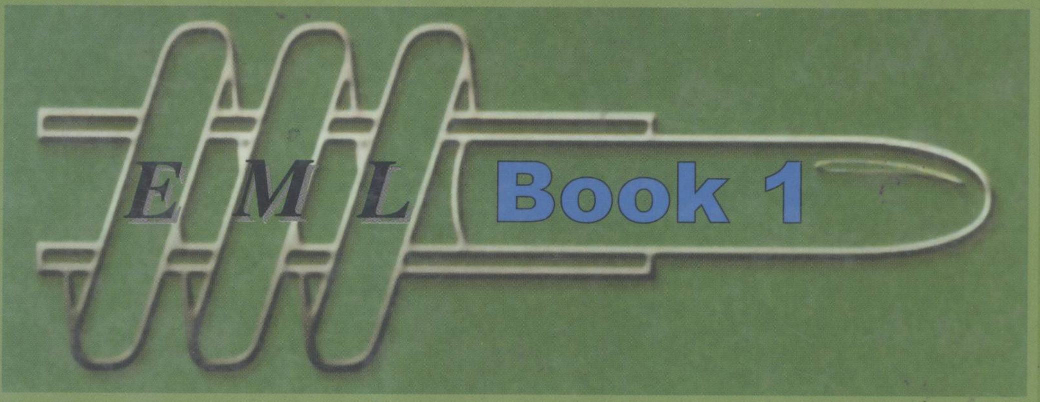

PHYSICS OF ELECTRIC LAUNCH

by

Wang Ying
Richard A.Marshall
Cheng Shukang

Science Press, Beijing

EML Book 1

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Brief to Authors

Wang Ying was born in Suihua, Heilongjiang Province, China in January 1938. He graduated from Harbin Institute of Technology in 1964. Worked in the Northwest Nuclear Technology Institute, and was engaged in the research of pulsed power technology. From 1981 on, he has been engaging in the research and the teaching work of the electromagnetic launch technology and the new concept weapons in the Ordnance Engineering College. He is the director of the New Concept Weapon Institute and president of the Electromagnetic Launch Society of China.

He designed and led the research of the assembling of the first oil line strong current electronic beam accelerator (IMV), the electric explosion device (800kA), and the first inductance energy storage flash X-ray camera (400kV) in China. So far he has applied and acquired 10 invention patents. He has authored five monographs in Chinese or English including *High Power Pulsed Power Supply*, *Principle of the Electric Gun*, *Principle of the New Concept Weapons*. So far more than 30 students have graduated under his supervision with the master and/or doctor degree. Among them his doctorial student Li Jun won the first Peter Kemmey Youth Student Scholarship in the world. He is a visiting professor of Wuhan University and an adviser or a concurrent professor of other 6 institutions.

Richard Astley Marshall was born in the Auckland suburb of Owairaka in 1927. After attending schools in Auckland, Napier, Wellington, and Whangarei he returned to Auckland to study at the University of New Zealand's Auckland University College as it was then called. He received their Batchelor of Science degree in 1951 and their Batchelor of Engineering Honours degree in 1952. In that year he was awarded Harvard's Saltonstall Scholarship and received Harvard's Master of Science degree in 1953. In 1979 he was awarded the Australian National University's Doctor of Philosophy degree based on examination and on his published work.

In his long working life he has spent various lengths of time, some short some long, in industry, governmental bodies, and universities in many countries including New Zealand, Australia, Canada, England, The Netherlands, The U.S.A., and The Peoples Republic of China.

The two bodies of work for which he is most noted are the 1.6 million ampere brush gear for the Canberra homopolar generator and leading the Australian National University's railgun team. Pertinent details of these works are included in our two books.

