Mega Trends in
Systems, Systems Engineering, and Sustainment

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Commonly, the words "Mega Trend" are used to trace an important shift in society, perhaps even in a civilization. The First Industrial Revolution was a watershed moment in world history with the birth of systems that were designed and deployed, for good or ill, by non-state actors. Starting in the late 1700's, individual innovators and businesses created more and more systems and, over time, systems became more and more numerous and complicated. This trend led to the birth of complex systems, systems engineering, and a systematic way to keep complex systems viable for decades.

I. Introduction

The First Industrial Revolution is the best place to start discussing the proliferation of systems that continues right up to our times.

Oliver Evans' Flour Mill[1] is often used as a convenient starting point for the First Industrial Revolution. Evan's big idea was setting up various machines as a continuous collection of processes. Thus, an important characteristic of his mills is also seen in modern factories: a collection of machines combined to support a specific overall mission. Compare this to the INCOSE glossary[2] which uses the ISO/IEC/IEEE definition of a system as "a combination of interacting elements organized to achieve one or more stated purposes". This creates one leg in the conclusion that the "birth of systems" occurred at the dawn of the First Industrial Revolution.

However, the phrase, "birth of systems", is too simple a statement to be entirely true. Commonly known technology has appeared in history prior to this that could easily qualify as a system. It certainly required innovative engineering and complex production processes to produce the Great Pyramid at Giza[3], or even just one of the great exploration ships such as Magellan's Victoria[4], not to mention the entire logistics-intensive enterprise of circumnavigating the globe. But these were exceptional one-time projects sponsored by entire states or nations. They were driven by singular leaders with considerable individual political power and concentrated wealth. Their effects were felt by many but not in the way that today's modern systems are completely ubiquitous. For systems to become as commonplace as they are today required a revolution in who could imagine and create such systems. Once this occurred, the stage was set for more and more systems becoming a more invasive part of everyone's lives. Thus, the premise of this paper

A short paper on a large megatrend must stay focused to achieve its purpose. However, it should be said that the phenomena of individual innovators[5] starting to create useful systems in this time period owes much to educational opportunities such as increased literacy due to printing presses, the ability to accumulate and exploit capital and labor (capitalism), and societal attitudes of Western Civilization in general -- as well as many other factors that could be listed and discussed ad nauseum. I personally believe the largest of these factors was the active and passive incentives from the British, French, and United States laws allowing for individual inventors to reap the profits of their innovations. However, why this all started when and where it did is not the topic of this paper.

This paper's scope is: a) the birth of systems, b) their increasing complexity and increasing capability to be used to spread prosperity or misery, c) the birth and maturation of systems engineering, and d) the outcome of more and more complex systems living longer and longer lives. In each of the following sections, certain selected individuals are discussed to lend emphasis to these trends. Sadly, and with apologies, in this short paper, many equally deserving individuals are left out.

