, the USA had began to work on a 1.5 metre search and a 10cm gun direction radar not unlike the Canadian GL3C system, and had produced the SCR 545[105]. However, its researchers soon moved to the concept of a single trailer containing a centimetric radar which would perform both search and gun-laying functions, automatically laying and training the anti-aircraft guns. To bring the concept to life, Ivan Getting and Lee Davenport built on MIT's expertise in servomechanisms massively to impress the US Army's General Coulton, after a visit prompted by Loomis in May 1941[106]. A formal order was laid on the RadLab, with backup by Bell Laboratories; but when the XT-1 prototype linked to the Bell T-10 director proved exceptionally accurate in drogue shooting on 6 February 1942, a full production order at once followed for 1,256 SCR 584s[107], as the set had been christened. Great engineering difficulties in its production were eventually overcome by Chrysler Corporation[108], with the SCR 584 and the M-9 (formerly T-10) predictor reaching combat zones early in 1944.

The British had indeed already perceived the same need for automatic gun laying, in part to economise on operators; the Army's 1,500 deployed radars used some 90,000 people on this role[109]. By September 1942, automatic tracking was specified as a requirement; but within a month Dr Solomon, the first and only US scientist sent as a liaison with the British Army radar scientists[110], told his British colleagues of the American developments which would lead to the SCR-584. Given that a

US design group over 1,500 strong was working on this[111], as opposed to the British Army's 20 scientists on GL3B, automatic following as an adaptation for Britain's GL3B was plainly likely to take much longer. Enquiries revealed that SCR 584 would become available after June 1943, and one especially ordered on high priority by Cockroft, Deputy Head of the original Tizard Mission, arrived for test in September, yielding very favourable results and an extremely positive reception from AA Command.

By that date, the defects of the Canadian GL3C, and the supply problems of the British GL3B, were apparent, and as a result of prompting from Cockroft, who was visiting the USA with the Watt Mission, an urgent request was placed with the USA in November 1943 for 200 SCR 584s[112]. 135 were delivered in early 1944, and a further 165 loaned to defeat the onslaught of the V-1 cruise missile after May. The Official History records[113] that there is "no question as to the overall superiority of the SCR 584", with its higher maximum range, self-scanning and putting-on; and of course automatic following in bearing and elevation, which the GL3B at this stage did not possess.

The observations to be made in this review of AA radar are, first, that the Air Ministry scientists again attempted to take over centimetric research, this time from the Army who were already working on it, but failed to achieve anything; second, that the small team of Army scientists, working closely with industry (even if, in the case of BTH, with a firm with no background in microwaves) succeeded in producing a prototype in very short order; the design could not then be finalised due to inter-service dispute with the RAF; production was then interfered with by a mistaken decision on priorities; and the situation was saved only by Allied supply, first the GL3C from Canada, then the SCR 584 from the USA, though in both cases liaison with the project teams was minimal and problems resulted. In both Canada and the USA there had been close liaison between research teams and manufacturers in achieving their ambitious targets – especially ambitious for Canada, who had no indigenous electronic industry of significance before this time.

Britain's first operational centimetric radar: Royal Navy Type 271.

It might be thought by this point that the British disputes and dissensions had rendered that nation incapable of producing effective centimetric radar within compressed timescales. This was not so: but in the UK, the first operational deployment of centimetric radar had been by the *Royal Navy*, not the RAF or the Army, and for the most part that achievement did not depend on Rowe's TRE, though its inception certainly took place at Swanage, or more accurately, at Leeson House, Langton Matravers.

This girls' school had been occupied by the TRE centimetric research team, in part because of its good view towards the sea and the Isle of Wight, both useful radar targets. At the end of October 1940, Commander Fawcett and Lt Cdr Bayldon, the first responsible for liaison with the RAF's Coastal Command and both in the Admiralty's Anti-submarine Warfare Division, were given a demonstration of the detection of small ships by an experimental 9cm radar mounted in a trailer[114]. A more senior group of Naval officers quickly followed on 8 November, and further interest was generated by the tracking of a submarine, HMS *Usk*, in front of two of its members on the 11th[115]. A week later, the Admiralty arranged for a group of four scientists (Landale, Cochrane, Croney and Owen[116]) to be attached to Leeson House; they arrived within three days and stayed for a month, working closely with Skinner.