Cheng Shukang was born in Qixian, Shanxi Province, China in June 1946. He graduated from the Electrical Machinery Department of Harbin Institute of Technology in 1969. Now he is a professor of Harbin Institute of Technology (guidance teacher of doctoral students), vice president of the Electrical Engineering and Automation Institute of Harbin Institute of Technology, member of The Fourth Discipline Appraising Panel under the Degree Committee of the State Council, senior member of the China Electrical Engineering Society, vice director committee member of the Micro and Special Electrical Machinery Committee, vice director member of the Electromagnetic Launch Technology Committee, council member of the Micro and Special Electrical Machinery and Components Profession Society under the China Electronics Components Society, member of the editorial board of Harbin Institute of Technology Journal, member of the editorial board of the periodical Micro and Special Electrical Machinery. He got 4 second-class prizes and 5 third-class prizes of scientific technology progress at province and department levels; applied 4 invention patents and one practical new type patent in Japan; applied 8 invention patents and 6 practical new type patents in China; published 6 monographs and more than 200 academic papers. He is mainly engaging in the study of electrically operated motor cars and related technologies; micro and special electrical machineries and their driving control systems, anti-conventional concept electromagnetic devices *etc.*

Foreword

Electromagnetic Guns Come of Age

The ability to use electromagnetic energy to propel objects controllably, and particularly to accelerate materials to extremely high speeds, has broad and important implications for most parts of our society including transportation, communications, energy, national defense, and space exploration. Our use of electromagnetic energy may even provide insight into the origins of the earth and solar system.

The EML book 1—*Physics of Electric Launch,* by Prof. Wang Ying, Dr. Richard A. Marshall and Prof. Cheng Shukang, is the first comprehensive compilation of the underlying physics and engineering of electromagnetic launch. The book provides, for the first time, a thorough and detailed presentation of the physical principles of all types of electromagnetic launchers. It makes an important and vital contribution to the development and implementation of this technology.

The ability to accelerate materials using electromagnetic energy had its beginnings in the early 1800s when the Danish scientist, Hans Christian Oersted, discovered that an electric current flowing through a wire produced a magnetic effect on a compass needle held close to the wire. Fascinated by this observation, the great English physicist and chemist, Michael Faraday, invented the first electric motor that produced rotary motion from an electric current. A decade later Faraday made the critical connection between electricity and magnetism. His discovery of electromagnetic induction led him to invent the first electric transformer and later the first electric generator. These simple but brilliant observations and discoveries provide the basis for all of our electromechanical devices. Electric motors, generators, transformers, inductors, and other electric components now permeate every element of our society, and our daily lives are much easier and richer as a consequence.

As electromagnetic technology advances, we are finding new and important ways to use it. For example, we use electromagnetic devices to propel structures of all sizes, ranging from hybrid electric vehicles (HEVs) to aircraft launched from naval vessels. We even use electromagnetic technology to propel and levitate large electric trains (or MAG LEV). The extensive use of HEVs and MAG LEV offers the prospect of a revolution in efficient transportation and energy conservation.

The ability to accelerate materials to higher and higher velocities has been a continuing goal of mankind for centuries. As new technologies have enabled us to reach new, higher plateaus in velocity, these technologies have concurrently had an enormous impact on every element of society. But, for the past six hundred years, the ability to launch materials to extremely high velocities has remained the province of chemical propellants and explosives.

Using these energetic chemicals, a propulsion force can be created by the combustion of chemical propellants or detonation of explosives whose gas products provide high temperatures and pressures (conventional guns) or high-combustion gas exhaust speeds (conventional rockets). The speeds obtainable by the combustion of propellants depend on the size of the molecules resulting from the combustion process. Practically, this limiting speed is about 2 km/s for high-performance guns (1.5 km/s is the speed of a typical high-performance tank gun). Over the centuries, chemical guns and rockets have reached a high state of maturity and are now highly developed technologies that are used extensively worldwide.

However, over the past two decades, a revolution has occurred in the physics of electromagnetic launch, and after five hundred years of dependence on chemical energy, we are now entering the age of electromagnetic launch technology.

The Age of Electromagnetic Launch Technology

The technology for using electromagnetic energy pulses to accelerate materials to extremely high speeds has only recently advanced sufficiently that it can be exploited reliably for practical applications. For example, electromagnetic launchers are now used to evaluate the survivability of space structures and the survivability and lethality of military weapons systems. In fact, electromagnetic launchers are now capable of accelerating objects to such high speeds that projectiles are able to travel many hundreds of kilometers or penetrate the most advanced modern armors. Electromagnetic launchers have even propelled objects to sufficiently high speeds to put them in orbit around the earth.

Electromagnetic launchers can propel objects to these high speeds because, in contrast to chemical guns and rockets, they provide all of the accelerating force through the interaction of electromagnetic fields and strong electric currents.