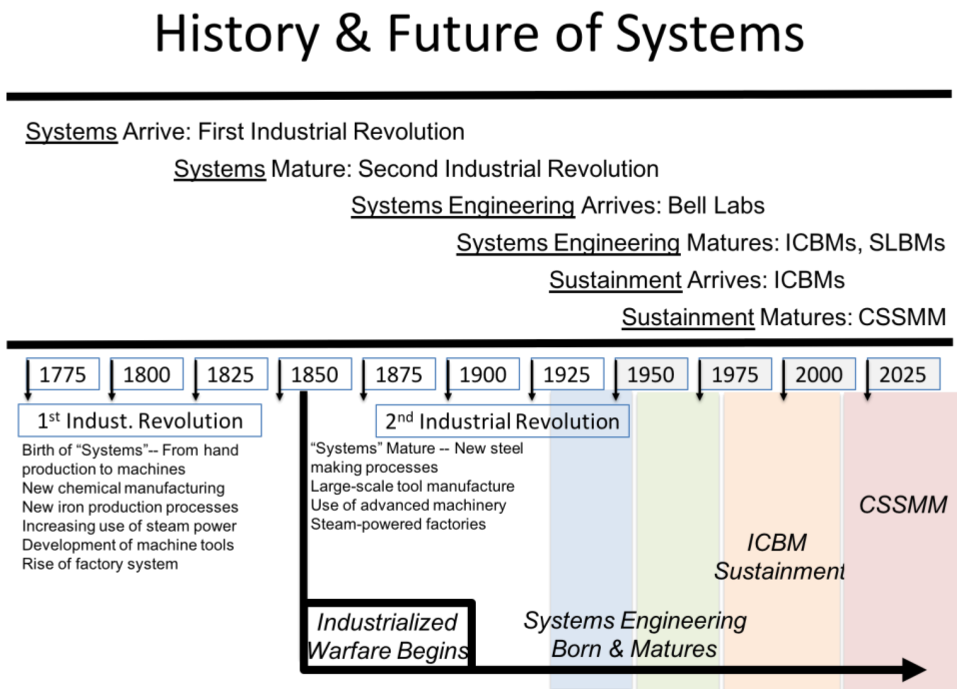


Figure 1: History & Future of Systems. *A summary of the megatrend*

II. 1790-1865: The Birth of Systems

See figure 1. Evans has already been mentioned as possibly creating the earliest version of the modern factory. Other characteristics of the First Industrial Revolution were the movement from hand-work to machines including new machine tools and factory tooling, new chemical manufacturing processes, new iron production processes, and the increasing use of steam power to drive the factories and other machines. One very notable steam-powered machine was the railroad steam engine. That invention, plus all the machinery and logistics associated with it created a powerful system to open up rural areas in the USA, England, France, and others to booming economic development.

Important other new systems were the factories that were able to mass produce firearms and rifled bullets, telegraph networks, and the new fledgling aeronautics industry. All of these inventions were critical in making the American Civil War the best example of the first modern industrial war.

Just because the conditions were right for individual actors to drive the Industrial Revolution did not mean the State was no longer an actor. A system is a combination of interacting elements organized to achieve one or more stated purposes. And if you, as the State, find yourself with a mission to kill or maim as many of the enemy soldiers as possible while destroying their possessions and institutions, new modern systems are an obvious solution. This is especially true if you are the industrialized North and fighting a less-industrialized South. If the best measure of the effectiveness of industrialized warfare is rapid death, it should be noted that 600,000 died in a nation of 35,000,000 in a little over 4 years. These were mostly men of the same generation, often family members fighting other family members. It was a tragic and traumatic national experience whose effects are still with us today. Sadly, as we shall see, it is not the largest of the tragedies aided by systems.

Learning from the past means we do not flinch and look away. What did this war teach us about systems? The Civil War employed the steam engine not only in the railroad systems but also their ships. Perhaps even more important than arming the troops with accurate guns (rifled barrels) and mass-produced bullets was the ability to create all these things at a high rate using steam-powered factories.

To the open-minded military mind, the importance of a strong industrial base was a key lesson of the Civil War. But not all lessons are learned the first time around. It will become clear later why it is important to mention here the use of reconnaissance balloons in the Civil War. The best and most famous aeronaut fought for the North, Thaddeus S. C. Lowe. It took flamboyant characters like the "Professor" to haul sulfuric acid on wagons, throw iron filings in them to produce highly explosive hydrogen gas, dangle in the sky within reach of enemy weapons at the end of redundant tethers and wires in search of important intel, and telegraph from the air that intel to the leaders who needed it immediately.

A famous story, possibly larger in the re-telling, has his 20-something Parisian actor wife disguising herself as an old hag to ride her buckboard across territory held by the South to rescue her downed husband. More to the point, Professor Lowe is considered responsible for very notable contributions to the war efforts of the North. For instance, he predicted Confederate troop movements precisely enough to have saved the isolated army of General Heintzelman. However, despite great stories and important tactical victories, aeronautics was not viewed by a sufficient number of military leaders as a significant contributor to the Civil War. More lessons were to come.

American was a very different country after the Civil War. But hidden among the gut-wrenching death and destruction, end of slavery, and huge social upheaval, it is sometimes lost how much more *modern* the country was in the second half of the 1800s than the first half. Railroads opened up the West bringing people, tools, communications, and prosperity undreamed of prior to the Civil War. The Second Industrial Revolution was well under way.

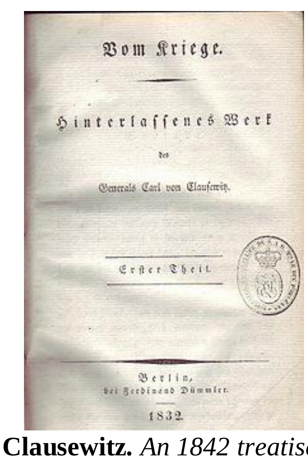
III. 1866-1938: More Systems and More Complicated Systems

More and more complicated systems arrived during this time period of post-Civil War to pre-WWII, impacting both civil and military institutions, culminating in the military and civilian innovators combining forces to prepare to defeat the Axis Powers.

The Great War (that is, WWI) and the Spanish Civil War continued the aeronautical trend mentioned in the last section. WWI saw the use of heavier-than-air craft whose mission was often to bring down reconnaissance balloons. Air to air combat and air to ground attacks were also used but were not fully developed. Just a few years later, the Spanish Civil War saw the horrible effects of strategic bombardment from the air, most notably the city of Guernica as captured in the famous painting by Picasso. Deaths from these wars were estimated at 17,000,000 and 200,000 respectively.

