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From Science to Overmatch: A Case Study of the Ballistic Research Laboratory Prior to and during World War 2

by Alexander Kott

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14. ABSTRACT

This report explores the extant literature regarding the history of the Ballistic Research Laboratory (BRL) prior to and during World War 2 (WW2) for the purposes of 1) identifying examples of research that contributed to recognized overmatch over the adversary, documented in an unambiguous, objective fashion, and 2) identifying related potential lessons learned for defense science and technology (S&T) organizations. The report identifies several important contributions of BRL's scientific endeavors into WW2-era overmatch; highlights the need for systematic, longitudinal studies and documentation of science's contribution to military capabilities; and notes that organizational climate and recognition of an S&T organization's contributions are challenges that require continuous efforts to overcome.

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1. Introduction

The purpose of the US Army Combat Capabilities Development Command Army Research Laboratory is "to create and exploit scientific knowledge for transformational overmatch" (CCDC ARL 2020). Here, transformational overmatch is best explained as military capabilities (enabled in part by creating and exploiting scientific knowledge) that exceed the relevant capabilities of the adversary by a significant margin, so much so that the US Army is afforded options in pursuing innovative, transformative ways of warfighting.

About 2 years ago, while preparing for a public talk, I decided to find a few inspiring examples where the Army scientists created and/or exploited scientific knowledge such that it resulted in transformational overmatch. I reasoned that the best source of such examples would be the history of the Ballistic Research Laboratory (BRL), particularly its contributions to World War 2 (WW2).

Indeed, BRL is a notable ancestor of the DEVCOM Army Research Laboratory (among several other laboratories). By mid-1990s, when DEVCOM ARL was formed by merging several preexisting laboratories, BRL was probably the largest, oldest, and most accomplished of those labs. And WW2 is an appropriate historical period in which to seek an inspirational example: it was the most destructive and fearsome conflict in the history of the humankind, the only major conflict of the last 100 years where the United States fought a peer adversary, and the noble victory of the Greatest Generation of the United States of America.

With all this in mind, I decided to perform a study of the available literature, seeking BRL's scientific efforts toward notable overmatch manifested during WW2. For the purposes of the study, I focused on only one organization—BRL—for reasons stated previously. I also focused my study only on a particular historical period—from the mid-1930s to the end of WW2—also for reasons stated earlier. For sources, I started with two publications that were specifically intended to document the history of BRL (BRL 1995), as well as its parent organization, the Ordnance Department (Green 1955). I augmented these key sources with other literature where relevant information was likely to be found; see Section 5. Needless to say, I limited the sources to public-domain information. Although this approach may overlook some of important contributions to overmatch, I do not see evidence that the missing part (if any) is so large so as to change my findings and conclusions.

The purpose of the study was two-fold. The first one was to identify examples of BRL's scientific endeavors and accomplishments leading to overmatch during WW2. In each case, I made sure not to take claims of such accomplishments uncritically. I asked myself, "Do we have objective, tangible support to the claim and does it really represent a contribution of science to an acknowledged military overmatch in WW2?" In particular, even if a certain research effort was described in BRL technical reports, I sought separate documented evidence that the results of that research actually contributed to an overmatch. The second one was to seek insights and lessons learned that could potentially inform future endeavors of such military science and technology (S&T) organizations.

While some of my findings are inspiring and encouraging, others are not entirely comforting. I do believe, however, that they deserve to be discussed openly and truthfully. Frank examination of past challenges helps us to deal with such challenges in the future.

This report is the summary of my findings and conclusions from the study. The rest of this report is organized as follows. In Section 2, I discuss arguments for and against choosing a different time period and a different approach to such a study. In Section 3, I review multiple accomplishments of BRL that could have been and, in many cases, actually were indispensable contributions to military capabilities, including overmatching capabilities of the US military during WW2. This is followed by observations and conclusions in Section 4.

2. Alternative Approaches

Granted, I could have chosen a different time period and a different methodological approach. For example, it can be argued that the WW2 period was unrepresentative and perhaps a study anchored at that period may project a misleading picture of the value of S&T to a war effort.

First, at the beginning of WW2, BRL was a rather small organization and its capacity for research was inevitably resource constrained. Then, with the start of WW2, BRL was dramatically expanded in the chaos of wartime transformation. From a total personnel count of 65 in 1940, BRL grew explosively to about 730 people at its peak in 1945. Clearly, this introduced inevitable organizational and management challenges, some of which we discuss later. Second, WW2 was a long time ago. Today, we cannot interview someone who actually worked at BRL during WW2. As such, we must rely on documentation, which might make BRL's contributions to the wartime effort rather opaque.

In comparison, one might argue that the period of the Cold War would be a better time period to consider. During the Cold War, BRL was already a well-established organization with a stable and mature S&T culture and resources. In addition, we could glean important insights from interviewing the BRL alumni who worked there during the Cold War.

I respectfully disagree with the first argument. The size of BRL in 1940 was the size that the nation and its military leadership considered acceptable, given the fiscal constraints. Such constraints are always present and no useful lesson of S&T history can be ever learned if we restrict ourselves to those very uncommon (if ever found) times when S&T expenditures are unlimited.