Physics of Electric Launch performs a vital role by providing an excellent presentation of the fundamental physical principles and by laying the engineering groundwork for this technology.

The U.S. National Hypervelocity and Electromagnetic Launch Program

In the late 1970s, several totally independent research efforts were initiated in an attempt to develop a practical electric launcher. The motivation for the research ranged from electromagnetically levitated trains (MAG LEV), to launching materials to space, to impact fusion, to military weapons. A small group of physicists at the Army's Picatinny Arsenal began investigating a number of military applications, including long-range artillery, anti-tank guns, and electric catapults for launching aircraft from ships. Following a presentation I made to a colloquium held by the Office of the Secretary of Defense (OSD), I was asked to develop a U.S. national research program, coordinating efforts in the Department of Defense, the National Aeronautics and Space Administration (NASA), and the Department of Energy, and to form an advisory panel to oversee all U.S. research and development efforts. A search of scientific and engineering literature identified isolated attempts to develop electric launchers in the past (some as early as the early 1900s), but generally, all of the previous attempts at achieving hypervelocities had been quite unsuccessful.

The remarkable exception was a successful experiment performed by Prof. Richard Marshall and Dr. John Barber at the Australian National University in Canberra in the 1970s. Using a large, homopolar generator (550 MJ), they were able to accelerate intact a 3-g Lexan projectile to 5.9 km/s in a five-meter-long railgun. This was a world-record launch velocity for electromagnetic guns and demonstrated that electromagnetic guns could enter the realm of hypervelocity.

At approximately the same time, Prof. Gerald O'Neill at Princeton University and Dr. Henry Kolm at the Massachusetts Institute of Technology proposed using a coaxial electromagnetic launcher, the "Mass Driver" , to launch lunar ore to the L-5 orbit for use in building cities, farms, and industry in space. They collaborated at the Francis Bitter National Magnet Laboratory to build a laboratory launcher, which accelerated a relatively large mass (weighing several kilograms) to only a modest velocity. But, the experiment generated enthusiasm and public support for space colonization and exploration.

In response to the tasking from the OSD, the U.S. Army and the Defense Advanced Research Projects Agency (DARPA) became the initial primary sponsors of the national research program on electromagnetic launch technology and hypervelocity physics. NASA and the U.S. Air Force also provided some limited funding. The focus was to advance and develop the critical electrical components and evaluate the feasibility for any of a broad spectrum of military applications and direct launch of materials into space (NASA and the Air Force). Since large electric power sources were not readily available, a team from Lawrence Livermore National Laboratory and Los Alamos National Laboratory, led by Ron Hawke and Dr. Max Fowler, was funded to use an explosively driven magnetic flux compressor to accelerate a small projectile in a railgun to more than 7 km/s.

I understand that there had also been Russian research on electromagnetic launchers during this time frame, but a major stimulus to this program was provided by an impromptu workshop (organized by Dr. Max Fowler from Los Alamos) with Russian and U.S. scientists participating, at the second Megagauss Conference in Washington, D.C., and there has been an active research program in Russia since that time. In 1980, there was a decision to present the U.S. program to senior officials at NATO in Belgium, but there was at best a lukewarm response from the Europeans toward participating in the effort at that time.

In the mid-1980s, the Strategic Defense Initiative Organization (SDIO) emerged as the major funding source and changed the primary U.S. focus to address the technology required for extremely high-velocity launch and hypervelocity impact of guided launch packages from electromagnetic launchers based in space. As a consequence of this redirection of emphasis, the critical component and underlying science and technology issues were substantially different. The SDIO program was also motivated to obtain involvement (and thus, political support) by countries in addition to the United States. Financial support was provided by SDIO for analytical and experimental efforts, and as a consequence, several significant efforts were initiated in Europe and Israel.

During the early 1980s, the Army and DARPA funded a Westinghouse team led by Dr. Ian McNab to build a laboratory system to launch a projectile weighing a third of a kilogram to 3 km/s. This provided a U.S. demonstration of the feasibility of the technology. Because the Army and DARPA envisioned military railgun applications involving atmospheric flight, an upper bound of approximately 3 km/s was chosen to eliminate complexities from aerothermodynamic heating of the projectiles. Later, under joint sponsorship of DARPA, the Army, and the Defense Nuclear Agency, two large (90-mm) railgun facilities were constructed, one at the Center for Electromechanics (CEM) at The University of Texas, using homopolar generators as the power source, and one at Green Farm in California using capacitors as the energy source. Both of these facilities were capable of accelerating projectiles weighing several kilograms to hypervelocity and achieved 9MJ kinetic energy at launch.