But the Great War also was responsible for another 60,000,000 deaths worldwide from the mis-named Spanish Flu. Is it fair to imply that industry and systems are someway responsible for these deaths as well? Did the peculiar conditions of close quarters and high rates of violent, quick death in the trenches help to breed this killer disease and unleash it on the world as the conflict ended and soldiers returned home? If this position is taken, it helps systems engineers of today to realize that complicated interacting systems may lead to results that were nowhere near the intended purposes. In fact, systems engineers today readily agree that a system may be labeled “complex” in that certain states can emerge that were unforeseen. But perhaps systems engineers don’t yet appreciate the full implications of this concept.

Back in the 1930’s, the American Civil War, the Great War, and the Spanish Civil War were on the minds of the US Army Aviation Signal Corps as they developed the US Army’s military doctrine on strategic bombardment[6]. Von Clausewitz, in his famous treatise, “On War”[7], said that a successful army determines and defeats the enemy’s “center of gravity”. See figure 2. The big idea of the Signal Corp officers was to identify that center of gravity as the nation’s industrial capability and develop an aerial strategic bombardment doctrine that would jump the trenches of WWI and reduce and eventually destroy it.


Vom Kriege.

Hinterlassenes Werk

des

Generals Carl von Clausewitz.

Erster Theil.

Berlin,
bei Ferdinand Dümmler.

1832.

Figure 2: On War by General Carl von Clausewitz. *An 1842 treatise that still steers our Air Doctrine today.*

Many debates were held on what the most vulnerable targets might be. Should attempts be made to destroy the entire steel industry or is that too distributed? Should all dams be attacked or are they too hard to destroy? Perhaps there is some single item that is easier to destroy but would have a devastating effect on a nation’s industry?

This kind of mental preparation laid the foundation for President Franklin Roosevelt, whose term started in 1933, to start preparing the nation for the eventual conflict in Europe. The year 1938 was chosen to end this section because that was the date the first B-17 all metal, high-tech bomber flew for the first time. We will see in the next section what the best targets turned out to be. This was also the year that Hitler invaded Austria, starting his acquisition of sovereign countries and Britain's policy of appeasement.

Backing up and looking at the civil systems side of the United States we see that necessity truly is the mother of invention; a new nation had demands to place on its innovators, inventors, and entrepreneurs. Certainly, innovations continued in transportation, automated factories, and farming. The best example in the constraints of this short paper to illustrate this trend is the telephone.

In 1874 Alexander Graham Bell conceived of the modern telephone. By 1910, there were 6 million phones in the Bell system in the US. By 1925, Bell Labs was founded. There were 17 million telephones in the United States, 12 million were in the Bell System. By 1934, Bell Telephone was a federally regulated monopoly. By necessity, due to this level of complexity, Bell Labs developed the basic ideas of systems engineering. These ideas served them and the nation well in the years leading up to WWII and after where they made significant contributions to the war effort with their systems[8].

A few examples will suffice. In 1938, Bell Labs set up the Whippany Group in response to the US Navy's desire to employ radio waves to detect other ships, i.e. Radar. From 1937 to 1940, George R. Stibitz of Bell Labs was creating electronic (analogue) computers which, in 1940, would form the heart of their work on advanced fire control systems. Similar work was starting on SONAR and the complex communications demands of wartime.

IV. 1939-1980: Birth and Maturation of Systems Engineering

If a Pharaoh could demand a Great Pyramid and King Charles of Spain could fund Magellan's 4-ship journey around the globe, how much more could the worries and priorities of America's President Franklin Roosevelt from 1933 to 1945 propel America to create the complex systems needed to triumph in WWII? Massive numbers of modern all-metal aircraft flying in protective formation[9] is a good example to illustrate how complicated systems were to become. The complexity includes many examples. For instance, huge daily strategic bombing campaigns and forward-deployed maintenance to factories back home in the "arsenal of democracy".

As stated, back in the 1930's, although isolated by two huge oceans, key American leaders could see that the Great War in Europe had resolved nothing and a greater war with even more destruction was likely. The Civil War and its impact pitting brother against brother and destroying a generation of good men was still fresh in their minds. Many of those same leaders had witnessed first-hand the industrial-scale killings of WWI where machine guns forced troops into hellish trench warfare. Then the bombing of Guernica from the air added another layer of horror to any potential future war. On top of this, post-war prosperity was short-lived as the Great Depression struck the world and Germany plotted revenge for the Treaty of Versailles.

FDR and other leaders had some good ideas on airborne strategic bombardment to help guide some of their choices. Good-sounding doctrine is one thing. Successful realization of that doctrine is quite another. Strategic bombardment was not easily achieved, but it was eventually demonstrated during WWII by bold leaders such as General Curtis LeMay[10]. LeMay took the new doctrine of strategic bombardment against the enemy's industry and proved it could work. D-Day was possible because of the efforts of the Allied Combined Bomber Offensive in destroying German industrial capability. In the Japanese Theater, full realization of this doctrine evolved to the point where one aircraft could stop industry in one city within hours with one B-29 bomber and one very deadly bomb. See figure 3. This culmination of strategic bombardment doctrine effectively ending WWII but left our nation realizing our own vulnerabilities from other nations.