The dramatic growth of BRL during wartime was undoubtedly disruptive, but that is precisely the kind of time and circumstances when a military S&T organization is most needed and must rise to the occasion. Such disruptive events are precisely those from which we can learn the most important lessons. In fact, BRL did pass this harsh test in WW2, as shown by its numerous accomplishments and contributions.

Regarding the second argument that the WW2 time period is too distant and has left us with too few documents, I disagree as well. In general, the WW2 period is one of the best-documented periods in history, especially in terms of the history of military technology. In particular, we have voluminous documentation—published and preserved reports—of research conducted at BRL prior to and during WW2.

On the other hand, as I show in this report, we do lack a different kind of documentation—documented study of tangible links and transitions between research and actual weapon systems. This is a major finding of this report: Research institutions—such as BRL in its time and DEVCOM ARL today—must (and currently do not) conduct systematic, long-term, longitudinal studies of the impact their research had over time and of specific paths of evolution that lead from science to practical impact.

Regarding the Cold War period, it is important to mention Project Hindsight (Chait et al. 2007), an excellent study of the development of technologies and major weapons systems (roughly in 1970–2000) in terms of Critical Technology Events (CTEs). CTEs were advances—a total of 135 were identified in the studies—that were vital to the capabilities with which a system was ultimately endowed. Identification of CTEs relied on extensive interviews with scientists, engineers, and managers who were directly involved with the developments. CTEs occurred in multiple organizations, government laboratories, industrial corporations, and others. In particular, Army S&T organizations were shown to contribute extensively. Appendix A presents a few excerpts from the Project Hindsight report to illustrate some of the post-WW2 accomplishments of BRL once it became a mature, well-established organization.

My focus here is different, however. I do not mean to compete with well-funded, multi-year projects like Hindsight and Hindsight Revisited, which explored essentially the entirety of the United States' S&T complex. I focused on one organization and believe we can learn plenty from that one organization.

Furthermore, I emphasize the concept of overmatch. The Hindsight series of projects did not address whether or not the technology families they explored led to actual, proven overmatch. There is an obvious reason for that: WW2 tested the US military-technological overmatch in the most brutal, violent manner, in large-scale combat against a peer competitor. Nothing like that, thankfully, occurred during the Cold War. Endless studies will continue to wonder and debate forever what would have happened if NATO had gone to full-scale war against the Soviets. In that sense, the WW2 period presents us with uniquely clear—and terrible in its cost in blood—evidence of overmatch, or lack thereof. It was a unique moment in history, and we should hope it will remain such.

3. Accomplishments

3.1 Broad Range of Outstanding Basic Research Accomplishments

The history of BRL in 1930s and during the war years of 1940–1945 describes a large number of important research efforts and results. These included new projectile drag functions, a theory of recoil forces, characterization of explosive fragmentation phenomena, tools like the supersonic wind tunnel and spark photography, early computers like the Bush differential analyzer, insights into the mechanisms of chuffing and hangfires, foundational results for composite propellants, the study of chemical erosion, a theory of movement of powder gases, the role of the Magnus force, a theory of finned projectiles, a theory of shock waves, characterization of blast waves, a theory of shaped charges, and formulas for target penetration depth (BRL 1995, p. 18–50).

While these were undoubtedly valuable research results, we do not have evidence that they contributed directly to overmatch during WW2. Indeed, the official history of BRL (BRL 1995) is careful to make no such claims. Granted, basic research results, with relatively few exceptions, take significant time, often on the order of decades, to produce downstream contributions to military capabilities. Therefore, it should not be surprising that basic research performed by BRL in the period covered by this study did not manifest itself directly in military overmatch during WW2.

On the other hand, one has to wonder whether a more careful analysis might reveal that basic research did contribute to BRL competencies and skills that in turn helped produce WW2-era contributions to overmatch. Unfortunately, we do not find such an analysis offered in the available literature. Instead, in order to describe "…the Laboratory's contributions to victory over Germany and Japan," the authors of the BRL history (BRL 1995) intentionally wrote a separate chapter, titled "Applied Research and Related Activities," to which I turn shortly.

3.2 Applied Research with Difficult-to-Assess Overmatch Impact

The history of BRL (BRL 1995, p. 52–58) describes a number of applied contributions to the war effort. These included (besides several I discuss in more detail later) the following: publication of ballistic engineering data, recommendations on fuze settings, training of artillery personnel, recommendations on the pattern of bombing, suggested guidance for aerial gunners, suggestions for the design of mortars, recommendations for the reduction of the recoil of lightweight rapid-fire guns, and methods for surveillance of ammunition.

Undoubtedly, these were valuable efforts and outputs. Unfortunately, the specific details of how and to what extent these applied research efforts impacted military capabilities—and especially whether they directly resulted in overmatch—are not available, with some important exceptions I discuss next.

This amplifies the point I made earlier: the importance of ongoing analysis and documentation of connections between research results and eventual assessable military capability.

3.3 Hispano-Suiza 20mm Automatic Aircraft Gun

The BRL history book chooses to place a special emphasis on this particular example of its contributions to wartime military capabilities: "A good example of the Laboratory's practical contributions in this field is found in its work on the development of the American version of the Hispano-Suiza 20-mm automatic aircraft gun…BRL designed a new lightweight version of the gun for turret mounting…[T]he result was an excellent 20-mm cannon for aircraft use" (BRL 1995, p. 57).