It is significant that all of these large demonstrator devices provided initial important results but are no longer in operation and have been dismantled. They clearly demonstrated the feasibility of accelerating large masses to hypervelocity, but they also helped identify numerous critical fundamental issues that needed to be resolved before continuing with further large and expensive demonstration experiments.

Institute for Advanced Technology (IAT) Created

In 1990, the Institute for Advanced Technology (IAT) was created at The University of Texas. The purpose was to establish a research organization dedicated to developing the fundamental physical principles, computational tools, and experimental research capability to provide the scientific underpinning for hypervelocity electric launchers and hypervelocity impact physics.

In just a relatively short time, an impressive list of issues previously regarded as "show stoppers" or major technical hurdles has yielded to the combination of theoretical analyses, computations, and novel experiments, and electromagnetic launchers are now being developed for a broad range of applications.

Applications

The Army has been the most consistent supporter of the technology in the United States. Its primary interest has been a future hypervelocity electromagnetic gun.

Compact energy storage and power conditioning has been the pacing technology. The U.S. program has focused on energy storage by inertial high-speed rotors, integrated into some form of electrical pulse generator.

The critical challenge is to reduce the size and weight of these pulsed alternators so that they are compatible with lightweight, mobile vehicles.

The U.S. Navy is currently evaluating two competitive electromagnetic aircraft launch systems as an electrical alternative to steam catapults. The major challenges are engineering issues with extremely high requirements for control, reliability, and robustness in a relatively hostile physical environment. The Navy is also considering the potential to launch hypervelocity projectiles from a ship-based electromagnetic gun.

Launching material directly to space with an electromagnetic launcher is an intriguing goal, and could be a means of reducing the cost of supplying water and other vital materials to stations in space. Compared to the cost of using conventional rockets, an electromagnetic launcher could provide savings that have been projected to be 300 to 1,000 times that amount. But space launch is clearly the most stressing of the possible applications of electromagnetic launch. It may well be, however, that low-cost access to and commercialization of space will be enabled by hypervelocity electromagnetic launch.

The ability to use electromagnetic energy to launch materials controllably to hypervelocity has advanced significantly in recent years. Much more research is needed, but several important applications—with results that are not achievable by any other means—now appear to be possible. I believe that the development and exploitation of electromagnetic launch science and technology will be as important and will have as strong a revolutionary impact on society as the early employment of steam or jet engines or chemical explosives or propellants.

Publication of Research on the Science and Technology of EML

In 1980, a new biennial symposium, the U.S. Symposium on Electromagnetic Launch Technology, was organized to provide a forum for presentations and discussion of research in critical science and technologies for accelerating macroscopic objects using electromagnetic or electrothermochemical launchers. To ensure the quality of the research and to ensure that the early results of this new science and technology would be archival, symposium organizers made an agreement with the Institute of Electrical and Electronics Engineers (IEEE) to review and publish the symposia proceedings in the *Transactions in Magnetics*.

In the late 1980s, the European Electromagnetic Launch Society was formed (EEMLS). The society meets biennially and provides a forum for European scientists to present "works in progress." The presentations at these meetings have generally not been published. The 1998 U.S. Symposium on Electromagnetic Launch Technology was held for the first time outside of the United States at the Royal College of Physicians of Edinburgh, in Scotland, in May 1998. In addition to strong European participation, there was evidence of strong and growing participation from Pacific Rim countries. For example, the national overview of research in China was co-authored by Prof. Wang Ying and Prof. Ren Zhaoxing and delivered by Mr. Li Jun. Mr. Li, a graduate student with Prof. Wang Ying, was awarded the first student scholarship in honor of the late Dr. Peter Kemmey at the symposium.

It was announced at this symposium by the U.S. EML Permanent Committee and the EEMLS that future Electromagnetic Launch Symposia would be consolidated, with oversight and guidance provided by an International Permanent Committee. The Institute for Advanced Technology continues to sponsor and provide editorial responsibility for all of these EML symposia held in the U.S. and abroad.