Figure 3: After the Bomb. *Japanese family lives in ruins of Nagasaki in a shelter of bits of debris, on a terraced hill that was once row on row of houses. Truman Library Accession Number: 98-2462*

To answer the question posed above, very effective targets in Europe proved to be industries like oil refineries, rail road switching yards, and ball bearing plants. See figure 4. This required low-level precision bombing resulting in relatively few casualties on the ground (although it was relatively deadlier to the bombers and crews). Japan's industry, on the other hand, was powered by small industries that were spread around within large cities built primarily of very vulnerable wooden structures. Incendiary bombs were used against this cities and massive civilian casualties were a very predictable by-product. The argument has been made that massive formation bombings killing 50,000 to 100,000 in a single night were considered entirely acceptable because Americans hated Japanese and considered them racially inferior. Others argue that this was simply a by-product of good industrial warfare tactics. General LeMay famously said in both theaters that if you kill enough of them, they stop fighting. This sounds monstrous, but his thought process was that a quick resolution of the war would actually save lives[11]. All agree that, just as in previous modern industrial wars, the use of advanced systems can be made to kill people and destroy things at a very high rate.

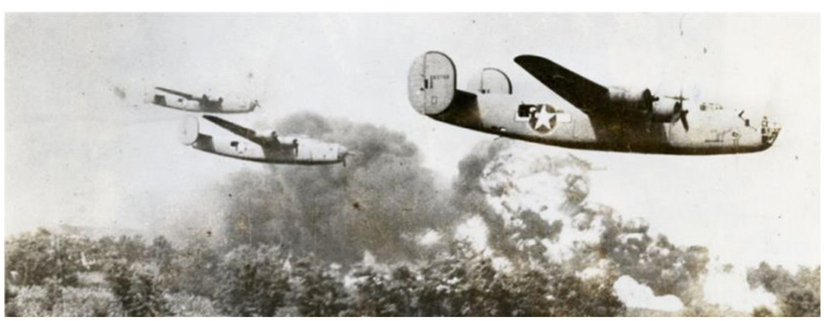


Figure 4: Attacking a Nation's Industrial Capability. *B-24 Bombers Over Ploesti Oil Refineries*

General LeMay also led the Strategic Air Command (SAC) after WWII. The mission of SAC (in cooperation with the Navy nuclear-tipped missile submarine fleet "boomers") was deterrence. Leaders in the United States immediately after the war came to the disturbing conclusion that, having proved to the world that strategic bombardment is highly effective against an industrialized nation, our nation was now unacceptably vulnerable to attack. Two large oceans were no longer a significant protection. For instance, the USSR, a WWII ally, retained considerable experience and capable aircraft and appeared to have few inhibitions against improving and using this power. US and European leaders knew that Jozef Stalin was personally responsible for 23 million deaths not associated with the war. And Soviet premier Nikita Khrushchev was famous for rhetoric such as "We will bury you", a phrase he used addressing Western ambassadors at a reception at the Polish embassy in Moscow on November 18, 1956.

After the War, the USSR quickly developed atomic and nuclear weapons and the means to deliver them, detonating their first bomb in 1949. Those individuals who still felt the problem of attacking the US was still too difficult quickly changed their position after the USSR's Sputnik flew overhead in 1956. The US rejected the idea of a first strike to remove the Soviet threat and, instead, developed the doctrine of deterrence. In other words, no rational national leader would mount an attack against the United States if the response would be immediate destruction of their nation via our considerable nuclear attack capability of manned bombers, Intercontinental Ballistic Missiles (ICBMs), and Sea Launch Ballistic Missiles (SLBMs).

Meanwhile, back on the civilian side, with all of these key engineering developments, the United States enjoyed the prosperity inherent in moving from a war-footing back to civilian industry in a country virtually unscathed by direct attack. New personal automobiles were once again a technology open to most. Airlines formed based on technology and pilots from the war. Radio remained popular and TV emerged. Telephones, refrigerators, washing machines, and modern fabrics reshaped everyone's lives. The ability to transport perishable items in air-conditioned trucks over the new interstate highway system improved everyone's life. The GI Bill transformed colleges and created the core of a new economy. On the civilian side, the steady drumbeat of more and more systems along with their associated production and logistics systems continued and grew.

As mentioned above, systems engineering was born at Bell Labs in the mid 20th century to deal with the trend of the increasing complexity of War Department demands for more and more sophisticated systems. Here are a few more examples that happened during WWII: During WWII, rubber was hard to get so Bell Labs made significant contributions to the creation and use of synthetic rubber. By the end of the War General Eisenhower in Africa could communicate with General MacArthur in Australia. In fact, during the War, Bell Labs had to manage over 2,000 important but disparate projects, a significant systems engineering problem in itself.

