19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

A RETROSPECTIVE OF THE PAST 50 YEARS OF WARHEAD RESEARCH AND DEVELOPMENT – THE PRE- AND PRESENT COMPUTER MODEL ERA

Donald R. Kennedy

D.R. Kennedy and Associates Inc., P.O.Box 4003, Mountain View, California U.S.A.

This paper discusses the differences between warhead research and development (R&D) in the 1950's and 1960's before the availabllity of computer models and the changes that evolved with introduction of workable computer models beginning in the 1970's. The early period was marked by empiricism and much innovation both in the design of the warheads and also in the experimental procedures to test the designs. Warhead R&D was then comparitively inexpensive and was completed in short order, often in a matter of weeks or months. Although computers were available, their use was limited because they were generally unaffordable due to the low budgets typically allocated to warhead programs. However with the advent of advanced desk and laptop computers and their general usage, the bulk of the design activity has now shifted to computer models, often on the engineer's personal computer. The warhead design trend has been to refine old technologies rather than to create new ones, and to take much longer and expend much more funds in the execution of today's development programs. The exploratory research that fed the innovations so prevalent in the 1950's is now seldom allowed by the accountants controlling the R&D budgets.

INTRODUCTION

The author of this paper has been continuously involved in defense R&D since 1948 and in warhead R&D since 1950. He has been involved in virtually every aspect of non-nuclear kill mechanisms research and development, including anti-armor, anti-aircraft, anti-missile, anti-submarine, anti-hard-target, and anti-personnel, to further include warheads utilising high explosives, and even those with chemical and biological payloads. The author's experience includes both employment in a Government laboratory and in private industry. He has acted as a design consultant to the industry at large since 1978. Many techniques in use today throughout the world have come from his innovative efforts, much of it from research in the earlier years. Although best known for his work in the shaped charge, innovations include many other aspects including certain of the modern armored vehicle technologies as well, the "flip" side of the anti-armor efforts. Examples of some of the design and experimental methods are discussed, both from the early years as well as from some of the more recent computer model supported warhead design studies.

In a recent warhead design project, the author found himself competing directly with a U.S. Government organization equipped with the highest technology computational models and experimental facilities available today. The competing agencies basic design approach was based on a design originated in the 1950's by the author as an outgrowth of exploratory research and a subsequent reduction to practise of a highly potent, advanced technology, anti-armor warhead.

THE 1950's and 1960's –THE PRE-COMPUTER MODEL ERA

Warhead research, and development in the 1950's and 1960's was characterized by innovation, empiricism, limited access to technical documentation concerning warhead technology, and very limited funding. What was available, as a result of World War II, was a plethora of information concerning the vulnerability of a broad spectrum of targets to the blast and fragmention effects of the weapons employed in such a great quantity in that war. By 1950, we had entered the era of the guided missile and operations research. One of the post-war realizations was the need for optimization, for better control of fragmentation size and shape for warheads used against critical targets, primarily aircraft, by the new guided missiles, and also the need to better understand and improve the shaped charge anti-hard target mechanism introduced and employed so successfully in the defeat of armored targets in WWII.

THE WARHEAD DEVELOPERS IN THE 1950's

U.S. Government orgnizations concerned with warhead development included the Army Picatinny Arsenal with technical support from the Ballistics Research Laboratory at Aberdeen Proving Ground, the Naval Weapons Laboratory at Dahlgren, VA supported by the Naval Ordnance Laboratory, White Oak, MD, the Naval air weapons operations at the U.S. Naval Ordnance Test Station, China Lake, CA, and the U.S. Air Force Armament Laboratory originally at Wright Field, Dayton, OH, and later transferred to Eglin Air Force Base, FL. Anti-airtarget warhead research also took place under Navy support at the New Mexico School of Mines, Soccorro, NM.

