<論　　説>

航空機事故に見る技術的リスクとその克服

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要旨と解説

本稿の目的は，新技術がある一定の経験の蓄積によって，急速に事故確率を下げる傾向のあることを，航空機を事例として検証することにある。本文に先立ち，要旨と解説を付記しておく。

技術ライフサイクルを知る手掛かりとして，W. アバーナシーのガソリン内燃式エンジン車の事例がある[1]。19 世紀後半，自動車の動力源として，蒸気機関，電気，ガソリン内燃機関の 3 種類のエンジンが試作・実用化されていた。ガソリン内燃機関は，エンジンの始動が早く馬力もあったが，時に爆発事故を起こすことが最大の問題であった。その後，ピストン内の摩擦熱を下げるためにエンジンオイルによる潤滑化等を進め，実用化を促進する。

アバーナシーは，1908 年のＴ型フォードの完成を，ガソリン内燃式自動車の「ドミナント・デザイン」と見ている。ドミナント・デザインとは，作る側からも使う側からも，一応納得が得られるような支配的な製品形態を意味する。無論，それ以降の改良も必要になるときが来るが，一度ドミナント・デザインが確立されると，品質が安定し，ラディカルな製品革新は影を潜め，むしろ生産工程の効率化と製品価格競争へと，事業展開の方向に変化が現れる。

つまり，ドミナント・デザインの成立は，製品ライフサイクル[2] を揺籃期から成長期にシフトさせ，競争の焦点を品質競争から低価格化競争へと移行させる。このことは言わば，深刻な事故の克服を意味しているとも言える。

こうした事例に基づく検証には，開発プロセスに関する記録が不可欠であり，その点比較的新しい事例が研究対象として重要となる。本論で検討する事例は，ジェットエンジン機の開発に関するもので，世界で 1950 年前後から始まった新規技術であり，開発プロセスに関する記録が比較的よく揃っている。

開発当初は，深刻な事故が多いが，絶えざる試行錯誤による改良改善が積み重ねられる。合理性に限りのある人間には，先験的に技術的リスクを予見することが難しく，やってみなければ分からないことがたくさんある。ところが，この繰り返される試行錯誤のうちに，ある時急速に事故率が低くなる時点を迎える。すなわち，ドミナント・デザインが成立し，新製品はここからコスト的にも急速な低下を実現し，成長過程に入ることになる。

著者が，かかる技術的ライフサイクルに関心を持つのは，この概念が原子力発電技術ないし原子力発電産業の将来を展望する上で，適切なアナロジーを示してくれると考えるからである。

現在，日本は原子力発電を促進すべきか，踏みとどまって撤退・転進すべきか，その判断の岐路に立たされている。フランスは，原発推進の姿勢を鮮明にしている。ドイツは，メルケル政権下で脱原発の決定をした。このヨーロッパ二大国の正反対な意思決定こそ，人間の限定された合理性を象徴しているように見える。

原発は，改良によって将来性を開くことができる技術なのか，それとも改良がさらに増幅されたリスクを生んでしまうような，「デッド・エンド・テクノロジー」[3] なのであろうか。この問題に対する解答を得る上で，限定された合理性によって繰り返される試行錯誤としての開発プロセスを，他種産業の事例を手掛かりに類推してみることが有効ではないだろうか。

開発プロセスとは，言わば技術的リスクの克服過程だが，新技術には新しいリスクが伴う。これをさらに新しい技術で解決しても，さらに新しいリスクが随伴する。こうして技術という「禁断の知恵の実」を一度口にした人類は，永久に技術革新を続けねばならぬ宿命を負った。

現在，旅客機の事故確率は 100 万分の 1 にまで下がっていると言われる。それでも飛行総数からすれば，約 1 年に 1 機の割合で墜落事故が起きる。自動車による死亡事故はケタ違いで，日本だけでも年間 4000 人程度の死亡事故がある。しかるに，この大型ジェット機 10 機分の自動車による死亡事故よりも，1 機の旅客機の事故の方がセンセーショナルに語られる。この点，原発事故もこれに似ており，事故防止のための安全対策が極めて厳格に要求される。

自動車に続いて，ジェット機の技術的リスクとその解決プロセスを調べることによって，我々はそのアナロジーを以て原発技術の現状と将来を見据えることができるかも知れない。

注

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3. Oyama, K. “Nuclear Power Technology in Post-Industrial Civilization – A Comparative Study of France and Japan –” Chap.3-3 pp. 28-32. The Official Report of EHESS in Paris 2022

Overcoming Technological Risk: A Case of Aviation

We can utilize the automobile industry as an analogy to describe the nuclear industry. This is due to the industries shared phenomena as processes of new technological development. W. J. Abernathy’s theory is useful for understanding the normal progression of a new technology.[1] We can use this theory to predict the future development of the nuclear industry.

In this article, another analogy of a jet-airplane industry will be developed. Through our understanding of the technological improving process in various industries, we can find a present state of nuclear industry, moreover, we can predict a future condition of the industry.

1. Trial and Error in a Fluid Stage

We define the “fluid stage” as the period during which a breakthrough technology emerges, and a dominant design is established, in any kind of industry. During the fluid stage, an active trial and error process is developed. Naturally, many failures or accidents occur during this period, and various improvements are subsequently adopted. This trial-and-error process is inevitable when constructing a dominant design that is feasible, credible, and easy for both manufacturers and users. Once such a standard is constructed, it rapidly becomes stable.

Another analogy for the nuclear industry

In this article, we examine the aviation industry as another analogy for the nuclear industry. We also utilize Abernathy's theory, introduced by the automobile industry, to understand and explain aspects of the aviation industry. These two transport industries have some commonalities; for example, both industries are popular, widely influential on human life, and attract attention for their performance and safety.

However, J. S. Alarcos points out that the degree of attention paid to accidents in these industries differs.[2] For example, in 2017, approximately 40,000 people were killed in automobile accidents in the United States (U. S.). The total number of deaths (approximately 40,000) was comparable to fatal mishaps of 100 large passenger jet airplanes. However, such a number of aviation mishaps should never be accepted by society. Clearly, the security of the aviation industry is subject to more intense social scrutiny and attention than the automobile industry. Of course, when examined, psychologically, it makes sense that hundreds of deaths, all occurring at once, creates a more serious shock than tens of thousands of cumulative deaths per year. Moreover, aircraft passengers are considered completely passive, which differentiates them from drivers and passengers in automobiles.

From this perspective, the nuclear power industry is more analogous to the aviation industry, than the automobile industry. Accidents in the nuclear power industry are also subject to more intense social scrutiny, even if few deaths are caused by such an accident. As we investigated the case of the Fukushima nuclear accident, in which no one was killed by direct exposure. Nevertheless, the accident at Fukushima nuclear power plant received considerable attention worldwide. Indeed, in the case of nuclear power accidents, the influence of radioactivity has a special feeling in society. Regarding the existence of the strict, inquisitive eyes of society on the nuclear industry, even if far fewer numbers are killed by accidents than those of the automobile industry, the aviation industry is similarly situated to the nuclear power industry in terms of concern with its security.