Unfortunately, the latter statement has to be qualified in at least two ways. First, it implies that BRL single-handedly produced decisive improvements of the cannon. In reality, throughout the entire war, numerous organizations—both military and industrial—undertook numerous and extensive modifications of the Hispano-Suiza 20mm (Chinn 1951).

Second, the characterization of the resulting weapon as "excellent" is far more optimistic than found elsewhere in literature on the subject. The US version of the Hispano-Suiza 20mm was known as unreliable and was endlessly undergoing redesign efforts toward resolving its various performance problems (Chinn 1951). In US aircraft service during WW2, the Hispano-Suiza 20mm was often replaced by the .50 cal Browning machine gun (Williams 2004). After WW2, the US Air Force quickly switched to the M39 20mm cannon, which is based on a different principle of German design.

"[The cannon's] wartime performance, good or bad, was the result of having been bought in desperation, put into mass production without first having been adequately proved, and then modified regularly to meet a future commitment before the previous model had been made to function reliably" (Chinn 1951, p. 590). The Hispano-Suiza 20mm autocannon was probably a largely adequate weapon, but in itself is hardly a good example of overmatch.

On the other hand, the cannon was an element within a much larger overmatch—US air power overall was an indisputable overmatch in WW2. While the Hispano-Suiza 20mm cannon by itself was not the primary source of this overmatch, it is also clear that the cannon was critically necessary to the number of US warplanes. Furthermore, the redesign performed at BRL appeared to rely on competency resulting from the basic research mentioned earlier—the theory of recoil forces. From this perspective, here we indeed have an example of science leading to a contribution to overmatch.

3.4 Bombing Tables and the Norden Bombsight

Although BRL's extensive work on compiling ballistic data for aerial bombing is described in the history of BRL (BRL 1995), the important link to the legendary Norden bombsight is not covered there, surprisingly.

Elsewhere, we find that "…the work of the Ballistic Research Laboratory at Aberdeen in compiling a complete set of ballistic tables for use with the Norden bomb sight contributed greatly to more effective bombing" (Green 1955, p. 443).

The overmatch of US air power in its WW2 strategic bombing campaign of Germany is unquestionable. So, is this perhaps a good example of BRL's work being a source of WW2-era overmatch? This is not entirely obvious, for the following reasons.

First, the wartime claims of Norden bombsight's legendary effectiveness—"dropping a bomb in a pickle barrel"—have been extensively questioned in the past 20–30 years. It turns out the Norden bombsight and the much simpler British Mark

XIV sight had a comparable error on the order of 300 yd (Correll 2008; Wakelam 2009, p. 212). Furthermore, the bulk of that error seemed to result from operational conditions and not from the technology of bombsights (including any corresponding bombing tables) (Wakelam 2009, p. 212). There is no evidence that the somewhat similar German bombsight Lotfernrohr 7 was overmatched by the Norden.

Second, it is difficult to argue that the bombing tables were the primary source of the Norden's accuracy. The bombsight was an integration of several advanced technologies, such as the gyroscopic stabilizer and a rather sophisticated mechanical calculator. The bombing tables were necessary, but hardly the primary contributor.

The sources of US air power overmatch were the prodigious quantity and magnificent capacity and quality of its aircraft, such as the B-17, not necessarily the accuracy of bombsights or the bombing tables. To put it differently, let us ask this question: If the United States and Germany had the same number and quality of bombers, would the BRL's bombing tables deliver the United States a tangible overmatch? It is difficult to find support for an affirmative answer.

On the other hand, it is clear that any bombsight required bombing tables and the quality of the tables did matter. BRL's bombing tables may not have been the primary source of the US strategic bombing overmatch, but without competently developed, accurate tables, the bombing campaign would have been far less accurate. Therefore, BRL's bombing tables should be recognized as an indispensable supporting element in the overall overmatch.

3.5 Firing Tables

Firing tables were a major, highly demanded output of BRL and, along with related instrumentation and computers, took the most prominent place in the history of BRL (BRL 1995). Could these firing tables be an example of "science for overmatch"?

In the official branch history of US field artillery (Dastrup 1992), WW2-era US field artillery is depicted as clearly overmatching the German's ability in firepower. It also discusses key factors of the overmatch: plentiful supply of ammunition; Fire Direction Centers (FDCs), which enabled rapid massing of fires on critical points; organic ground and air observers; and motorization that improved the mobility of artillery pieces. As for BRL's firing tables, they are not mentioned even once, nor is BRL.

In another major official history of field artillery (McKenney 2007), BRL is mentioned once and only in connection with the fact that "…the Army arranged with its Ballistics Research Laboratory at Aberdeen Proving Ground, Maryland, and the Jet Propulsion Laboratory at the California Institute of Technology to study the possibilities of long-range guided missiles." Although this study was followed by the guided-missile development projects Hermes and Nike, there is no evidence that BRL participated in them. In any event, there is no mention of BRL's firing tables.

Furthermore, there is no evidence that German firing tables were in any way overmatched by US firing tables. For example, Hexter (1944) describes the German graphic firing table without any suggestion of its inferiority to US products. It is not even clear whether BRL had the research tools to overmatch German ballisticians. Just as an example, German scientists had a supersonic wind tunnel as early as 1940, while BRL only obtained one in 1944 (Green 1955, p. 346).