During their first fortnight, the Admiralty party first constructed a microwave installation of their own, "apparatus C", and developed it into a full system, including antenna, inside "the Admiralty trailer"[117]. Range tests were carried out against the 92-ton trials boat *Titlark* from various locations to test performance at low antenna height, equating to mast-head heights; and then, as a palliative to the natural pitch and roll of a warship at sea, A.C.B. (now Professor Sir Bernard) Lovell suggested the use of cylindrical paraboloid "cheese" aerials[118], which would become standard in most small boat installations. These were tested satisfactorily on 19 December, and within days the "Admiralty trailer" departed to Eastney, Portsmouth.

In the Admiralty laboratories at Eastney, 12 sets were to be built as a matter of extreme urgency, and at the end of February 1941 the first was ready for installation, 11 more almost ready, and parts ordered for a further 150[119]. The drawing office of the industrial firm Allen West Ltd of Brighton were fully involved in the design stages of this equipment, christened Type 271X, and were nominated manufacturers of the production run. The first Type 271X was installed on the new corvette HMS *Orchis*, and successfully trialled on 25 March[120]; the design was frozen and Allen West proceeded at full speed onto the manufacture of the 150.

An interesting memorandum from Lewis of TRE to Rowe[121], stimulated by Tizard's suggestion that TRE and the Navy's Signal School should co-operate more, comments that the Navy have fitted "10cm apparatus which is very far from ideal and which it is hoped soon will be obsolete" in a "vigorous programme for fitting corvettes". TRE's AIS, by contrast, has "not yet been able to accept anything but the best"; Tizard was, of course, aware of both US and Naval progress, and seems to have been urging TRE to speed up.

By September 1941, 32 corvettes were fitted with Type 271; a modification to the antenna allowed its fitting in destroyers also, under the designation Type 272. Further development produced a big-ship version, Type 273[122].

But before many vessels had been fitted, the merits of Type 271 for coastal gunnery had been identified, and an experimental set placed at Lydden Spout, Dover. Modified by the Army's radar researchers, it was extremely successful as a coast-watching radar, forming the "K" stations of the Coastal Chain and extending quickly to some 62 sets for coastal battery control[123].

Allen West's order was expanded to 350 sets, and a redesign to optimise Type 271's mechanical engineering was commissioned from Metropolitan Vickers; 1,000 of this production design were ordered late in 1941 and completed before the end of 1942[124].

The facts of significance in this case are first, the smooth and rapid integration of the Royal Navy's research scientists with the equipment manufacturers, Allen West; second, the early fixing of the design; and third, the production of manufacturing drawings at a very early stage. The contrast with the dealings of the TRE scientists with GEC could hardly be more complete.

Navigation and Blind-bombing Radar: British and US experience.

This paper has referred to the lack of liaison between Allies in the case of anti-aircraft gunnery radars, and shown the rejection of Allied-produced equipment in the case of the early American AI radar. Allies cannot, of course, reasonably be expected to agree on everything; but in the case of Navigation and blind-bombing radar, disagreement became on two occasions a disruptive open conflict, whose details we now examine.

In the case of airborne radar, the British radar researchers at TRE had never forgotten that their mission was to aid air attack as well as air defence, and it had provided a metric-wavelength pulse-modulated navigation device, *GEE*, to that end. TRE's development of air interception radar on centimetric wavelengths was, with unacknowledged assistance from GEC, to lead to TRE's *H2S*, an equipment providing the bomber navigator with a crude radar "picture" of the ground beneath the aircraft, in which the differing radar characteristics of urban and rural landscapes yielded brighter and darker patches on the display screen. H2S would also lead to two disputes between US and TRE scientists, to which we now turn.