The nuclear industry began development in the late 1940s and beginning of the 1950s, after World War Ⅱ. This occurred, in a manner similar to the technological development of jet engines. However, from the perspective of dominant design construction, these industries have a little difference. While there are dominant designs of jet aircraft that are credible and stable products, even now nuclear reactors have various of fundamental models. Certainly, some dominant designs of nuclear reactors have been recognized; however, the dominant design of nuclear reactors is not as stable as that of a jet engine aircraft.

An immature dominant design of any technological breakthrough brings about both social anxiety and social expectations, due to the potential risk as well as the possibility of impressive performance. Therefore, social scrutiny pays specific attention to nuclear accidents, even if only a few victims die.

Conversely, some people believe that the nuclear power industry cannot be compared or made analogous to other industries. This is, due to the after-effects, specific to nuclear accidents, that occur in the area. For example, in the case of a large mishap involving multiple passenger jet airplanes, the maximum damage occurs at the time of the accident.

However, in the case of nuclear accidents, an accident will have a negative effect on the area for decades. Research has shown that leukemia, thyroid cancer, and physical deformities due to radiation exposure from a nuclear accident can often last for generations.

Nevertheless, any accident, not only nuclear accidents, creates negative after-effects. For example, some side effects of medical drugs cause diseases or induce physical deformities in the next generation. This includes other types of accidents; for example, children who lose their parents due to automobile or airplanes accidents, also experience serious negative impacts on their lives.

Concerns with the negative after-effects of nuclear exposure have been researched through investigations of the children of atomic-bomb survivors for over 60 years. Thus far, significant evidence of genetic effects has not been reported.[3,4] Through research on radiation exposure and health, significant negative effects have been observed in exposure over 100mSv; however, in the case within 100mSv exposure, no significant negative effects have been reported.[5]

Evidently, negative genetic effects due to exposure are denied, at least at this point. Moreover, radioactivity restricted to within 100mSv is not harmful to humans. Radioactivity can be controlled through rational activities. The excessive anxiety or fear on ambiguous grounds leads to minus-bubble, the distraught escape from necessary investment or trial in an industry.[6] The plus-bubble distraughtly rushing into investment or trial in an industry with the excessive expectation or hope on ambiguous grounds, is based on the same mechanism with the exact opposite direction of the minus-bubble.

Although each industry obviously has its characteristic elements, if we focus on their critical trial and error processes, we find important commonalities between different types of technologies through their process of improvement. For example, we find commonalities when examining how active trial and error processes are developed during the fluid stage, after the invention of a breakthrough technology. We also find them when observing, how a dominant design develops through the fluid stage, how accidents decrease, and how the risks of new technology are overcome in various industries.

Subsequently, we will utilize or apply the analogy of other industries to understand and predict the future of the nuclear industry.

Dominant design after trial and error

The concept of technological hierarchy can be explained as follows.[7] The core technology is the most fundamental part of a product or process, and it is the starting point of the technological hierarchy. The core technology is applied and developed through trial-and -error to achieve the practical technology. The development process is constructed using a hierarchy of problems and solutions.

In the final stage of the technological hierarchy, the dominant design is realized by improving the process of breakthrough technology. Abernathy explained that a dominant design is the stable style of a new product and is constructed using a new core technology. This is, because of the convenience for both the makers and users, after the trial and error of a new technology.[8]

Abernathy pointed out that the first dominant design of gasoline-engine automobiles was Model T, produced by the Ford Motor Company in 1908. Prior to the creation and acceptance of the dominant design, various types of cars were produced. Abernathy refers to the age before the dominant design as the fluid stage.

In the fluid stage of automobile development, which occurred in the late 19th century, three types of core technologies competed with each other. These three core technologies were steam, electric, and gasoline engine systems. As their core technologies were different, each engine contained both merits and demerits. For example, a steam engine had sufficient power, but took longer to start, because water must be boiled to produce steam. The gasoline engine could start rapidly and was powerful, but it occasionally caused accidental, fatal fires. The electric engine was safe and easy to start but lacked power in those days.

After adequate trial and error, the issue of fire accidents caused by gasoline engines was resolved through an improvement to the engine system. Subsequently, gasoline engine cars became the industry's dominant design.

Breakthrough in the aviation industry

In the 1950s, after World War II, the jet engine system was created and accepted within the airplane industry. A jet-gas turbine engine system is fundamentally different from a propeller one. Subsequently, the development of the jet engine airplane was a breakthrough in the airplane industry. In the first stage of development, a trial-and-error process was required to establish the dominant design. Figure 1 shows how many accidents occurred before certain stable or credible dominant designs were established.[9]

First, the breakthrough of the jet engine system was realized through the development of military aircraft. Various types of jet-engine fighters were developed and implemented for military use. Figure 2 shows how various designs of fighter jets were developed in the U.S. Navy and Marine Corps in the 1950s and the 1960s.[10]

During the same period, the commercial aviation industry was also attempting to develop passenger jet plane by creating a stable and credible design. Figure 3 shows the high rate of commercial aircraft mishaps in the 1950s and 1960s.[11]

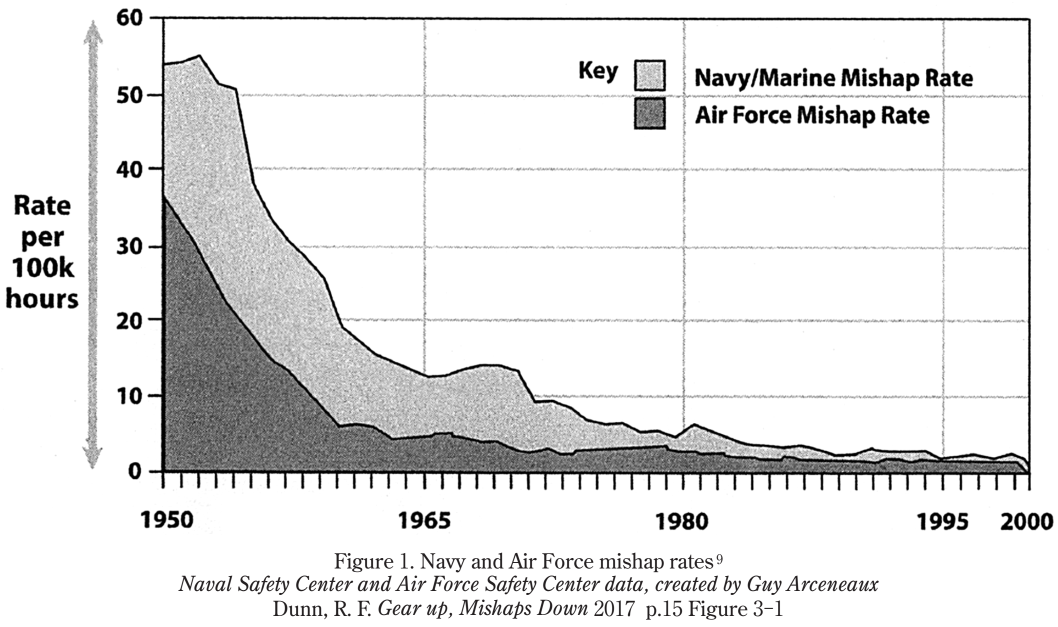

Figure 1. Navy and Air Force mishap rates[9]
Naval Safety Center and Air Force Safety Center data, created by Guy Arceneaux
Dunn, R. F. *Gear up, Mishaps Down* 2017 p.15 Figure 3-1