Overall, it is difficult to claim that the overmatch of US field artillery was due to its firing tables. Let us ask the hypothetical question: if German field artillery was provisioned similarly to US artillery, and enjoyed the similar (highly effective) invention of the FDC and similar organic observers and motorization, would its firing tables produce overmatch for the United States? I find no evidence for an affirmative answer.

On the other hand, let us ask another hypothetical question: could all the factors of the US artillery overmatch mentioned previously, particularly the FDCs, be effective without competent, detailed, accurate firing tables? The answer has to be the negative. We may conclude, therefore, that even if BRL's firing tables were not by themselves a primary source of US artillery overmatch, they were certainly an indispensable supporting element of that overmatch.

3.6 Contribution to Bazooka

The bazooka was clearly an overmatch. This anti-tank handheld weapon was an outstanding innovation of American military engineering. For a period of time, it offered American infantry overmatch against German panzers. Germans soon improved upon the bazooka with their Panzerfaust, and the ubiquitous Soviet rocket-propelled grenade (RPG)-7 owes its genesis to the bazooka as well. Leslie A Skinner is known as one of the developers of the bazooka.

The BRL history (BRL 1995, p. 23) suggests that early research on related rocketry occurred at BRL, or in some connection with BRL: "The development of the rocket as a major weapon of modern warfare did not take place until after World War II had begun, and, consequently, little was done between the wars in the field of ballistic research for rockets. However, in the 1930s, Lieutenant Leslie A Skinner, on his own initiative and with makeshift equipment, conducted a number of tests at Aberdeen Proving Ground to obtain information that would be useful in rocket development. While his work was inconclusive, his findings indicated broadly what should be investigated once the development of rockets was seriously undertaken."

However, the literature seems to associate the work of Skinner and the development of bazooka with the Indian Head Rocket Laboratory (JBSIP 1946; Washington Post 2017; "Leslie Skinner" 2022; Schwantes 2021). On the other hand, tests and perhaps other efforts are mentioned in conjunction with Aberdeen Proving Ground (APG). Goddard had done rocketry research at APG, Skinner performed experiments "his own time and his own money" at APG (Washington Post 2017), and APG has been mentioned in connection with rocket research (but not necessarily the bazooka) (JBSIP 1946; "Leslie Skinner" 2022).

Furthermore, as mentioned earlier, fundamental work on shaped charges and propellants was performed at BRL, which occurred in physical proximity to the manufacturing of rounds, innovations of the bazooka launcher, and active testing and demonstration of the bazooka's capability to leadership, all among a very small group of people. Therefore, it is quite possible that BRL's basic research, particularly in the theory of finned projectiles and shaped charges, contributed to the success of the bazooka.

Although circumstantial evidence is substantial, we do not have a solid documental basis for firmer conclusions, unfortunately.

3.7 Aerial Gun Control

A 1946 report of the National Defense Research Committee (Bush et al. 1946, p. 187–188) notes, "The Ballistic Research Laboratory at Aberdeen has done a tremendous amount of work in analyzing the motion of a bullet fired from a moving airplane."

Then, it continues less encouragingly: "…Ballistic Research Laboratory finally was able to carry out an experiment in which the trajectories were measured which could be compared with the corresponding computed trajectories.…While this was sufficient to check the analytical work it was not at the target course that would normally be used for the combat."

The chapter in which these statements appear implies that the information developed by BRL was probably used in the development of airplane (and air-defense artillery?) gunsights, but no specific details of such use are given. Related work is also mentioned in the BRL history book (BRL 1995, p. 54–55), adding that recommendations were produced and provided to relevant organizations, but the degree to which the recommendations were applied and implemented, and what impact, if any, they had, are impossible to determine.

3.8 Tapered-Bore Guns and Sub-Caliber Rounds

The history of the Ordnance Department (Green 1955; p. 349–350) relates the following:

> "In 1941, when the British captured from Rommel's army, near Halfaya Pass, a light antitank gun with bore tapered from 28mm to 20mm and a few rounds of its 'arrowhead' ammunition, American interest in Gerlich-type weapons revived. A report describing the distinctive features of both gun and ammunition, and British reports of tests, inspired the Ordnance Committee to request immediate design of weapons and projectiles as nearly identical to the German as possible. At the same time, because a report from the Ballistic Research Laboratory indicated that equally high velocity could be obtained without tapered bores, the decision was reached to make several cylindrical bore guns employing ammunition similar to the hard-cored soft-sleeved German type, in order to compare performance with that of American copies of the German and with that of a captured model to be sent to Aberdeen."

It continued that

> "…careful tests convinced the Ordnance Department by late 1943 that in all artillery a cylindrical bore without an adapter but using a light hard-cored projectile served every purpose of the tapered bore. The former suffered far less wear, gave greater accuracy of fire, and over long ranges maintained higher velocities. Thereafter the Ordnance Department bent its efforts to developing tungsten carbide-cored rounds for conventional weapons and delegated to NDRC the pursuit of discarding sabot projectiles and other ways of attaining hypervelocity" (Green 1955).