Lord Cherwell, at a meeting in Swanage on 26 October 1941[125], stated that Bomber Command needed a radar bombing aid, self-contained within the bomber. Dee, who perhaps had already had the idea of testing whether a downward-looking centimetric radar could distinguish town from country, gained GEC's Dr O'Kane's approval to flight-testing the idea, and O'Kane worked on modifying GEC's AI scanner (rejected by TRE) to look downwards[126]; the first tests on 1 November revealed that town/ country distinction was both possible to display, and useful as a bombing and navigational aid. The reward of O'Kane was to be excluded by Rowe, the head of TRE, from succeeding meetings, on the grounds of "security"[127] – a strange rationale, given that O'Kane would be responsible for most of the air-tests of the equipment which resulted!

Within two months, Cherwell had secured Ministerial directives to test further this embryonic device, H2S, and to order 50 sets from EMI (not, it will be noted, GEC). Rowe instructed Bernard (now Professor Sir Bernard) Lovell to take over the project[128], which initially appeared to be a modification of the AI 7 air interception radar for which klystron power would be adequate; there were at this time severe misgivings about use of the magnetron over German territory, for fear of revealing the magnetron to the Germans. In practice, the required modifications turned out to involve a complete redesign; initial results were very poor; and in the middle of the test-flying, the radar researchers were relocated from Swanage to Malvern, and one of the test aircraft crashed, killing EMI's world-class circuit genius Alan Blumlein and other key scientists aboard[129].

Cherwell, however, had already committed Churchill and his Cabinet to a major campaign of dehousing German workers by bombing[130], and Churchill, at a meeting on 3 July 1942, instructed that 200 H2S sets had to be available by October[131], the 50 ordered from EMI plus 150 from TRE's own Research Prototype Unit (RPU) – again, it will be noted, trusting production to a new, untried group rather than to GEC, and extending the concept of "Research Prototype" considerably!

The problems of H2S - which at this initial stage was truly a crude device with many faults, but better than nothing for the bomber crews - were known in the USA, and it appears that experiments were carried out there which convinced Bowen and TRE's single liaison scientist on this project, the same Robinson who had been in charge of TRE's ill-fated GL radar, that even such major conurbations as

Pittsburgh could not be seen on H2S[132]. When one views photographs of the early H2S displays, and considers reports that towns on the navigator's display could appear and disappear at differing heights and ranges, such a view is understandable. This lack of success, coupled with the prevailing fear that the magnetron could be revealed to the Germans from a shot-down aircraft (as in fact happened), stimulated a visit to Dee and Lovell by Isidor Rabi, Associate Director of the Radiation Laboratory, and his determined attempt to have H2S cancelled as "unscientific and unworkable"[133]. Hard words were exchanged, and Lovell writes[134] of "a good deal of antagonism being imposed by American opposition" to H2S. In the event, the British solved the need for more power by clearing the magnetron for flying over Germany, and there was set in place an intensive programme of test-flying to improve results, the brunt of which was of course borne by GEC's O'Kane. By the end of the year, EMI had more than fulfilled its target of 50 H2S sets; the TRE Research Prototype Unit had produced none at all[135], which, given that this venture of a scientific establishment into manufacture had no experience of volume production, is not surprising.

In parallel with this work, the USAAF made its first raid on France on 17 August 1942, and soon began to appreciate the difference between the clear skies of Arizona bombing ranges and operational flying over a cloudy and smoke-hazy Europe. Following the relative success of H2S in RAF Bomber Command in the winter of 1942/3, and consequent demands from USAAF commanders for H2S, TRE was asked by 15 March 1943 to instal H2S in USAAF aircraft in addition to those of Bomber Command[136]. It was by then recognised both US and British researchers that still further improvements in H2S were needed, and that greater definition could be gained by moving from 10cm to 3cm; the TRE team were at this time more than fully loaded with the work requested for both RAF and USAAF. It therefore created further friction when no less a personality than Lee DuBridge, Director of the Radiation Laboratory, visited TRE to propose that the British 10 cm H2S be cancelled and replaced by the American 3cm development, H2X[137]!