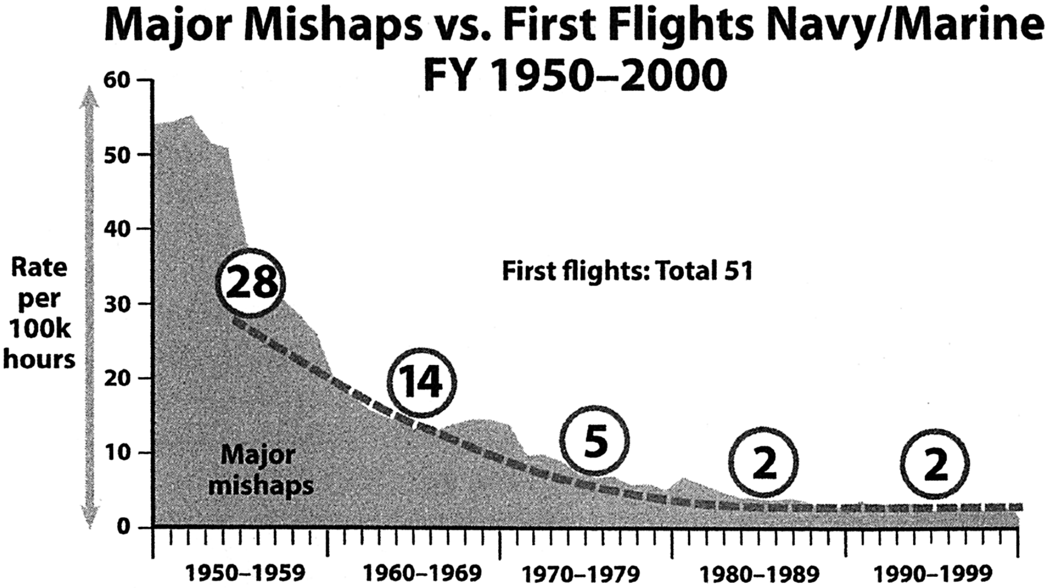

Figure 2. Graphic major mishaps vs. first flight[10]
Data from Rausa's Pistons to Jets, *created by Guy Arceneaux*
Dunn, R. F. *Gear up, Mishaps Down* 2017 p.103 Figure 13-1

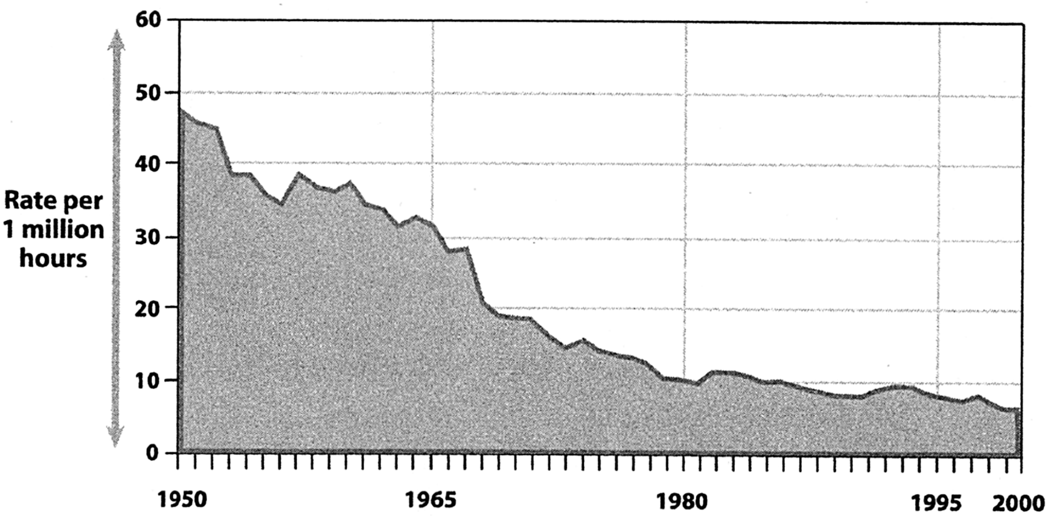

Figure 3. Mishap rate of commercial air flight[11]
Data from Rausa's Pistons to Jets, *created by Guy Arceneaux*
Dunn, R. F. *Gear up, Mishaps Down* 2017 p.16 Figure 3-2

The fluid stage, just after the breakthrough, trial and error processes, was necessary to accomplish the dominant design using a new core technology. In this article, the process of overcoming the technological risk of jet engine aircraft is investigated.

Improvement process of breakthrough technology

As breakthrough technology is inherently not yet mature, it must be improved through active trial and error processes to be considered a practical technology. The high mishap rate of jet airplanes in the 1950s and 1960s indicates brave trial and error activities in the fluid period of jet engine development.

As R. F. Dunn reported in Figure 1, the rate of the U.S. military jet accidents was 55 per 100,000 hours of flight in 1950. In the same year, 227 pilots were killed in 1,488 accidents.[12] In 1954, the rate of accidents was 56 per 100,000 hours, and there were 536 deaths due to naval-aviation mishaps. Subsequently, Dunn describes a significant reduction in the number of accidents, citing only 29 per 100,000 hours in 2000. Moreover, the number of pilot deaths in the line of duty was reduced from 46 in 2000, to 20 in 2014. Using this data, Dunn pointed out an amazing amelioration effort.

We can hypothesize that rapid improvement at the fluid stage of a breakthrough technology through active trial and error is a typical phenomenon in various types of technologies, such as those of the automobile and aviation industries.

Improvements to jet engine technology were made gradually, as any type of breakthrough technology, mutual interaction between causes and solutions to technological risk is attempted using feedback information. The causes of accidents fall into two categories: technological and social causes. The solutions also fall into two categories of solutions: technological and social devices.

In the case of jet aircraft, there are many technological causes of accidents in the fluid stage, as well as other types of new technological breakthroughs. In the initial stage of development in the 1950s, there were problems with the jet engine system itself. Therefore, various types of engines, various improved parts, and multiple aircraft designs have been attempted, developed, and implemented. However, some of them were not suitable due to the high rate of accidents mentioned.

Many technological devices and instruments for jet engine systems and maneuvers have been developed to overcome the risk of technology in the fluid stage. The safety of the jet engine system and a credible model of the aircraft were gradually improved. Moreover, autopilot systems have gradually progressed to resolve maneuverability issues.

As a result of the progress of the autopilot system, the electronic maneuver system has become considerably complicated. This was a new effect caused by both pilot errors and accidents. This new technology risk was attempted to be overcome by newer technology and social devices via training or education for pilots.