In this example, BRL scientists contributed to overmatch, even if somewhat indirectly. Indeed, the US armored forces and tank destroyers as a whole overmatched the German armored forces in Europe in their overall capabilities, despite the fact that an individual Panther or Tiger overmatched an individual Sherman. BRL contributed to this overmatch by preventing the US military and industry from unproductive investments. Although the Gerlich principle (aka tapered bore or squeeze) guns remains a potentially promising research and development direction even today, back in WW2, it would have been unlikely to succeed, and BRL scientists prudently advised to pursue more conventional approaches.

In a more direct manner, BRL made a major contribution to the overmatch of the US armored and tank destroyer forces by studies and recommendations leading to the development of the M93 high-velocity armor-piercing tracer (HVAP-T) tungsten-carbide cored round (Kent and Zaroodny 1942; Hitchcock 1944; Cosme et al. 2018). Although BRL's recommended muzzle velocity was not achieved (due to the Ordnance Department decision to reduce the cannon length to compensate for turret binding), the HVAP round was of critical importance.

"The true benefit of the HVAP shot was opening up the front of the Panther turret as a viable target, albeit at close range. The effective range was within typical tank engagement ranges in the European Theater of Operations, and even though the bow armor was still invulnerable, the HVAP gave the US Tank Destroyer and tank crews a chance against the Panther front face via the turret" (Cosme et al. 2018).

Although the US 76mm gun, even with the HVAP round, was not exactly an overmatch to a German tank gun, the overall might of the numerous US tanks and tank destroyers was an overmatch, on the whole. BRL's contribution to the HVAP round helped maintain that overmatch.

3.9 Alternative Gun Proposed for the Sherman Tank

This contribution of BRL is an impressive example of science for overmatch in WW2 and has to do with the well-publicized saga of the Sherman tank guns: "…[T]he Sherman's greatest deficiency as far as the European Theater was concerned was its inadequate firepower…" (Hunnicutt 1978, p. 185).

"Although the Sherman could effectively deal with the Panzer IVs the appearance of the Panther and the Tiger I on the battlefield drastically changed the situation. The 75mm armor piercing round could not penetrate the glacis plate of either of the new enemy tanks even at pointblank range, but the 7.5cm KwK 42 and the 8.8cm KwK 36 of the Panther and Tiger I could destroy the Sherman from any angle at maximum combat range" (Hunnicutt 1978, p. 184.).

In an influential article on January 5, 1945, *The New York Times* thundered, "Why, in this late stage in the war the American tank is inferior to the enemy's?" This was merely a belated reflection of US Soldiers' frustration. For example, Brigadier General JH Collier wrote around that time that "the consensus of opinion of all personnel in the 66th Armored Regiment is that the German tank and anti-tank weapons are far superior to the American" (Zaloga 2008, p. 268–269).

This is where BRL shined and would have shined even more if its excellent proposals had been implemented. In October 1942 (and possibly even in 1941), the APG-based BRL suggested that research begin into two options: 1) arming the M4 medium tank with the 90mm gun (if need be by altering the cartridge case and gun) and 2) designing a 3-inch gun firing a 15-lb (6.8-kg) shot at 915 m/s (3,000 ft/s) (Hunnicutt 1978; BRL 1995, p. 56). A preeminent historian of US tanks, RP Hunnicutt, gives a prominent place in his history of the Sherman tank to BRL, specifically focusing on the 1942 proposal by BRL scientist Serge J Zaroodny (Zaroodny 1942). See Appendix B for additional details.

As early as 1941, BRL researchers anticipated that the development of German Panzers wwould soon necessitate significantly more powerful tank guns. Throughout the war, BRL produced a number of reports concerned with US tank firepower (Zaroodny 1941; Kent 1942a, 1942b; Kent and Zaroodny 1942; Hitchcock 1944; Tolch and Bushkovitch 1945) Among other issues, BRL researchers continued to argue for the need to achieve higher muzzle velocities, particularly in conjunction with sub-caliber penetrators (Hitchcock 1944).

> "There was no technical reason that the US Army should have been the only major army in 1943–1944 to fail to develop a new high-velocity tank gun capable of dealing with the panzer threat. The 76mm was a mediocre, half-hearted attempt that was inferior to its contemporaries such as the German 75mm KwK 43 on the Panther, the 17-pounder on the British Sherman Firefly, or the Soviet 85mm gun on the T-34-85. In 1944, Ordnance again improvised using the 90mm antiaircraft gun, but this barely matched the capabilities of the smaller and lighter British 17-pounder or German 75mm gun, and it did not approach the performance of the German 88mm tank gun" (Zaloga 2008, p. 328).

Developing a new tank gun capable of overmatching the German Panzers was exactly what BRL was proposing, with supporting science and technical detail: "[BRL's] design closely paralleled that of a highly successful British 17 pounder… later proved to be the most potent weapon carried by the Sherman during the World War II" (Hunnicutt 1978). A recent US Army Armament Research Development and Engineering Center analysis report (Cosme et al. 2018) confirmed the potential efficacy of wartime recommendations produced by BRL scientists.