After WWII, systems engineering was brought to maturation by the USAF and US Navy as they created the highly complex ICBM and SLBM weapon systems. (More on this complexity in the next section.) One of the remarkable stories of systems engineering was the birth of TRW, Inc based primarily upon Simon Ramos and Dean Woolridge's delivery of systems engineering services to Bernard Schriever, the USAF general charged by President Eisenhower to create ICBMs[12].

V. 1980-2019: More Complex Systems Living Longer Lives

As these nuclear deterrent weapons were kept employed over decades, a threshold was passed in the late 20th century that demanded that various sustainment tools and approaches be re-organized into a systematic way to sustain these ever longer-lived and more complex systems. Specifically, ICBM sustainers, out of need and ability, came up with the complex system sustainment management model to ensure continued mission support.

Modern Trends in Systemic Death

Before tracing that trend, we will take a step back to the Civil War, the world's first industrial war, and look forward to today, trying to tally the human suffering attributable to the misuse of industrial power via complex systems. The measure will be human carnage. The reason for this analysis is to remind us of the power of efficient systems and how that power can be tragic when concentrated in the wrong hands. Closely related is the justification for creating and threatening massive world-wide retaliation in an effort to stave off these potential abuses in the United States, that is, the doctrine of deterrence. One of the most important questions of our time remains (and will not be answered here) does the combination of these systems result in a stable world or will the nuclear deterrent be added to the list below?

To restate, mass death tolls[13] from the American Civil War to the post WWII era points to the ability for large efficient systems to produce human misery and death on an unprecedented scale. For comparison, over the period of the start of the 1800's to the end of the 20th century, the global population rose from 1 to 12 billion. The world's population trend is roughly exponential with 3 billion attained around 1960. In some of these examples below, such as the Spanish Flu and Mao's reforms, the rapid demise of huge numbers of people turned out to be an unintended consequence of a system meant for a more noble purpose. Others were much more intentional.

Some of these numbers have already been quoted above:

Industrial War Death Toll Estimates, Major Examples
Civil War: 600,000 dead
Great War: 17M direct combat, 60M Spanish Flu
Spanish Civil War: 200,000
WWII: 60M

Industrial Dictator States Non-war Death Toll Estimates, Major Examples
Ottoman Empire, Ismail Enver Pasha: 2.5 million deaths
(1,200,000 Armenians, 350,000 Greek Pontians, 480,000 Anatolian Greeks, 500,000 Assyrians)
Belgium, King Leopold II: 2-15 million deaths
Japan, Hideki Tojo: 5 million deaths
Nazi Germany, Adolf Hitler: 17 million deaths
USSR, Jozef Stalin: 23 million deaths
Cambodia, Pol Pot: 1.7 million deaths
North Korea, Kim Il Sung: 1.6 million deaths
Peoples Republic of China, Mao Zedong: 49-78 million deaths

Deterrence as a National Policy Results in Complex ICBM Systems

Given the ability for humans to inflict such devastation in our modern times, and given the reluctance of American's national leaders to engage in first strike tactics to destroy building threats, a policy of deterrence, for all its flaws, seemed the only choice: *Hold a pistol to the head of the armed adversary and maybe he won't attack.* This approach has been created and implemented out of fear. It is a reasonable fear, but the author hopes following generations find a better solution for world stability that retains the ability to keep massive death at bay[14].

All of this, and more, set the stage for the creation and deployment of a massive, complex system to precisely and accurately deliver nuclear death halfway around the world. The Triad of Deterrence consists of Intercontinental Ballistic Missiles (ICBMs), Sea Launched Ballistic Missiles (SLBMs), and manned bombers.

To make the point of this paper in the space allotted, the focus is on ICBMs.

The task to develop and deploy ICBMs came from the President directly to General Bernard A. Schriever and he did not hesitate to use the top executive power of the US to get the job successfully accomplished[15]. This team of experts, military and contractor, needed to create, operate, and maintain ICBMs was somewhat isolated from the rest of the USAF. This focus on tribe across operators, developers, maintainers, and executives forged a strong bond and a winning team.

Top uniformed military, civil service, and contractor minds developed the basis for keeping ICBMs available, reliable, accurate, hard against nuclear attack, safe, and sure for decades. TRW continued to deliver systems engineering and technical assistance until 1998 when they competed and won the USAF contract to deliver Prime Contract services to the USAF. In 2001, Northrop Grumman acquired TRW, Inc. At the end of the 15-year ICBM Prime Contract contract, a shift in DoD policy led to the USAF taking on more ICBM systems engineering and integration roles, managing multiple contractors themselves while simultaneously developing the next generation ICBM[16].

ICBMs are complex systems. See figures 5 and 6. They include the missile with all of its integrated subsystems, the launch facility, launch control facilities, support equipment, training devices, logistics systems, technical orders, personnel, and all of the USAF and contractor personnel providing sustainment services. There are over 400 missiles currently deployed across the Nation's northern tier[17].