In the commercial jet aircraft industry, large aircraft sizes are inevitable because of the economies of scale. A large passenger aircraft allows cheaper airfare for each passenger. Longer distance flight was also necessary to achieve economies of scale because of the reduction in the number of flights. However, scaling up and expanding the flight length of aircraft makes maneuvering complicated. Furthermore, security is of utmost importance, especially for passenger flights.

Dunn showed the rate of mishaps for commercial flights in Figure 3. The mishap rate is aggregated per million hours. This is contrary to how military aircraft calculate their mishap rate, as the rate is aggregated per hundred thousand hours. The two types of mishap rates are similar. However, the peak mishap rate of commercial aircraft accidents was kept approximately ten years after the peak for military aircraft.

The highest rate of mishaps for military aircraft occurred from 1950 to 1955, after 1955, dramatically decreasing. This indicates that active trial and error, introducing new technologies, and specialized training were intensively pursued by the U.S. Navy and Air Force from 1950 to 1955.

The commercial aircraft industry has implemented new technologies, assembly styles, and components for jet airplane systems that were developed for military aircraft. As the commercial aircraft industry follows the lead of military aircraft development, there may be a lag of approximately 10 years between when the two industries experience their peak mishap rate.

Similarity between the mishap rate curve and product innovation curve

Abernathy presented the product innovation curve, which described a high rate of major innovation before the dominant design, and rapidly decreasing major innovation once the dominant design is established. Figure 4 shows the relationship between product innovation and process innovation in the development process of the automobile industry.[13]

In the fluid stage, before the dominant design, the rate of major innovation of products is high, while after the dominant design, it rapidly decreases. Contrarily, the rate of major process innovation is rapidly rising after the dominant design of products. This is because, job shop manufacturing is the main mode until the product model is stabilized. However, once the dominant design of the product is established, mass production systems with special-purpose process equipment can be utilized.

We find similarities between the mishap rate curve（Figure 1 and 3）and the major product innovation rate curve（Figure 4）. This similarity is recognized as the dominant design of the product can prevent serious accidents in the fluid stage of breakthrough technology.

Moreover, we recognize the appropriateness of the analogy between the automobile industry and aircraft industry through the similarity of their curves of mishap rate and major product innovation rate.

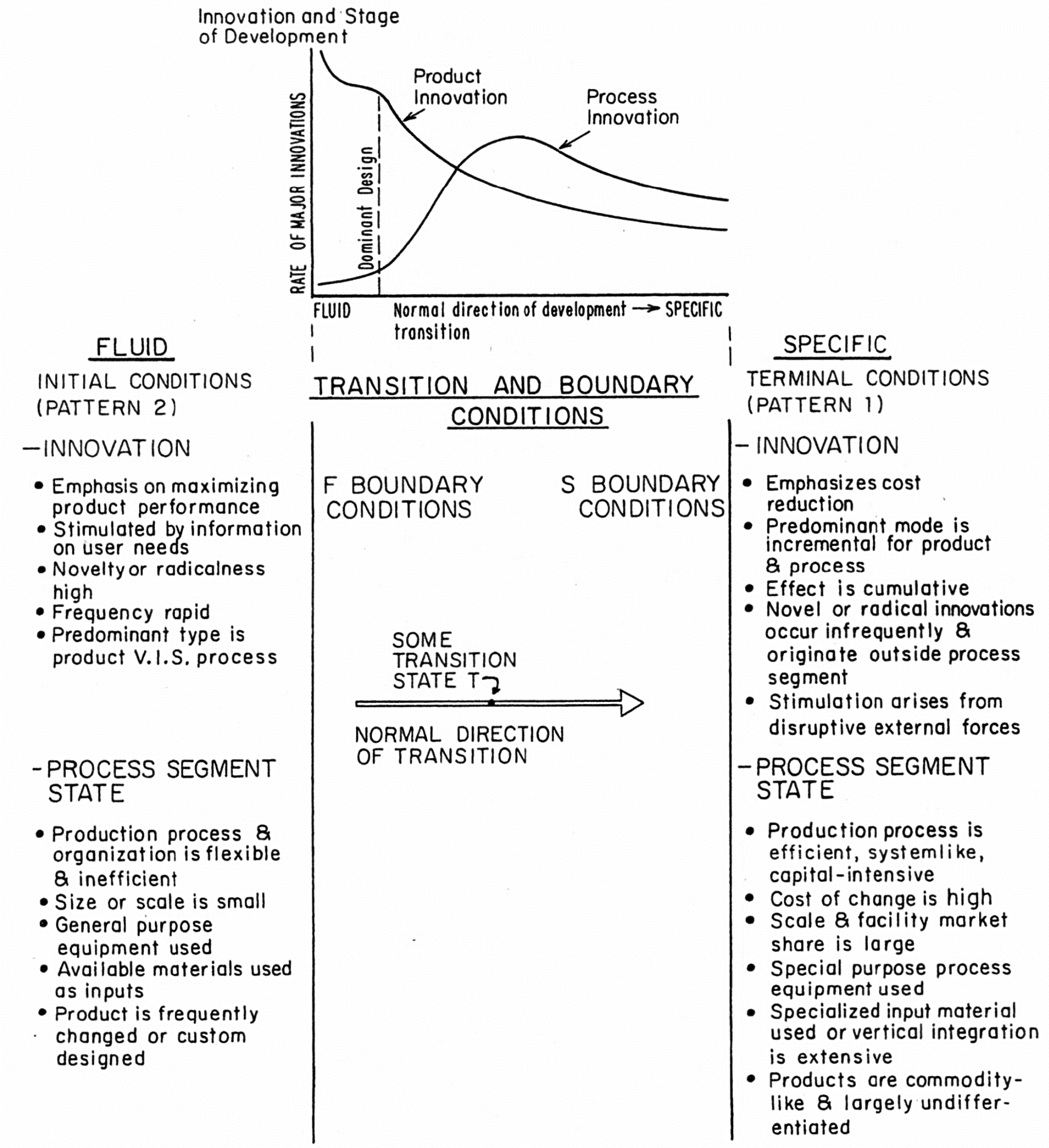

Figure 4. Transition, boundary conditions, and innovation
Abernathy. W. J. Productivity Dilemma 1978 p.72 Figure 4.1

2. Social Devices as Solutions for Technological Risk

The technological risk is constructed using both technological and social factors. Therefore, we can solve this risk using devices of technology and society. As any new technology has many technological causes for risk, many technological devices that are concerned with engineering are created to solve these causes in the fluid stage. Based on the preparation of technological devices, social devices as solutions for technological risk（e.g., special training, leaning, and manuals）are maintained.

Organization as a social device

Dunn emphasized that the U.S. Navy and Air Force solved the technological risk of jet engine systems through organizational learning.[14] Organizational learning has been discussed in the theory of organization since the 1950s and 1960s.[15,16] The essential function of organizational learning is communication and sharing of information, experiences, and knowledge among members of the same organization. The following organizations that gather and analyze numerous accident data have realized the organizational learning effect.

Figure 5 shows how organizational correspondence contributed to a decrease in accidents. First, the Naval Aviation Safety Center was founded in 1953, to solve the risk of mishaps caused by the novel technology of aircraft. Subsequently, the Naval Aviation Maintenance Program was created in 1958, and the Naval Aviation Safety Center established the Human Error Research and Analysis Program (HERAP) in the same period. Furthermore, Replacement Air Groups (RAG) was founded in 1960, and the Naval Aircraft Training Operating Procedures (NATOPS) Program was organized in 1962.