One could argue that, in this case, BRL's contribution was merely a "might have been" and no actual overmatch materialized because BRL's recommendations were not implemented. (The reasons not to implement the recommendations had little to do with S&T and are outside of the scope of this report.) However, I look at the matter differently. The key role of a military scientific laboratory is to identify and offer the appropriate decision-makers a range of options that could yield overmatch. BRL did exactly that. BRL scientists' recommendations were insightful and prescient, and offered a potential for overmatch.

4. Observations and Conclusions

4.1 Need for Longitudinal Study of Research Impact

The inadequacy of available literature and documents was perhaps the most common and frustrating of my observations. Research institutions owe it to society to conduct persistent and systematic analysis and documentation of their research's long-term impact. Traditional technical reports and journal publications alone are insufficient for this purpose. When the history of BRL in the interwar and WW2 periods was written—in the early 1990s—most of personal and institutional knowledge about the impact of that period's research was already lost. Reports and articles tell us about the research conducted at the time, not about its impact years later. Attempts to connect a given technology with research conducted decades earlier are difficult, uncertain, and often unsuccessful.

Furthermore, it is possible that, to a large extent, BRL never had a full awareness of the impacts that its research produced within other organizations and industry. Definitive connections between BRL's contributions and the tangible, major military capabilities of WW2 are impossible to recover without timely, persistent, and systematic investigation and documentation over a significant period of time, starting back at the time when the research was originally conducted.

Many phenomena are path-dependent (e.g., the final state depends on the path that led to the state). Knowledge is likely similar. It is important to know how, and through what path, the knowledge was produced. Much can be learned from this for effective production of further knowledge. Similarly, knowing the history and the path of an organization, along with its impact, is important: it helps to understand how to design and operate organizations in the future. And the human entities who fund the creation of knowledge need insights on why and how the funds were—and should be—expended.

Research institutions—such as BRL in its time and DEVCOM ARL today—must conduct systematic, long-term, longitudinal studies of the impact their research had over time and the specific paths of evolution that led (or could lead) from science to practical impact.

4.2 Multiple Science Contributions to WW2-Era Overmatch

In the previous section, despite the disappointing shortage of documental evidence, I described a number of cases where BRL's scientific research clearly contributed to an overmatch of US WW2 capabilities. These included the following:

- The improvements to the Hispano-Suiza 20mm cannon contributed to the overall overmatch constituted by US air power.
- Similarly, BRL's bombing tables were an indispensable supporting element in the overall overmatch of the US strategic bombing force.
- BRL-developed firing tables were an indispensable contribution to the US overmatch in field artillery.
- BRL's contribution to the HVAP round helped maintain the overmatch of the overall might of the numerous US tanks and tank destroyers over their adversaries in Europe.
- BRL recommendations for producing new designs of guns and ammunition for the Sherman tank, if implemented, would have greatly improved the lethality of the Sherman tank, and in combination with its many other outstanding features, would have presented an overmatch to comparable assets of the opponent.
- BRL's research likely contributed to the development of the bazooka, although definitive documented evidence of such a contribution is lacking.

This list of overmatch-producing contributions is likely not exhaustive. For example, it is possible that some contributions that supported overmatch in WW2 remain classified and therefore are outside the scope of this report. It is also entirely possible that some important contributions somehow failed to find their way into any currently accessible public documents. Nevertheless, I do not see evidence that the missing part (if any) of this list is so extensive so as to change my findings and conclusions.

Other applied contributions, such as recommendations on fuze settings, training of artillery personnel, recommendations on the pattern of bombing, suggested guidance for aerial gunners, suggestions for the design of mortars, recommendations for the reduction of the recoil of lightweight rapid-fire guns, methods for surveillance of ammunition, firing and bombing tables, and so on, probably produced positive impact, and in some cases, certainly and crucially supported war efforts.

In addition, fundamental research results, although not yet ready to influence practical contributions in WW2, have certainly supported future work during the post-war and Cold War periods.

4.3 Organizational Climate, Trust, and Teaming

The official history of the Ordnance Department (Green 1955) dedicates significant attention to issues of wartime personnel morale and relations between management and employees. I was surprised to discover that one organization was given particular attention—BRL. I can only assume that appreciable morale issues (and corresponding complaints) surfaced at BRL during WW2 and necessitated a comprehensive investigation. Green (1955, p. 167) describes the results of a comprehensive survey of employee relations at BRL during the war:

> "When the scientists spoke confidentially, and under the cloak of anonymity, they were frequently vitriolic in condemning certain aspects of their employment…The complaints most frequently voiced were: (1) salaries were too low; (2) there was too much red tape, too many "channels" causing delay and frustration; and (3) professional men were not treated with sufficient dignity and trust. Among scientists with high professional ratings, one of the grounds for dissatisfaction was the Army-wide practice of placing commissioned officers in top positions—and then transferring them as soon as they became familiar with their jobs. Many scientists resented having to take orders from officers with less experience and less professional education than themselves, and then being denied personal recognition for their own achievements…They [military officers] are not interested in projects because they don't expect to stay long."

Nobody should underestimate the differences in the cultural, professional, educational, and even ethos backgrounds of warriors and scientists. Bridging this gulf—patiently and persistently—toward achieving trust and teaming relations must always remain a high priority in a military S&T enterprise.