This proposal apparently originated in an impressive demonstration given in the USA to Lord Cherwell under highly favourable conditions, and was rejected after urgent lobbying by the TRE scientists. It certainly was not a consequence of US equipment being available – in the US, US Assistant Secretary of War Robert Lovett and his radar adviser David Griggs had stated a requirement for an H2S-clone in March[138], for delivery by September. While RadLab research into 3cm equipment was well advanced and the better discrimination of 3 cm equipment seemed easily within reach, a RadLab crash programme for 20 hand-built sets was called into existence as late as June - none was even begun at the time of DuBridge's visit to TRE in late May/June, and deliveries would reach the UK only in October, and production equipment in February 1944.

For the RAF, the price of UK rejection of US manufacturing capability was that TRE then had to manage the modification of 200 10cm H2S sets to 3cm by Christmas of 1943[139], a goal only partly achieved. The USAAF itself used British H2S for its first blind-bombing raid on 27 September, its own 3cm H2X equipment being first used on 3 November over Wilhelmshaven. In the event, operational trials showed H2S and H2X achieving broadly similar results; neither was as accurate as Oboe or as visual marking. Additionally, Lovell has stated[140] that the eventual success of UK 3cm H2S Mk III essentially depended upon US magnetrons, these being more powerful than the UK equivalent.

The lesson to be drawn from this episode is that of maintaining teams of sufficient size to conduct effective liaison and avoid confrontational disputes. Two people, Bowen and Robinson, each with other duties, were self-evidently numerically inadequate; the Radiation Laboratory's British Branch (BBRL) was essentially a later development with a distinct mission, but TRE at this time numbered over 2,000 and it is difficult to conclude that no more staff could be spared for liaison to avoid misunderstandings in the USA. In this case, TRE's persistence in its chosen path was a correct decision, the US early proposal for cancellation being based on an assumed clear sky over Europe, and the later proposal to replace all British blind bombing radar with an as yet unbuilt 3cm platform being non-credible until the platform was constructed. TRE's assessment of its own powers was not, however, always accurate; we now examine the poor early operational results of the 3cm H2S Mk III and its surprising consequence – the "Revolt of the Scientists".

Centimetric Scientists against Air Marshals.

Of the 53,000 sorties by Bomber Command in 1943, 66% were led by 10cm H2S Mk II, 33% by Oboe. From late December 1943, 3cm H2S Mk III, from whose improved definition much was expected, began to be delivered, but results were ineffective in terms of damage done. The TRE scientists were sceptical of the operational use of this 3cm equipment by Bomber Command's Pathfinder Force, who marked the target so that the Main Force could bomb more accurately; a preliminary investigation showed that, instead of being used by selected experienced crews to deliver improved results, the 3cm sets were being used as wastage replacements, spread indiscriminately throughout the Pathfinders[141]. A suggestion that they be used to refine blind bombing was therefore made to Harris, the Head of Bomber Command.

Harris, then fighting the Berlin bombing campaign with heavy losses each night, was not known as a commander marked by restraint. His response began "Tell TRE to mind its own ruddy business..." and described the scientists as "pimply prima donnas struggling to get into the limelight"[142]. Lovell "had never seen Rowe so angry", and the scientists began a campaign "to get rid of Harris". It is worth pausing to compare the position and power of radar scientists across the combatant nations at this point; even the idea of scientists campaigning to "get rid of Goering", or one of Stalin's Marshals, or for that matter of "Hap" Arnold or "Tooey" Spaatz, two key US air Generals, is so outlandish as to be inconceivable. The fact that there was such a campaign in Britain is an interesting reflection of the value the TRE scientists thought they had to the prosecution of the war, and of their view of their lobbying power.