These organizations and programs sought to gather information on numerous mishaps. They also served to list numerous documents related to the trial and error of new aircraft technology and try to analyze the logistics of what caused the mishaps and what effects they produced. Additionally, they shared the information or knowledge among members of the organization and referred the aircraft maintenance and training information to pilots. According to the trial and error process, the results of various solutions were reflected in the next generation of solutions through the feedback information process.

Technological devices such as flight recorders and cockpit voice recorders, have improved organizational learning about accidents. In almost all cases of fatal aviation accidents, the testimonies of pilots cannot be collected. This is especially true for commercial flights that do not carry escape devices. The use of flight recorders and cockpit voice recorders began in military and commercial airplanes, in the1950s and 1960s respectively. Using this technology, information about the causes of fatal mishaps involving both technological and social causes (human factors) could be shared within an organization.

This is an example of an important interaction among technological risks, technological devices, social risks, and social devices.

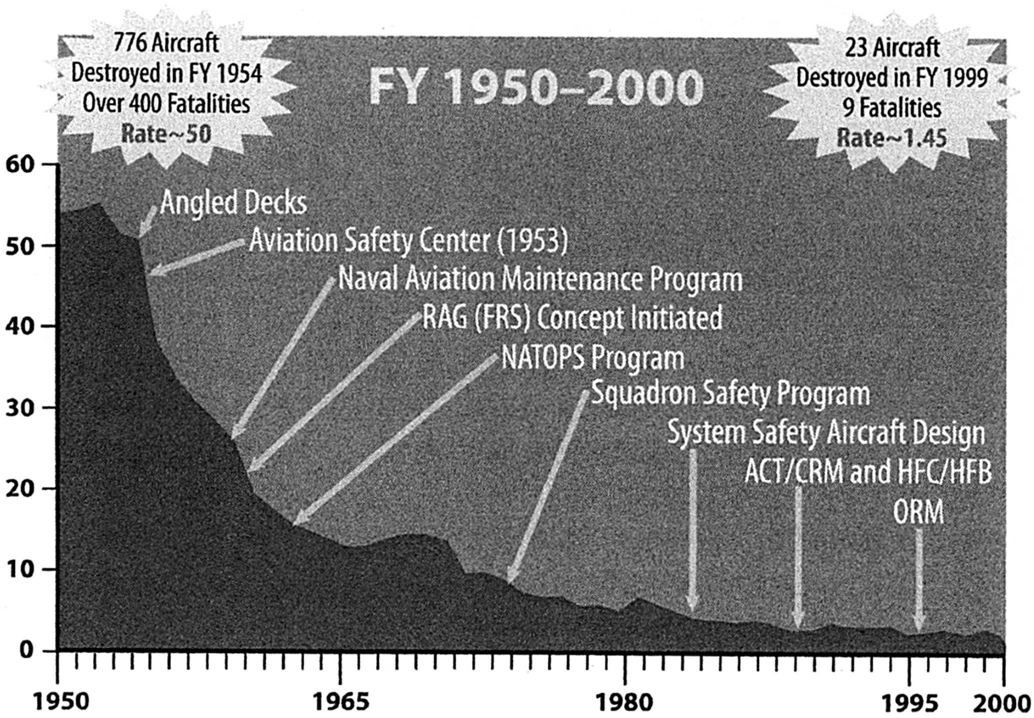

Figure 5. Organizational approach against mishaps[10]
Naval Safety Center data, created by Guy Arceneaux
Dunn, R. F. *Gear up, Mishaps Down* 2017 p.18 Figure 3-3

A report by HERAP pointed out that human factors caused over 55% of all naval aircraft accidents. It is sometimes difficult to determine the cause of the human error. For example, a pilot's error or a mistake by the flight crew is categorized as a human error. However, maintenance members' mistakes usually emerge as mechanical malfunctions of an aircraft. This begs the question of, whether a malfunction is caused by mechanical failure or maintenance members' human errors.

Another report on the analysis of aircraft mishaps noted that over 80% of accidents were due to the pilot's human error.[17] J. Lowery reported that pilots' various misunderstandings and decision-making cause aircraft incidents or accidents.

A pilot's misreading of a complicated instrument in the cockpit is certainly a human error, however, improving the readability of the instrument can solve this problem. Therefore, mechanical conditions are also a cause of accidents. If many pilots misread the instrument, the accident is caused by a mechanical issue rather than a human factor.

Since the 1950s, autopilot systems have improved and advanced. Nowadays, the probability of a large, fatal aircraft mishap may be one-millionth. The autopilot system has an almost perfect level of safety and efficiency. At this stage, the interaction between humans and machines is becoming a serious problem. We must remember that any new technology that overcomes old technological risks is accompanied by new risks. This cycle continues, as a newer technology that overcomes the "new" risks brings its own newer risks.

Focus on human errors

Owing to improved autopilot systems, the risk of difficult control functions now arises from the complicated instruments in the cockpit. A high-level autopilot system also attempts to simplify the mechanics of human-machine interactions. Although these engineering efforts are important, training and educational programs are also extremely important, because some fatal mishaps are caused by the careless mistakes of pilots or maintenance members. Currently, human factors are recognized as key elements of both accidents and solutions to aircraft- equipped autopilot systems.

We can compare this context with the risks and solutions in the nuclear industry. In reality, many nuclear accidents are caused by human error, such as careless mistakes or violations of the manual. These social risks can be solved by using both technological and social devices.

Lowery analyzed cases of fatal aircraft accidents using his own lived experience as a pilot.[18] He points out some of the causes of fatal mishaps with pilots. First, he indicates that a training shortage is the most fundamental cause of accidents. He insists that both the quantity and quality of training are important. Although the quantity of training can be calculated by flight time, the quality of training cannot be measured similarly. However, flight training under severe conditions, such as flying with only one side engine, in bad weather, in darkness, while experiencing the malfunction of an instrument, etc., are all examples of training quality. He recommends special training programs for experienced pilots using a safe training machine.

Second, Lowery insists that careful inspection and preparation before the flight are important to preventing serious accidents. Some careless mistakes or misunderstandings have caused fatal mishaps. For example, Lowery reports that a lack of confirmation of fuel conditions, can cause fatal accidents.

Finally, he warns that a pilot's inflated sense of self-confidence is an ominous cause of fatal aircraft mishaps. He reports that the demographics of pilots for both non-fatal and fatal accidents of commercial airplanes in the U.S. were heavily concentrated in 40s and 50s pilots who had sufficient experience. Figure 6 shows the rate of non-fatal and fatal accidents by pilot age.[19]

In any commercial aviation company, these middle-aged pilots are usually distributed over longer flights. Therefore, they frequently face various severe conditions such as bad weather, nighttime takeoffs, and nighttime landings, causing accidents to be naturally concentrated among pilots of this age group.