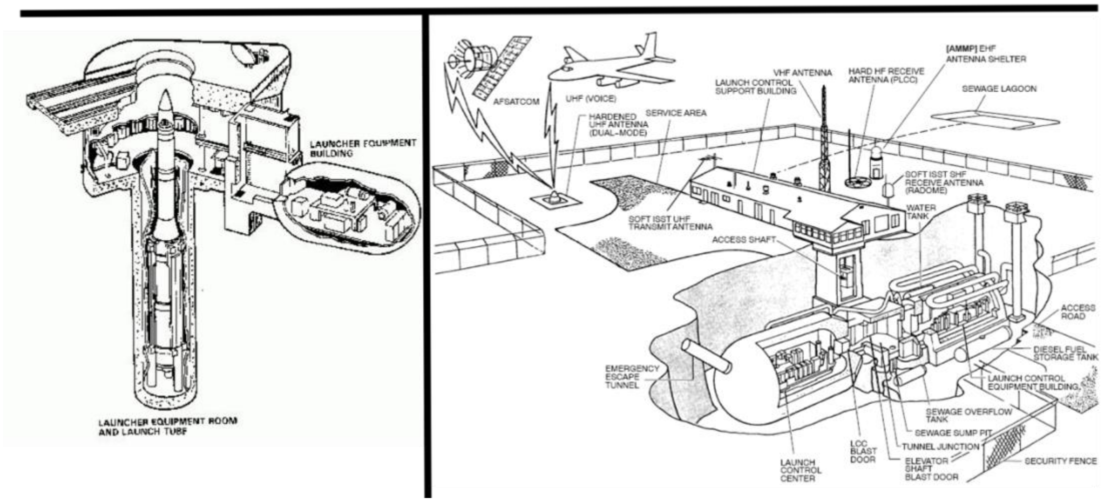


Figure 5: Minuteman ICBM Launch Facility with Missile and Launch Control Facility. *A complex system*

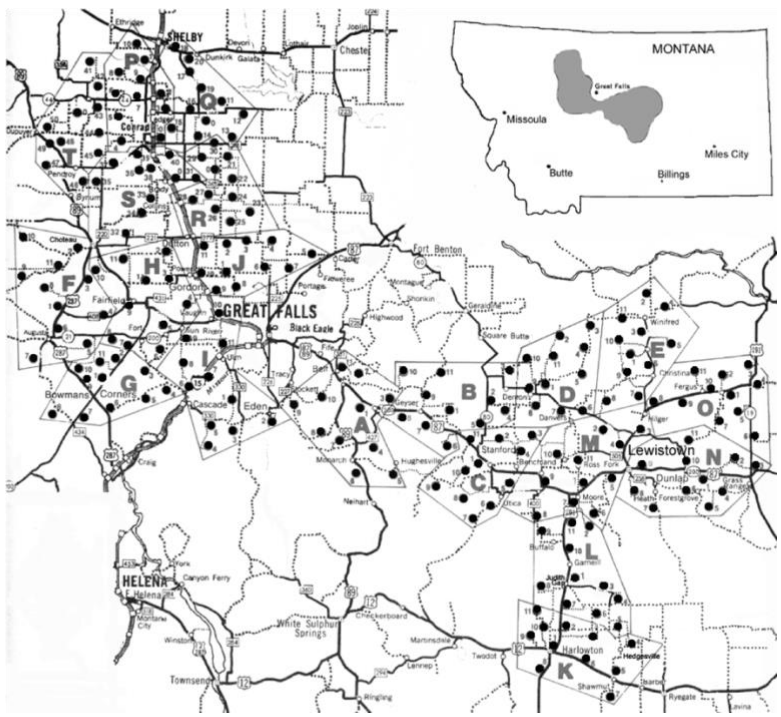


Figure 6: ICBM Sites. *Not only complex, but remote and numerous. Two other bases exist also.*

The Complex System Sustainment Management Model (CSSMM)

This author was hired by TRW Inc, in 1985 where I began my ICBM career providing technical advice to the creation and deployment of training devices. My very first task was the trainer for the sump pump at the bottom of the missile silo. When I retired in 2014, I was the Prime Contractor’s manager for the ICBM Guidance Department. In the span of those 29 years there was a lot to learn about the best ways to sustain this massively complex system. This approach basically applied systems engineering to the problem of sustainment. In retirement, I have written and spoken across the country on this integrated approach which I have generalized to any system and called the Complex System Sustainment Management Model or CSSMM.[18] In those writings, successful sustainment is defined as:

“The continuous, effective support of the system to ensure mission success”.