INDUSTRIAL AND ACADEMIC PARTICIPANTS

Industrial support was provided by a large group of industrial organizations and and academic institutions, many of whom were suppliers of materiel to the Armed Forces in World War II. These included such organizations supporting warhead and explosive munitions research and development such as the Firestone Tire and Rubber Co., Honeywell, General Tire and its Aerojet General subsidiary, American Machine and Foundry, Chicago Midway, the Chamberlain Co., Rheem Manufacturing, AVCO, Aircraft Armaments, and several others. Even Lionel, the makers of toy electric trains was a contractor for munitions development at one time. Most activity by the industrial organizations was in the manufacture and development of specific items in response to requests for proposal from the Military arsenals. The big three developers by the end of the 1950's were were Avco, Honeywell, and Aerojet Ordnance. Aerojet had absorbed the Rheem organization in 1959 and in so doing became one of the three largest United States munitions R&D organizations, complimented by a strong research department. Academia was represented by Carneigie Institute of Technology, Stanford Research Institute, University of Utah, and others. Personnel in these organizations included several who had come from the military agencies or had served in the armed forces in World War II. Many others were recruited from the colleges and universities and trained by their own staffs. Engineers, in particular, mechanical engineers, made up the bulk of the R&D organizations. Most were undergraduate level. Relatively few had advanced degrees.

APPROACH TO WARHEAD R&D

There were no computer models for the design of warheads. The experience of the warhead designer, usually based on his own research and personal observations of his experiments, his own intuitions, and his personal data banks was the principal means of design. Much depended on direct participation in experiments, observing cause and effect. A natural curiosity that came out as "what if" and of even greatest importance, working for an organization that promoted and funded exploratory research where ideas could be tried out was vital. Exploratory research when combined with a loose goal, without expectation that a specific goal would be achieved in a finite time and for a finite amount of money, was an ideal working environment. Such research would frequently point up something unexpected that resulted in a redirection of effort. This often led to significant findings, in some cases rebutting work reported by other investigators who reported that a certain line of study was a useless endeavor. It sometimes seemed that one was better off NOT knowing what some other investigators had reported. In our experience, some things we observed and later discovered to be significant were found in the literature and had been declared a dead end. The use of aluminum as a shaped charge liner is a case in point. Had we seen certain literature as we were planning our research we probably would not have attempted some of the experiments that turned out to yield major findings. We were fortunate in working in environments that minimized restrictions on what we could do or how much high explosives we could detonate in a single event. There was always someone encouraging us to do things in small scale when the scaling laws were as yet unknown. By working in full scale against actual targets such as aircraft and tanks, it was much easier to observe things in real scale and real time, and more important, to convey the readily recognizable results of those experiments to those of the Military users who made the decisions on what would be developed into future weapons.

THE MATHEMATICAL TOOLS IN THE 1950's AND 60's

Although computers had existed since the mid-1940's, the early models were quite limited in their capability as well as very large in size and complexity. As a result, few computers were available in the U.S., and most of those were in major Government laboratories such as the Army Ballistics Research Laboratories (BRL) at Aberdeen Proving Grounds MD. Computers in the 1950's were of very low power and used employed for such routine calculations as the development of ballistic tables (e.g., at BRL). For most of those designing warheads, even those at high technology U.S. Government Laboratories such as the U.S. Naval Ordnance Test Station, the principal tools available were still slide rules, math tables, and mechanical calculators that could not even perform simple square root calculations. Accuracy demanded laborious calculations with logarithmic tables. This situation continued even into the late 1960's when electronic calculators with CRT displays became available (at a considerable cost) but with the capability of doing square root, a "must" when working with the Gurney equation, etc. Computers available in the 1960's were much more capable but still cost too much in both original investment and running time, to be affordable to the non-nuclear warhead design and development projects, which were all notoriously low budget operations. Some examples are listed below under "Funding of Warhead R&D".

THE 1950's DIAGNOSTIC TOOLS

Perhaps the most widely used diagnostic tools in the 1950's period were the high framing rate cine cameras such as the FASTAX with framing rates on the order of 8000 frames per second and frame edge timing marks. These were eventually replaced by higher framing rate cameras and by other manufacturers products. Both streak and ultra-high speed framing cameras came along later in the 50's that permitted up to 36 exposures at rates up to 1.5-million frames per second. The few more fortunate research facilities also had flash radiographs that made X-ray observation of the shaped charge jet possible. Radiograph tubes of the early years were large, expensive and often difficult to protect. Air blast over-pressures were often required to be measured. And both static mechanical "foil-pot indicator" gages and dynamic electronic pressure gages were developed for such use, although many of the early models were not reliable. Both jet long standoff velocities and fragment velocities were typically recorded by the cine observation of impact flashes in arena tests.