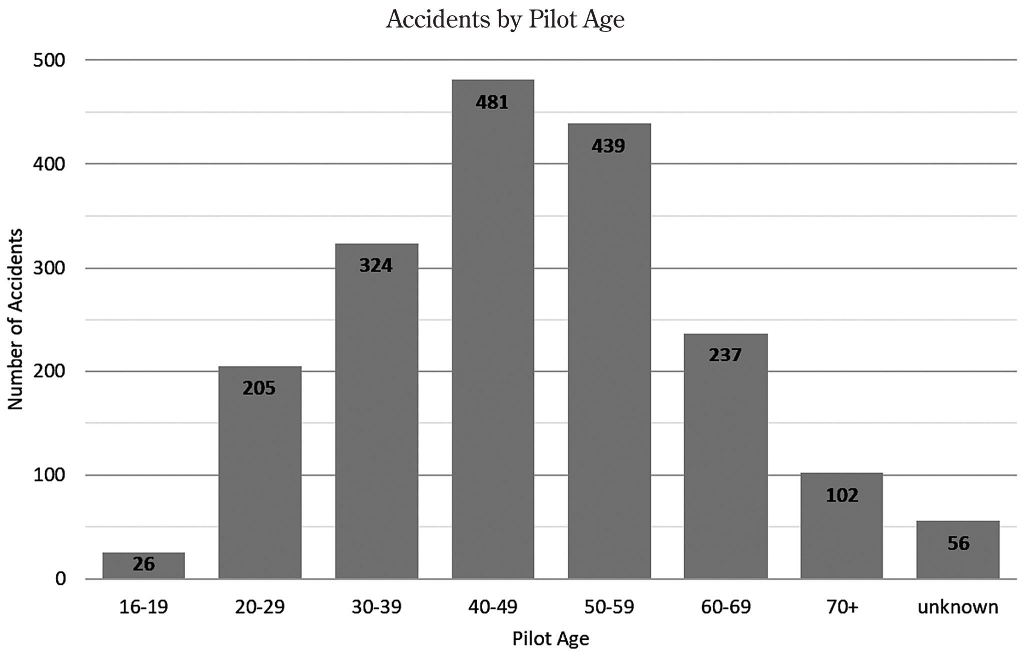

Figure 6. Relationship between accidents and pilot age[19]
Lowery, J. *A Pilot's Accident Review* p.10 Figure 1–4.
All accidents by pilot age（from a 1999 U.S. study）

However, Lowery reveals that inflated self-confidence, in both amateur and professional pilots, is a serious cause of forced flight in bad weather, nighttime, overcrowded schedules, or other dangerous conditions. In particular, Lowery warns that over-confidence, with a conspicuous or self-revealing desire, almost inevitably brings about fatal accidents.

We summarize Lowery's position, stating that the pilots' attitude that most readily ensures a safe flight is as follows: attention to health – both physical and mental –, ethical behavior, sufficient quantity and quality of training, and respect for flight manuals.

Incidents introduce accidents

T. G. C. Griffin, M. S. Young, and N. A. Stanton focused on commercial flight accidents, analyzing the causes of the accidents and proposing prevention methods.[20] At first, Griffin et al. note that, in terms of autopilot systems, human errors are considered a serious problem. New high-tech electronic autopilot systems sometimes introduce new problems in the man-machine relationships.

Regardless, progress to auto pilot systems dramatically decreased the rate of fatal accidents in commercial flights to one in a million. Griffin et al. also point out that the rate of serious accidents in commercial aviation has remained relatively stable over the last two decades. After equipping aircraft with nearly perfect autopilot systems, human errors were emphasized as the cause of accidents.

Griffin et al. showed the cause of "Heinrich's accident pyramid" which was first developed by Herbert William Heinrich, an American industrial safety pioneer.[21] Figure 7 illustrates, that fatal accidents account for only 0.3% of all accidents, and another 8.8% of accidents ended with minor injuries and 90.9% of accidents had no injuries.

Griffin et al. proposed that accumulative incidents cause accidents. Based on this proposal, 99.7% of accumulative accidents with minor or no injuries finally cause a fatal accident. They refer to 99.7% of accidents without major injury as "incidents". Griffin et al. analyzed the human factors that cause accidents, defined as "human error" by James Reason, who created the famous "Swiss Cheese Model",[22] and investigated several models of human factors or human errors.

First, they considered the Domino model created by Heinrich. In this model, one small incident triggers a larger incident, and more serious incidents are accumulated sequentially, and finally, at fatal accident occurs. Heinrich also proposed the case of multiple human error processes, in which multiple minor incidents cause the subsequent serious incidents.

Griffin et al. investigated Reason's Swiss Cheese model, which shows that the risk of a serious accident can pass through multiple stages of an organization. This model is useful for understanding the weaknesses of certain checking lists or systems. An ordinal examination of the checking system

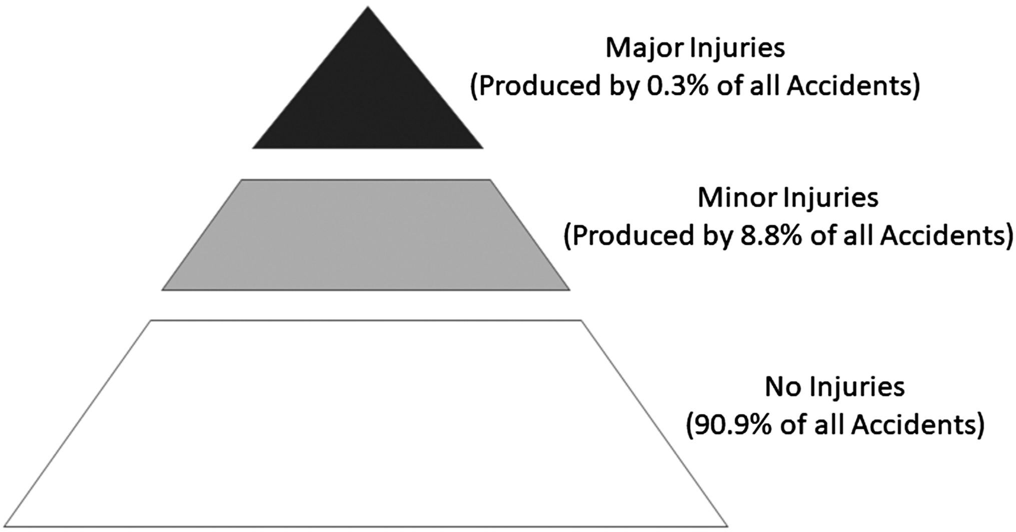

Figure 7. Heinrich's accident pyramid [21]
Griffin et al. *Human Factors Models for Aviation Accident Analysis and Prevention* p.19 Figure 1.2 Heinrich's accident pyramid