In a nutshell, sustainers must know the mission well enough to define and track those handful of readiness factors which are used to detect emerging failure modes with sufficient time to mitigate risks to the mission. Readiness factors, such as reliability and availability are precisely defined and tracked via a strong observation and assessment program. Much attention is paid to developing the people, ensuring adequate data bases and associated tools, and following strict process discipline. The titles of a few typical periodic reports can shed light on this approach:

Age Surveillance Integrated Approach Plans
Risk Data Base linked to Risk Mitigation Programs
Weapon System Effectiveness
Long Term Planning
Integrated Deployment Schedules

1985 was a time of increased hiring at TRW in Utah, and like many at the time, a few key events shaped our direction. More and more effort was going into sustaining the current systems. This is why the increased hiring in Utah at Hill AFB, a logistics base. There were still many who sincerely believed that the Minuteman ICBM was just another ICBM that would soon be retired for the next, better ICBM. This was reinforced by executive decisions that would establish a time in the near future for the system to be retired. Planning tended to revolve around holding things together for another few years[19].

The more savvy realized that this game would repeat and continue for decades, so they searched for a more permanent approach to sustaining this complex system. Many sophisticated pieces to this sustainment approach already existed, so the task of putting their pieces into a logical, integrated, and systemic approach was that much easier.

Many ICBM sustainers had studied at the University of Southern California, attaining a Master of Science in Systems Management. This degree was offered to USAF captains who needed a master's degree to achieve further promotion and was attuned to the needs of the officers who would be managing very complex systems. Many of these officers spent countless hours, weeks, months, and years on strategic alert (including ICBM missile combat crews, that is, the ICBM operators) with time available to study for a master's degree. USC catered to this need with an excellent academic program delivered effectively to any USAF officer who requested it. In the 1980's many contractors and USAF personnel had this academic degree and approached sustainment from the point of view of systems engineering and systems management.

The Future of Sustainment

Twenty years into the 21st century and things have changed. Those USAF and contractor personnel who invented a workable systematic sustainment approach are retired and, frankly, dying, just as more and more demand is arising for a systems sustainment approach for all weapon systems. For instance, the USAF now expects its aircraft to last for decades. The same applies to civil systems, commercial space systems, and more. Just consider the chief engineers of global companies in charge of world-wide requirements for integrated HVAC systems, medical systems, or agricultural fleets. They are all facing the same problems and issues with their complex systems[20].

Meanwhile, theoretical understanding of massive complex systems is now expanding into non-manmade systems such as Earth climate or global economic systems. It is my belief that these same sustainment principles can be usefully applied there as well.

2020-2040: Conclusion & Call to Action

The best conclusion for a paper on a mega trend is a prediction: If this Mega Trend continues, over the next two decades there will be a proliferation of papers, books, and presentations on the subject of complex system sustainment. This will occur in order to support the growing numbers of individuals tasking with performing this important activity. To put it another way, just as the fledgling WWII-era concepts of systems engineering matured into the establishment of a well-defined and well-respected branch of engineering, we will see the next two decades elevate sustainment into a well-defined set of agreed-to, top-level principles required to establish the same maturity for sustainment of complex systems.

Any such discipline can and should take into account the complex systems that are not man-made and those man-made systems that are turned, intentionally or unintentionally to disturbing (to say the least) purposes or missions.

At the same time, we are on the cusp of losing our understanding of the complex system sustainment management model. The Minuteman III ICBM from which these sustainment approaches sprang is about to be retired and replaced with a new system. That is, the focus is shifting from sustainment to development. Those who created and improved it over the years are retiring and many have already expired. The University of Southern California Systems Management Master's Program that was instrumental to the creation of the CSSMM was eliminated in 1992. Already many of the hard-fought understandings are being re-developed with much blood, sweat, and tears, independently by others facing the same issues. ICBMs, a community unto themselves, have not shared these insights on the world stage.

Complex systems are a serious business. They can destroy cities half-way around the world with nuclear bombs or they can provide world-wide famine relief with better agricultural and transportation systems. Just because our death count in the 21st Century is less than the 20th is no reason to be complacent. Don't forget the 1M dead in the Middle East over the last few years. The choice is no longer ours to have or not have more complex systems. But it is our choice to use them wisely and better learn how to provide continuous, effective support of the system to ensure their mission success.

End Notes

[1] Information on Evans is easily found and seldom contradictory. The casual reader can reliably start with Wikipedia or a university history site and then expand your search from there.

[2] International Council on Systems Engineering (INCOSE)'s sebokwiki web site.

[3] I recommend Justin McMurray's INCOSE webinar for an entertaining discussion of the Great Pyramid and systems engineering. Webinar 117: The Past and Future of Systems Engineering.

[4] Ferdinand Magellan's circumnavigation of the globe started with four ships but ended with just one, the Victoria. It is important to remember that accomplishing this first-ever complicated logistical and navigational feat required much more than just having high-tech ships. How much of the logistics, planning, and other elements would benefit from a systems approach? Magellan was certainly a program manager of extraordinary talent, but how much of a systems engineer (well before systems engineering was created) was he? It is also fun to note his connection to his idol, Christopher Columbus, and how Ferdinand got his funding from the grandson of the same royal family that funded Columbus. Many sources are easily found so the research is left to the reader.