The published proceedings of the symposia have provided the primary reservoir of information on the development of electromagnetic launch science and technology. But, the important and vital contribution by Prof. Wang Ying cannot be overemphasized. His text, *Physics of Electric Launch,* presents the most critical information from these proceedings and other literature sources in an organized, cohesive, and comprehensive form. *Physics of Electric Launch* is the first English language book on electromagnetic launch and thoroughly describes the mathematical and physics foundation of all types of electric launchers. This book makes an extremely valuable contribution and will take its place in history as the first and preeminent scientific work in introducing and fostering the Age of Electromagnetic Launch Technology.

Harry D Fair

Chairman, International Permanent Committee
Electromagnetic Launch Technology Symposia
and
Director, Institute for Advanced Technology
The University of Texas Austin, Texas

October. 2003

Dr. Harry D. Fair

Dr. Harry D. Fair is the Director and founder of the Institute for Advanced Technology (IAT) at The University of Texas at Austin. The IAT, a University Affiliated Research Center of the U.S. Army, focuses on research in hypervelocity physics and electrodynamics. An experienced laboratory director, program manager, and physicist, Dr. Fair regularly creates, directs, and manages complex multi-disciplinary technical efforts of national importance. Among these are the Joint DARPA/Army/Marine Corps Program on Armor/Anti-Armor, the national Program on Electromagnetic Propulsion, the Advanced Kinetic Energy Technology Program for the Strategic Defense Initiative, the Army Propulsion Program, and the Army Program on Solid State Physics and Chemistry of Explosives and Reactive Materials. Dr. Fair holds a Ph.D. in solid-state physics and an M.S. in chemical physics from the University of Delaware; he received a B.S. in physics from Indiana University.

Preface

The techniques for propelling objects using pulsed electromagnetic force is called electromagnetic launch (EML) technology. Study of EML concepts has a history of nearly one hundred years. Its development has undergone ups and downs. It is an old but young question. Under the pressure of related modern scientific technical progress, EML has made great strides since the late 1970s (marked by the progress made by Dr. Marshall and his colleagues at the Australian National University.) The stage is set for it to be put into practice soon. Another related technique of propelling an object directly or indirectly using plasma generated by electrically heating a working fluid is electrothermal (ET) launch technology. Although it has a history of little more than 50 years, it has obtained significant development in the past 10 years. Its engineering practicality can be expected soon. It is logical to integrate the two into the single discipline, electric launch technology. Although EML technology has made great achievements in the past 30 years, its fundamental research was completed long ago. More than 20 countries around the world are conducting research in this area today. Knowledge obtained can be used to engineer accelerators in the near future.

From the academic point of view, it is still in embryonic form. So far no systemic monograph in English exists in the area of the EML technology or theory. Therefore there is urgent need for a comprehensive monograph on the subject of EML theory and technology, which sums up the research of the past 100 years, and especially the results for the last 30 years, and points to the directions of research and applications for the future. In order to lay a foundation and to develop the discipline as well as to make technical progress, we have written *Physics of Electric Launch* in English, which systematizes the complete theory of electric launch. It not only meets the need in the field of electric launch technology, but also points to its advancement as inevitable. The authors co-operated internationally to produce *Physics of Electric Launch*, the first book on the subject to be published in English, and to be available internationally. Its aim is to promote the development of the electric launch theory and technology.

Electric launch technology, especially the electromagnetic launch technology, is attractive to mankind because it can help advance scientific progress in many areas. For example, it can be used to launch vehicles and materials into space at low cost. It can be used to conduct experimental research on high-pressure physics state equations. It can be used to test the ablation effect when reentry vehicles and meteorite fall into the atmosphere. It can be used to fire tiny projectiles at hyper velocity at the targets so as to carry out inertial nuclear fusion research with the possibility of providing new methods and ways for the exploration of, and development of new energy sources.

EML technology may find a place in existing railways, in oil fields as electromagnetic oil pumps. While in the metal technological area, it can be used in electromagnetic forming, in aircraft launch, etc. Currently the research is focused on various tactical and strategic weapons applications such as the electric gun, the launch of torpedos, rocket launcher, aircraft catapults and so on. Among them the electric gun has been receiving the most attention. All three services (the Army, the Navy, and the Air Force) have need of such devices. At present we cannot predict what other applications may be important in the future. Judging by the research work conducted during the past many years, we deeply believe that the future application potentialities are tremendous, and it will play a role in promoting human social development and civilization.