EXAMPLES OF FUNDING OF WARHEAD R & D IN THE 1950's

The 6.5-inch shaped charge warhead and fuze for the 5.0-inch HVAR aircraft rocket was developed in the summer of 1950 in only 19-days time at the U.S. Naval Ordnance test Station, China Lake, CA. In that same 19-days time, 1000 warheads and fuzes were manufactured for initial delivery to Korea, and were used in combat on the 23rd day after onset of development. The total cost to the Navy of the new warhead and fuze development and manufacture was only $167,000! exclusive of the costs of the "off-the-shelf" 5-inch rocket motors. This development sparked a highly fruitful warhead exploratory research program at China Lake in the 1951–1953 period that was funded at under $195,000/year. Results of that research are still appearing in new developments in the year 2000. For example, in 1954, a highly advanced shaped charge warhead for the U.S. Army's DART antitank missile was developed for a total funding of only $54,000 for the entire research, design, and development process including warhead qualification testing. The blast fragmentation warhead for the NIKE HERCULES anti-air target missile was contracted for in 1954 at $109,000 for the entire design, development, test, and qualification program. This warhead weighed 499 kg and introduced a totally new manufacturing and fragment control technology, with over 18,000 each pre-cut 9-gram steel cubes laid up on a lightweight composite fiberglass structure. The Army was pleased to have a minimum parasitic weight warhead with a yield of controlled size, weight, and shape fragments that met the requirements of the Army's computer run encounter analysis program. The NIKE warhead contained 295 kg of H-6 explosive and was developed and arena tested entirely within the facilities of the Aerojet General Corporation at Azusa and Sacramento, CA. The basic warhead design layout was completed in a single day and it's understood that the warhead was still being manufactured to that original design as much as 30 years later in an Asian country. In the late 1950's the 204 kg inert parts assemblies were manufactured for only $1500 each, or $7.35/kg. The initial buy was for 20,000 inert parts assemblies and was funded at $30,000,000. Because of the successful NIKE warhead, the HAWK warhead was designed and manufactured using the same process. The method became a world-wide standard that is still in use. Funding costs comparisons must consider the inflation which has increased costs by 10 to 20 times those of the 1950's.

THE PRESENT COMPUTER AIDED DESIGN ERA: 1980's TO DATE

Although mathematical relationships describing the shaped charge mechanisms began to evolve in the 1940's, the ability to design a shaped charge utilizing those relationships was a tedious process. By the early 1970's, the nuclear weapons laboratories faced with major design challenges had developed "hydrocodes" to facilitate the design of nuclear explosives. Hydrocodes were based on the mathematical relationships describing the physical and chemical reactions and processes involved in the high pressure detonation process and its effect on surrounding or embedded metals. This writer's initial experience was with the Lawrence Livermore Laboratories in the early 1970's period. We had observed and recorded by a high-speed cine camera a jet from an experimental detonation wave-shaped charge called an "X-Charge" a name based on its internal configuration. The apparent jet tip velocity recorded over a standoff distance of 20 meters indicated an average velocity of nearly 13 km/sec for a jet that was ablatively burning away during its transit over the long distance. Because the observed tip velocity was so much higher than velocities reported in the literature for standard shaped charge jet performance, the charge design details were taken to the Lawrence Livermore with a request to see if their HEMP hydrocode could determine whether such a velocity was possible. It required several weeks of hard work and a need to introduce a different methodology, specifically a Eularian-Lagrangian transform, to be able to compute just the initial jet tip velocity. The finding was that the observed very high jet velocity was in fact possible and was entirely a function of the manner in which the explosive charge was initiated, whether by center-point or ring initiation, and also how it was affected by the material comprising the wave shaper.