[5] For a fascinating and long list of USA-centric inventions of this time period see: http://storiesofusa.com/industrial-revolution-inventions-timeline-1712-1942. Who knew there were so many sewing machines out there?

[6] U.S. Government, *The Development of Air Doctrine in the Army Air Arm 1917-1941 - Hap Arnold, Chennault, Douhet, Mitchell, Foulois, Drum Board, Alexander de Seversky, General Eaker, World War I and II* (USA, independently published in 2017 and sold on Amazon.com)

[7] Carl von Clausewitz, *On War* (Overland Park, KS, USA, Digireads, 2018) This version is in English as translated by J. J. Graham. Digireads publishes classic works of literature in inexpensive paperback form and sells them via Amazon.com and other outlets.

[8] M. D. Fagen (Editor), *A History of engineering and science in the Bell System: National Service in War and Peace (1925 - 1975)* (USA: Bell Telephone Laboratories, Incorporated, 1978). This is a must-have text for any systems engineer.

[9] You can find illustrations and stories about how WWII bombers flew in protective formations at reunion sites such as www.b24.net/MM031844. My father's diary/memoirs as a B-24 ball turret gunner is captured here https://charlesvono.com/staff-sergeant-michael-peter-vono-bombs-twinkling-like-stars/. I also highly recommend the 1949 movie "12 O'Clock High" starring Gregory Peck for initial background and frequent re-viewing. This movie, likely the most realistic WWII Combined Bomber Offensive movie ever made, is based closely on a true story. USAF and major corporations still use this film in leadership training. In addition, just about any internet search will yield great stories and illustrations.

[10] Warren Kozak, *LeMay: The Life and Wars of General Curtis LeMay* (Washington D.C.: Regency History, 2011)

[11] He also famously said: "I suppose if I had lost the war, I would have been tried as a war criminal." An hour spent looking up just his quotes is an hour well-spent. Recall, also, that when George Wallace ran for president, he was his running mate. Wallace's intentions were clear. But LeMay's speeches often discussed the importance of what we now call the "environmental movement".

[12] Timothy C. Jacobson, *TRW 1901 to 2001, A Tradition of Innovation* (Wipf and Stock, Eugene, Oregon, 2016)

[13] Perhaps the best approach to researching these deaths is the use of an internet search on the event or individual's name. One characteristic of these examples is the inability to precisely estimate the actual numbers of deaths. But I think this table gives the most honest comparisons.

[14] There is an important role to be played in nuclear deterrence by the anti-nukes protestors. The use of nuclear weapons as a deterrent should not be seen as a permanent solution, but one that works long enough to buy us time to find a

better solution. ICBM team members, for instance, have been and will be key in the reduction of nuclear weapons over time. This kind of support includes effectiveness assessments, design of new configurations, support for field inspections by treaty-signers, and more.

[15] Neil Sheehan, *A Fiery Peace in a Cold War: Bernard Schriever and the Ultimate Weapon* (New York, Random House Publishing Group, 2009) This is an excellent, thorough, and well footnoted discussion of what I have ruthlessly summarized in this paper.

[16] Those historical events discussed in this paper prior to 1985 have been footnoted to provide references to the veracity of the history discussed. Post 1985, the author claims the right to be the primary source, having lived this history.

[17] The author frequently gives hour-long presentations to the uninitiated on how ICBMs work and just how complex they are. Presentation charts and videos can be found at charlesvono.com.

[18] For an introduction to the Complex System Sustainment Management Model, see my paper, "Fundamentals of Weapon System Sustainment" from SciTech 2016, or similar papers or blog posts at charlesvono.com.

[19] A "wake-up call" for many of us was working on the 1987 and 1988 reliability studies. The efforts leading up to the publication of these two watershed reports demonstrated a clear need for an approach that was not a major effort every few years, but a daily approach to sustainment. The reports are official use only published by the ICBM System Program Manager in the Directorate of Material Management at Ogden Air Logistics Center, Air Force Logistics Command. *Minuteman III Reliability Assessment Report*, 1987 and *Minuteman II Reliability Assessment Report*, 1988. They were hundreds of pages each and had classified addendums. The scope was intended to be comprehensive, each missile subsystem, ground systems, support equipment, technical orders, personnel training, and more. Upon completion, while sighing with relief that this major task was successfully completed, many of us looked at each other and said: "Sure, but what about availability? Accuracy? Hardness from nuclear attack? Each of those is just as important as reliability".

[20] One example of this need can be witnessed by attending an INCOSE regional conference where the vast majority of attendees are engineers working for TRANE, John Deere, and other multi-national civil systems industries.