4.4 Even with Multiple Contributions, Recognition of Relevance Is Not a Given

I found and reviewed three official histories of US artillery and US armor that cover, among others, the period prior to and during WW2. In these three histories (Dastrup 1992; McKenney 2007; Cameron 2008), I found a grand total of one—yes, one! —mention of the Ballistic Research Laboratory or BRL. And even that one mention had to do not with the primary competencies of BRL at the time, but with a somewhat peripheral study of "the possibilities of long-range guided missiles" (McKenney 2007).

One cannot assume that the relevance of science to military capability—and eventually to victory in war and the preservation of peace—is sufficiently recognized by those outside the S&T community. Not even in such a seemingly obvious case, when the science is ballistics and the application is artillery. A military S&T organization must pay tireless attention to maintaining and vigorously communicating the relevance of science to military capability, especially the overmatch.

4.5 And the Last Point

We must recognize the magnificent contributions of BRL—civilian and military—to the great effort of the US victory in WW2. All these individuals answered the call of the nation and did everything they were asked to do. BRL faithfully executed its mission, above and beyond.

WW2 was the largest war, by any measure, in human history. It was also a war in which the causes of good and evil were expressed with startling clarity, more so than ever before. It was an exceptional war, and the wartime employees of BRL performed exceptionally.

Vannevar Bush wrote about wartime scientists (Bush 1945), "…who have left academic pursuits for the making of strange destructive gadgets, who have had to devise new methods for their unanticipated assignments. They have done their part on the devices that made it possible to turn back the enemy, have worked in combined effort with the physicists of our allies. They have felt within themselves the stir of achievement. They have been part of a great team."

Indeed, they were outstanding members of the Greatest Generation.

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Appendix A. Excerpts from Project Hindsight

This appendix presents a few excerpts from the Project Hindsight report[1] to illustrate some of the post-World War 2 (WW2) accomplishments of the Ballistic Research Laboratory (BRL) as it became a mature, well-established organization:

- "In developing the 120mm gun, the Army…funded a large research effort at BRL to perfect an armor-piercing, fin-stabilized, discarding sabot (APFSDS) round for the 120mm gun...This was important in the development of one of the mainstays of the Abrams' armament, the M829 series of APFSDS long-rod penetrators."
- "R&D work at Picatinny Arsenal and BRL also produced a series of designs for the sabot focusing on exact shape of the scoops or ramps. The final double ramp sabot shape used on the M829 was the result of computer modeling by BRL."
- "Staff at BRL used finite element stress analysis to establish the proper geometric design of optimized, minimum-mass, aluminum sabots for both the 120mm M829 and M829A1…Investigators at BRL—teamed with composite material specialists at the Lawrence Livermore National Laboratory and with industry—developed the means to design the architecture and processing for the first composite sabot used for the M829A2 round…."
- "Among the most important aspects of developing better propellants was modeling. Efforts at BRL resulted in an improved computer code called the XKTC…widely distributed among America's allies. Studies with a scanning electron microscope…led BRL to develop a new propellant design that…provided an increase in interior ballistic performance."
- "Staff at BRL designed a separate compartment to stow ammunition; the compartment makes use of automatic doors also provided sufficient venting for any explosion by installing blow-out panels that would direct energy from the blast away from the crew…BRL developed less shock and crush-sensitive warheads and included plastic shields between stowed rounds…."
- "BRL researchers developed new armor concepts, the most notable being one that incorporated DU [depleted uranium]…Selected for its high density and special performance in high-shear fracture, DU makes an ideal armor component. This upgrade was fielded on the M1A1 and M1A2 models."

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Appendix B. Biographical Note on Serge Zaroodny

In searching the Internet for additional information about the Ballistic Research Laboratory's (BRL's) World War 2 (WW2)-era proposals for an anti-tank gun, I stumbled into fascinating details of Serge Zaroodny's life. At the same time, I was unable to find even a short biography of his life and work. I felt that researching and writing a brief biographic note about this long-time BRL scientist would be a fitting tribute to his work. I wish we could document lives of all the employees of BRL who contributed so much to the US victory in WW2.

A.1 Serge J Zaroodny, a Biographic Note

Serge J Zaroodny was an American scientist who worked most of his life at the US Army BRL (later merged into the Army Research Laboratory), and whose accomplishments included a notable WW2-era proposal for a Sherman tank gun and invention of the first powered exoskeleton.

He was born on July 12, 1910, in St Petersburg, Russia,[1,2] in an upper-class family, and named Sergei Ivanovich Zaroodnyi. His grandfather and namesake SI Zaroodny was the author of the Russian Judicial Reform Act of 1864, which was exceptionally progressive for its time.[3] His uncle, Alexander Sergeevich Zaroodnyi, became an attorney noted for pro-bono defense of controversial cases like that of Mendel Beilis, the Jew accused (and later acquitted) of ritual murder. In 1917, he served as the Minister of Justice in the short-lived democratic Russian Republic overthrown by the Communists.[4,5] Serge's mother, Elena Pavlovna Briullova, a granddaughter of the renowned Russian painter Karl Briullov,[6] had been a social activist campaigning for improvements of education for lower-income populations.[1,2]

Serge's father, Ivan Zaroodnyi, was a naval officer, a metallurgical and electrical engineer, a successful inventor, and a manager of metallurgical enterprises.[2] During the Russian Civil War (1917–1923), he managed a system of steel mills near the Siberian city of Omsk controlled by the government of Admiral Kolchak, one of the White movements that fought against the Communists. In late 1919, as the Communists forces approached Omsk, Zaroodnyi had to leave his family behind and escape first to Japan, and later to Harbin, Manchuria (today in China). Harbin was an important place of refuge for large numbers of Russians escaping from the new Communist regime in Russia.