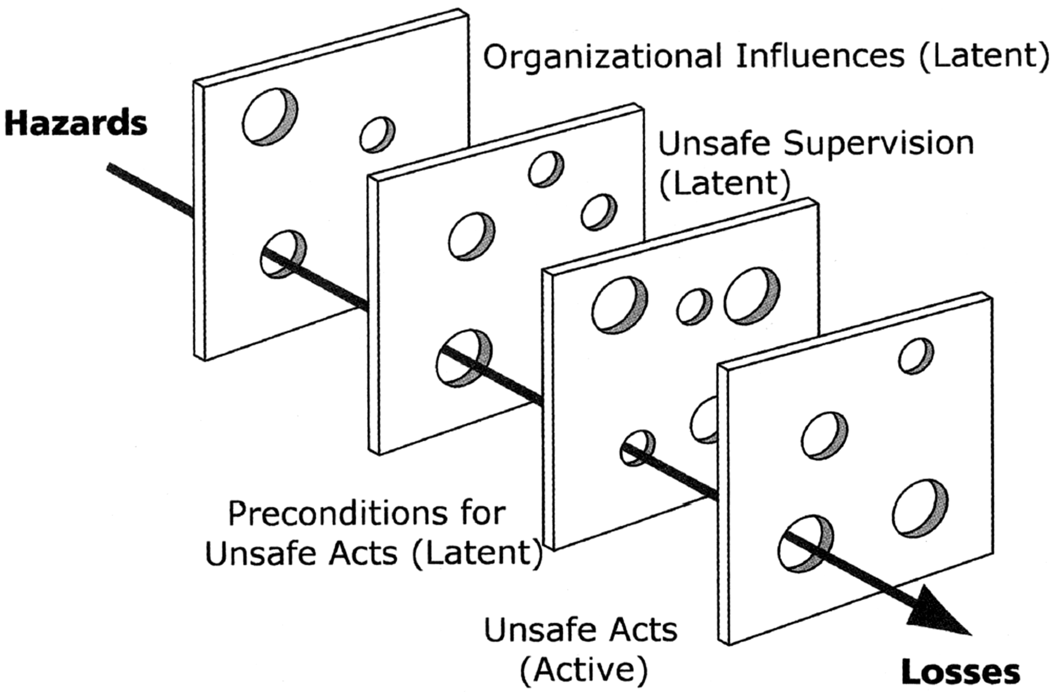

Figure 8. Swiss Cheese Model [22]
Griffin et al. *Human Factors Models for Aviation Accident Analysis and Prevention* p.34 Figure 2.3 Reason's Swiss Cheese Model of accident causation

is necessary to secure the system.

3. Teamwork between Humans and Machines

At the fluid stage of breakthrough technology, technological devices for solving the technological causes of accidents are created because of the many problems of immature technology. Special training is necessary to manipulate these new technological devices. Human factors for accidents are focused on eliminating engineering risks. Automation systems to help resolve human errors in accidents have been rapidly developed and equipped.

However, high-level automation systems cause serious problems when coordinating the complicated man-machine relationship. We can also analogize aviation cases to the nuclear industry here, as they both contain highly automated mechanisms and human manipulation.

Human factors after autopilot systems

As mentioned in the previous section, Griffin et al. emphasized the importance of a system for detecting minor human errors that can lead to serious accidents later. They warn that complicated checking systems create new problems. Although they admit that autopilot systems could dramatically decrease the rate of accidents, increasing automation complicates pilots' monitoring roles.[23]

Griffin et al. also caution that highly automated systems cause over-reliance on automation for pilots, which can lead to a loss of manual flying skills. If the autopilot system breaks down, and the pilot does not have manual flying skills, that can cause a serious accident.

Relying too heavily on either pilots' manual skills or autopilot systems, has trade-offs. However, at the beginning of the development process of the autopilot system, the mutual interaction between manual flying skills and machinery mechanisms played an integral role. Based on the advancement of the automation systems, pilots' critical skills gradually shifted from mostly manual flying skills to mostly monitoring skills.

Alarcos also notes problems surrounding artificial intelligence (AI) for pilots' flight maneuvers,[24] stating that human intuition is based on lengthy experience. He mentions an ironic phenomenon: evidently, in the first stage of flight mechanization, the auto system had insufficient accuracy and credibility. Therefore, AI pioneers for autopilot systems have valued the institution of skilled pilots.

After a perfect AI-controlled autopilot system learns from past information processing, it can change its mind similar to humans. Therefore, AI engineers do not need to respect human intuition or the experience of skilled pilots. In other words, high-level manual skills, that contributed to creating superior autopilot systems, are rapidly dying out with the advent of AI autopilot systems.

Alarcos emphasized that there have been many cases of near accidents that have been avoided due to the decision of a skilled pilot. This is often based on the suspicion that something is wrong and can also be termed intuition. These intuitive decisions solved problems before they turned into emergencies or fatal accidents.

H. A. Simon a professor of decision-making theory, argues that human intuition has a surprisingly high level of rationality because of long-term memory based on learning or experience processes.[25]

Alarcos also introduces the case of the Gimli Glider accident that occurred on July 23, 1983 with Air Canada. This accident was caused by a fuel shortage due to confusion between the yard-pound units and the metric system at the fuel supply point. All the engines of the Air Canada 143 flight stopped in the Canadian sky at an altitude of 12,000 m. The captain decided to glide the flight to the Gimli Air Force Base, which was the nearest airport. Fortunately, the captain had a hobby of gliding flight and the first officer had worked at the Gimli Air Force Base before.

Alarcos introduced this case as an example where human decision and manual execution solved an unexpected serious incident. He insists on the importance of human decisions based on experience and manual flight skills, as opposed to automated flight systems.

There are some differences between AI and humans in terms of their ability to process information, learn, and switch. Therefore, constructive cooperation between humans and machines is necessary. In general, humans have the advantage of making intuitive decisions, informed by long-term memories and impressions. Conversely, machines can run numerous repetitive operational tasks without fatigue, tiredness, disinclination, or errors.

Alarcos concluded that autopilot systems must be continually improved, because of the statistical evidence that high-tech automated maneuver systems dramatically decrease accidents. However, he also emphasized the importance of intuitional, human decisions, informed by experiences on unexpected incidents.

An information model of incidents and accidents

Griffin et al. propose an information model construction that could clarify the relationship between causes and accidents.[26] The flow charts illustrate not only linear information, such as the Domino model or Swiss cheese model, but also plural cases and accident relations.

They introduced an incident reporting program described by Van de Schaaf's seven-up framework, which was utilized by British Airways as follows.[27]

1. Detection (usually through reporting)
2. Selection for further analysis
3. Detailed description and investigation

4. Classification of the cases
5. Recognition and computation of patterns and priorities
6. Interpretation of results of investigation for recommendations
7. Evaluation and monitoring

This framework is useful for security in general industries, including the nuclear industry. Griffin et al. note that certain types of smaller incidents or minor mistakes cause of serious accidents are distinguishable from other small incidents using the information model of the incident-accident estimation system. Therefore, critical small incidents or minor near-misses can be eliminated before becoming larger issues.

In the nuclear industry, some human errors in the monitoring of large high-tech, automated instruments also cause small incidents. Subsequently, a few of them did cause serious accidents. The room for human error must be closed through the incident-accident information model, before small incidents become active causes of serious accidents.