To the 22nd April meeting convened to hear their case – and again, compare how unlikely it was that such a meeting would have even been convened on those grounds in any other nation in 1944 – came the Deputy Chief of the Air Staff and a bevy of senior officers; Harris, however, simply sent his emollient deputy, Saundby, to pour oil on troubled water, and Rowe departed disconsolate that the "revolt of the scientists" had not achieved the departure of Harris[143]. Unknown to the scientists, in terms of the politics of Bomber Command, the meeting in fact ***helped*** Harris considerably. Its practical outcome was that two bomber squadrons were transferred from the Pathfinder Force[144], a body which Harris had been forced against his will to set up, and given to one of the regular bomber groups – a move which Harris favoured!

It might reasonably be concluded from this episode that the scientists of TRE, perhaps as a result of their earlier successes in centralising almost all British centimetric research under themselves, first from GEC, then from the Army, then expanding this position to begin to establish their own production facilities, then (as they saw it) fighting off unwelcome American initiatives, had developed a view of their importance and position in the war which had begun to be at odds with the reality of how the war was conducted. It is a revealing insight into their psychology.

Conclusions.

A famous "Sunday Soviet" picture of TRE, designed to portray the closeness of its scientists to Cabinet Ministers, Royal Air Force users and staffs, well achieves that aim. But at the same time, it shows not a single manufacturer. It would be difficult to imagine a similar photograph in the USA which did not include an industrial firm; and it is not possible to plead that British industry had no staff equal to the university academics of TRE – Cossor's Laurie Bedford, MetroVick's Jock Dodd, EMI's Alan Blumlein, and – moving to the magnetron itself – GEC's John Sayers are of at least equal standing.

This paper has identified that TRE first established, then maintained, an iron grip on research in UK centimetric radar, sidelining Bowen and GEC's earlier work in producing a production-engineered centimetric AI system. The ill-feeling resulting did little to help produce AI radar in the shortest time possible, and was a factor in resolving a sub-optimal path of building later British AI radar, splitting GEC's work with a contractor, Ekco, who had moved to a new location with an inexperienced workforce.

The Tizard Mission allows a contrast with American methods, where industry was called in at the very start. Their speedily-produced AI system was tested in the UK, with good results, but not proceeded with in favour of British developments which then proved late and requiring high maintenance. Further American development of their earlier radar led to the SCR-720 AI, which displaced the British centimetric AIs and remained standard for years after WW2.

The Royal Navy's close relationship with Allen West Ltd allowed it to get Type 271 into service within weeks**,** early in 1941; this type then modified quickly into larger-ship and coast-defence variants. After a failed attempt by TRE to control Army centimetric research, the Army scientists' close working with the inexperienced contractor BTH resulted in a rapid prototype and a design for a production version delayed only by RAF intransigence over design and later by a mistaken decision by Cherwell over priorities. Cherwell wished to cancel the British AA radar GL3B to make parts available for more RAF bombing radars; the result was that the *Canadian* GL3C defended London during 1943/4 and the *US* SCR-584 saved Britain at the time of the V-1 cruise missile campaign. Both the GL3C and the SCR 584 were the result of close co-operation between scientist and manufacturer.

Less than adequate resources were devoted to inter-Allied liaison at the time of centimetric developments. Partly in consequence, the Americans tried to stop TRE's 10 cm navigation and blind-bombing radar H2S; later, having learned its value, they conceived a 3cm variant, H2X, and sought to secure cancellation of the British variant before the USA model had even been constructed. One reason for lack of such resources may have been that TRE, perhaps in consequence of difficulties resulting from its distancing from manufacturers, had by the middle of the war had extended its activities into operating its own rapid manufacture plant, which in the absence of staff of production engineering backgrounds, proved a significant headache.

The British Air Ministry model, of scientists closely co-operating with the military user but rather less with the manufacturers, has been shown in this paper to have the dangers of delaying to achieve a military capability as contrasted with British Naval, US and Canadian models where early involvement of manufacturers brought rapid results. This finding has considerable implications for the relative roles and functions of Government research and of defence contractors today.

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