In spring 1921, Serge's mother was executed by the Communists for her alleged "counter-revolutionary" activity.[1,2] Her young children—Serge and his five sisters—were left orphaned, without means of support, in the hungry, cold city of Omsk gripped by revolutionary chaos and violence. Then, in 1922, Charles R Crane, an American acquaintance of Serge's father, helped the children travel to

Harbin where they reunited with their father.[2] Crane was a wealthy American businessman noted for his philanthropic and diplomatic activities.[7]

Reunited, the Zaroodny family settled in Harbin. In 1927, Serge was admitted to the electromechanical department of the Harbin Industrial University.[2] Today that institution is known as the Harbin Institute of Technology, one of the world's highest-ranking engineering schools.[8]

In August 1931, helped once again by their American benefactor Crane, Serge and his older sister Margaret arrived from Harbin, China, via Yokohama, Japan, on a steam ship to Seattle, Washington, on student visas.[9] In 1932, Serge graduated with a BA from Pomona College in Claremont, California.[9] In 1934, Serge earned an MS in Electrical Engineering from the Massachusetts Institute of Technology. In 1935, the Society column of the *Washington Evening Star*[10] described a wedding attended among other notables by "Mr. Serge J Zaroodny of Harbin, Manchuria."

In 1936, in Saybrook, Connecticut, he married Vilma Fekete (1907–2006), a daughter of Hungarian immigrants who was born in Connecticut and worked as a music teacher.[2,11] In 1940, Serge worked as a laboratory assistant at Yale University.[12] The couple settled for a while in Bridgeport, Connecticut,[13,14] where Serge worked as an electrical-mechanical engineer at the Hartford Ordnance District.[1]

By 1941, he transferred to a position at BRL located in Aberdeen Proving Ground, Maryland, and relocated to Maryland to be close to the job. Since then, his professional life remained affiliated with BRL and with the Aberdeen Proving Ground.

In 1941–1942, he developed and published one of the most important of his technical contributions—a proposal[15] to develop a new, more powerful gun for the Sherman tank. Zaroodny correctly anticipated that the primary American tank—the M4 Sherman—would soon be outgunned by rapidly evolving German tanks. A preeminent historian of US tanks, RP Hunnicutt, highlighted Zaroodny's proposal as uniquely important.[16] Unfortunately, the US Army authorities did not pursue the proposal, and in 1944–1945, the Sherman tank crews did find themselves disadvantaged in the face of more powerful German tanks. It is possible, however, that Zaroodny's proposal helped influence the decision to install a 90mm gun (albeit a weaker one than Zaroodny proposed) on the American M36 tank destroyers and on the Pershing tank.

Most of Zaroodny's work continued to focus on guns, cannons, mortars, and rockets, mainly on mathematical and computational methods of modeling and analyzing various phenomena associated with motion and other behaviors within such weapons systems as well as with the flight of the projectiles.

In 1951, Serge started research that resulted in another pioneering contribution—the invention of the exoskeleton. In 1963, he published a report[17] in which he was the first to propose the concept of a powered exoskeleton. He also sketched the first-ever design of such an exoskeleton and identified key scientific and engineering issues associated with such devices.

Decades later, reviewing the state of exoskeletons in 2008, Dollar and Herr (in the world's most cited paper on exoskeletons) paid the following tribute to Zaroodny:

> "While mainly a concept paper, Zaroodny identified and began to address many of the fundamentally difficult aspects of implementing such a device, such as a portable power supply, sensing and control, physical interface with the human, and the affectation of the biomechanics of locomotion. The paper ends by describing the results of an informal evaluation of a pneumatically powered prototype device—possibly the first powered performance-augmenting exoskeleton ever created…[w]hile his proposal did not succeed in securing funding to pursue the project, this report is nonetheless the earliest publication in which the complications of engineering a performance-augmenting exoskeleton device were considered."[18]

Zaroodny was a prolific researcher. At BRL alone, he published about 50 formal research reports. A lifelong learner, in 1972 (at the age of 62), he earned PhD in Applied Sciences from the University of Maryland. His last report at BRL is dated 1976, which was likely the year when he retired. Besides being a scientist of wide-ranging talents, he was also a dedicated lover of poetry, able to recite by heart for hours.[19] Serge Zaroodny died on August 29, 1981. His wife outlived him by 25 years. Both are interned under the same gravestone at the Spesutie Cemetery, Perryman, Maryland.[20]

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List of Symbols, Abbreviations, and Acronyms

ARL	Army Research Laboratory
BRL	Ballistics Research Laboratory
DEVCOM	US Army Combat Capabilities Development Command
DU	depleted uranium
FDC	Fire Direction Center
HVAP-T	high-velocity armor-piercing tracer
NDRC	National Defense Research Committee
RPG	rocket-propelled grenade
S&T	science and technology
WW2	World War 2

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