Up until now workers have been busy doing experimental research without having free time to do systematic theoretical work. This has lead to confused terminologies and ambiguous concepts and definitions in the electric launch field, without an integrated scientific standard. The characteristics and contribution of this book are the following: (1) It presents a relatively scientific classification of all the electric launchers. It builds a structural framework so readers can see the relationship connecting the family members of electric launch technology at a glance. Thus they can master the general outlines of the electric launch technology rapidly. (2) It scientifically standardizes the technical terms in the electric launch field. Previously when the researchers published their papers they often randomly put forward or defined terms to suit their own research point of view. It has been difficult for them to express what they wanted to say precisely and objectively. So the terms in their articles often cannot be recognized and adopted by other people. This book attempts to standardize terms from a physics point of view. So henceforth there will be standard terminologies that can be accepted and acknowledged by everyone in the field of electric launch. (3) It gives precise and scientific definitions of the concepts involved. Previously workers defined and put forward concepts based on their own research experiences. Their meanings have sometimes been obscure and ambiguous which has made their work less acceptable. This book has made new scientific definitions for many important concepts and given them scientific meanings. We present rules for workers in the electric launch academic field to use in their future work thus aiding international academic interchange and development. (4) It systematizes EML theory; something that has been lacking until now. This book presents EML technology and theory as a relatively integral system. We believe that this will greatly help promote the development of the electric launch technology and academic research in the field.

In the concrete, our goal in writing this book has been to help cultivate EML professional teams. Because of the many applications of electric launch technology, and the man's desire to go deeply into the field, more and more people around the world are interested in electric launch technology and wish to enter the field. Thus there is an urgent need to have a readily available book, which lays out the elementary theory of EML. With this book, we systematically introduce the basic theory of electric launch to future workers. We hope this will help them. Whether he is a professional student, or a new comer to EML technology and related scientific research, or a teacher, if he gets the ABC of it from the book he will benefit by being fitted for entry into the field and to help him achieve research fruits in the field. Therefore this book, we hope, will play a significant role in the popularization and application of the EML technology.

This book is the first monograph discussing EML technology in English in the world. Previously Prof. Wang Ying and his colleagues in China wrote *Principles of Electric Guns* and *Principles of New Concept Weapons* in Chinese in the 1990s. Because of the limitation of the language, it was not possible for the rest of the world to understand it. Because of this many foreign scholars suggested translating it into English. But the book includes a large content, and most of the last half deals with the engineering technical problems; while in *Principles of New Concept Weapons*, except for the contents of electric launch technology, there are other subjects. Professor Wang Ying decided that the first six chapters he wrote in *Principles of Electric Guns*, and the four chapters of *Principles of New Concept Weapons* should be combined to form the content of this book.

This book expounds the electric launch technology comprehensively, but due to the limited space, we have not been able to discuss the high power pulsed power supply technology used in the electric launch. Fortunately, Dr. Marshall has finished the writing of Book II: RAILGUS: their SCIENCE and TECHNOLOGY, which is complementary to this book, Book I.

We conclude by expressing our special thanks to Dr. Harry D Fair, Dr. Ian R McNab, Mr. David Haugh, Dr. Thomas Weise, Professor Volodymyr Chemerys, and famous physicists and academicians Wang Ganchang, Cheng Kaijia, Yan Luguang, Yu Daguang, Ding Shunnian and other scholars and friends whose support and encouragement has given us the incentive to finish the book.

We also give our heartfelt thanks to the Chairman of the International EML

Permanent Committee who has written the prelude for our book. This also helps and supports the development of the EML research in China.

We also wish to thank Dr. Li Zhiyuan, Dr. Zheng Ping, Dr. Hu Jinsuo, Dr. Duan Xiaojun and others for their help.

This book has been the result of an international co-operation, but due to the inconvenience in contacting each other, and both being anxious to publish it in a short time, it is inevitable that there will be mistakes and errors in the book. We sincerely welcome readers to point out any problems and to give their advice to us so that we can revise the errors in the next edition.

The authors

October 2003, *Beijing, China*

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