The first shaped charge computer model appeared in the mid-1970's and required a computer of very high capability. Most of the more useful models known today, began to appear in the mid-1980's. Many non-government warhead design organizations could neither afford the computational tools nor the personnel required to develop and use the new computer models. As a result most of the warheads designed in the 1970's period continued to employ the old, pre-computer model methods. This was particularly true for the blast-fragmentation warheads. Most shaped charge designs also continued to use the old and familiar design methods. It is the writer's opinion that few, if any, of the warheads employed in the Gulf War in 1991 were designed by computer. In the 1980's an analytical shaped charge model based on the recognized shaped charge mathematical relationships and the actual reported results of hundreds of design configurations, world wide, was developed by the BRIGS Co. in the United States. After a short period where the initial model utilized programmable calculators, it was soon modified to permit its use on the early Apple II desk top personal computer. The model proved to be a designer's dream. It was fast enough to perform the calculations so that a complete sequence could be run in a matter of 20 minutes or less, yet was slow enough to give the designer time watch what was going on and to drink a cup of coffee. The model was soon refined and expanded to permit the complete design process and performance evaluation to be performed on a personal computer in a continuous sequence. Although this writer was the first to acquire the Century Dynamics AUTODYN hydrodynamic code in the mid-1980's, he continues to use the BRIGS analytical model as principal design tool [1][2]. The BRIGS analytical model was also adopted by defense research laboratories in both Canada and the Netherlands.

WARHEAD DESIGN IN THE PRESENT ERA – MID 1980'S – DATE

Today, several highly refined computer models are available to warhead design organizations that permit the optimal design and performance analysis of EFP, shaped charge, and blast-fragmentation warheads well before the need to cut metal and prepare demonstration models. Virtually any properly trained engineer can use these computer models to successfully design a modern warhead. However, it is highly desirable that the designer should also have practical field experience if he is to properly interpret what the model predicts will occur. As was the case in the pre-computer model period, there is no substitute for field experience to better ensure that the designer doesn't believe everything he sees just because it is printed by a computer program.

SUMMARY: PRESENT DAY COSTS AND DEVELOPMENT SCHEDULES

In marked contrast with the small budgets and rapidly performed developments characteristic of warheads developed in the 1950's through much of the 1970's, present day programs involve much greater funding, in many cases, far exceeding any inflationary effects, and require much more time to accomplish than in the past. Questions to be asked include (1) do the new warheads perform better and are they more cost effective than their pre-computer predecessors? (2) what causes development costs and time to be so great in spite of the use of the computer design tools?

Are Present Day Warheads Better?

Computer tools should permit the newly designed warheads to be qualitatively better because the computer permits an optimization of the design and knowledge whether the physical and terminal ballistics performance will meet design specifications. Modern day shaped charge warheads should perform better than could be designed without the benefit of computer models because a model permits making of incremental design changes and assessing their effects. Pre-model-era warheads were often just a best guess based on the opinions of a trained experimental observer. Lack of funding and time precluded doing the physical experiments to evaluate changes, often seemingly minor, that could have a profound effects. The writer once conducted over 200 individual test firings in only a few hours of time in an attempt to ascertain the trends in performance of aluminum lined shaped charges, because there was no information in the then available literature. That this could be done by computer model was beyond the forseeable state-of-the-art at that time.

What Factors Cause Such Great Costs and Long Schedules?

Inflation is certainly a major factor in the increased costs of research and development. However, many present day warhead developments are overly specified and overly micro-managed by the ubiquitous "bean counters" (accountants). Both factors are demonstrated to greatly increase both the cost and time required to do any engineering task. Numerous examples of these problems have appeared in both Government and industry research and development organizations. Certainly the general modern day restriction on funds and permission to perform exploratory research can do great harm to the development of knowledge in warhead technology. The idea that anyone can predict when and what will be found in the future of any research effort is ludricous. As one who has spent over 50 continuous years in the research and development of warhead related technology it is incredulous that R&D management by the accountants instead of engineers has generally become an accepted operational mode.

REFERENCES

1. D.R. Kennedy, "Design of Multi-staged Shaped Charges using the "Brigs" Analytical Computer Model" *Proceedings of the 12th International Symposium on Ballistics*, Vol. II 446–455, 1990
2. D.R. Kennedy, "The Design of a Tandem Warhead Precursor Shaped Charge Unit Candidate for SLAM-ER", *Contract from Naval Air Weapons Center, China Lake, CA No. 2000*