New risk from new technology

We can propose a thesis on technology for forbidden fruit. This thesis argues that once a new technology is created, endless innovation is generated because of the endless new risks that accompany new technology. These new risks need to be solved by newer technology, which subsequently carries its own new risks and issues. This creates an endless interaction between risk and solution-based technological innovation, where a new technology developed to overcome certain risks caused by current technology, raises new risks, which, in turn, must be solved by newer technology.

Alarcos proposed a similar structure in which a new technological innovation that solved some current risks provoked new ones. He mentions six typical examples of new technology- induced risks, as follows.[28]

1. An increase in navigational precision increases safety, but it can be used to decrease the distance between flying planes.
2. Better weather information can help planes avoid entering storms, but it can also be used to navigate planes near storms without entering them.
3. Improvements in landing systems can be used to achieve safer landings, but they can also be used in airports with insufficient safety facilities.
4. Improvements in engine reliability can decrease the number of engine stops, but it can also be an invitation to decrease the number of engines on a plane.

5. Better altimetry decreases the risk of midair collisions, but it can also be used to decrease the distance between planes as the risk of collision decreases.
6. Secondary radar decreases collision risk through better information, but it can be used to place more planes in the same airspace.

Alarcos concludes that new technological improvements to increase safety contribute to increased efficiency in exchange for safety. For a simple and typical example, take a plane with four engines, each of which produces 30% of the airplane's thrust. As the total thrust is 120%, 20% thrust is required for safety purposes. Subsequently, through technological innovation, the thrust of the engine is increased to 60% of that of the plane. A plane with two new engines also has 120% thrust.

Considering the risk of an engine stop, the former type of plane with four engines is safer, in the case of failure of one engine. If one of the four engines fail, the plane flies with 90% thrust. However, on the new type of airplane with only two high-power engines, if one engine fail, the plane must fly with only 60% thrust. Therefore, the accident risk increases in the case of an emergency, while overall efficiency is increased.

In the actual process of technological innovation, commercial aviation companies never equip more than two new types of engines on a plane, for increased security.

4. Environmental impact on security

D. Wilson and G. Binnema explain four main accident categories: aircraft collisions, adverse weather, physiological hazards, and the threat of controlled flight into terrain（CFIT）. From the perspective of environmental impact, their analysis of aviation risks can be summarized into three major environmental factors - dense aviation, bad weather or darkness, and the pilot's problematic inner condition.[29] Subsequently, these three environmental impacts trigger CFIT accidents.

Aircraft congestion causes of collisions

In densely populated areas, airplane collisions are more likely to occur in an airport or midair above the airport. Wilson et al. reported the number of collision accidents on guideways or runways in airports, emphasizing the difficulty in communication between the control tower and pilots, and the dangerous physical conditions of the runway.

Naturally, in the case of high-speed airplanes, conditions are changing rapidly. Reconfirmation of the plane's status must occur quickly. Moreover, misunderstandings or mistakes by pilots or traffic controllers cause collision accidents in airports. They recommend more intimate communication between pilots and control towers with several devices and repeat reconfirmation.

In the case of reconfirming between pilots, if they can see each other, Wilson et al. recommend reconfirmation by visual recognition or gestures. In particular, in an airport without a control tower, mutual pilot recognition is important.

This reconfirmation process is also important for large-scale equipment manipulation, including nuclear reactors. In some cases, nuclear center accidents are caused by miscommunication between operators and engineers within a nuclear center.

Wilson et al. presented a habitual cause of accidents by pilots. Every pilot has a habit of trying to start for take-off, immediately after preparation and confirmation of the departmental condition. Pilots are usually not trained for waiting. This is the primary cause of collisions on the guideway or runway at an airport.

This habit may be due to repeated training for take-off immediately upon finishing preparation for departure. Therefore, to solve these habit-induced accidents, the pilot's educational course should include training for the pilot to wait for the control tower's take-off clearance after the preparation of departure.

Wilson et al. also discussed accidents involving midair collisions in crowded airspaces, specifically those above airports. They recommend using instrument flight rules (IFR), even in visual meteorological conditions (VMC), to avoid various optical illusions that cause midair collisions. They point out that 88% of the causes of midair collisions are pilot misidentification or late identification. The fundamental causes of these identification problems are the illusion or camouflage effect, caused by dark-colored planes in the evening sky, silver planes in bright sunshine, and blue-colored planes against the blue sky.

Multiple methods of identification are recommended to avoid collision accidents, such as instrument, visual, control tower guidance, and maneuvering by multiple pilots. Moreover, they advise that the inside of the cockpit should be sufficiently clear to maintain a wide visual scope.

Multiple identification methods, communication among members and machines, and keeping things tidy and in order at the operational job-shop such as cockpit clearance, are important for avoiding accidents in various industries.

Adverse weather or dark conditions

Wilson et al. focused on icy conditions and convective wind, as examples of bad weather conditions. In clouds at high altitudes, iciness or frosting usually occurs. Even in an airport, wintertime iciness or frosting is common. Wilson et al. warned that iciness or frosting significantly decreases the propulsive force of the airplane. For example, the Air Florida Flight 90 accident on January 13, 1982, was caused by iciness on the wings. The aircraft stalled, hit a bridge on the

Potomac River, and crashed into the frozen river.

An investigation of the cockpit voice recorder after the accident revealed that the anti-ice device was off. Wilson et al. pointed out that the actual thrust of an aircraft with icy wings was less than the engine thrust indicated by the meter of the instrument. Therefore, in the IFR regarding icy wings, a stall accident is likely to occur, because the IFR controls the level of engine thrust according to the thrust of the engines on the instrument, instead of the actual thrust of the plane. In the case of iciness, changing to manual maneuvers from instrumental flight is necessary.

Moreover, in midair, auto-setting of the rise angle is dangerous in icing circumstances because of the remarkable decrease in thrust caused by iciness. This causes a stall accident. A defroster device is the most credible method for avoiding such accidents. Decreasing the altitude to avoid iciness in the air space is also useful.

Wilson et al. caution, "You can be your own worst enemy!"[30] This warning is similar to Lowery's warning against excessive self-confidence in pilots.[31] Wilson et al. emphasized the danger of VFR being forced into instrumental meteorological conditions (IMCs).

Convective wind or breeze is another bad weather condition. For example, wind shear is caused by front wind or topographical effects, such as large mountains. Specifically, a strong downdraft of the tailwind is likely to cause a stall. Wilson et al. recommend utilizing various helpful resources, such as mountain flying introduction and navigation.

Darkness is also dangerous, especially when coupled with the physiological conditions of pilots that can cause illusions and is sometimes directly connected to fatal accidents. Take-off and landing in the dark are particularly dangerous. Naturally, the visibility of pilots is limited in dark conditions caused by nighttime or bad weather.

Pilot's problematic conditions

Wilson et al. first warned of the danger of hypoxia in high-altitude air spaces. They insist that approximately 10,000 feet of altitude is the marginal safe altitude without an oxygen mask or airplane airtightness and pressurization.

They explain the two major symptoms of hypoxia. First, less serious hypoxia may appear as headache, nausea, dizziness, or tingling in the head and fingers. More serious symptoms include a sense of euphoria or elation. After these and other symptoms, such as loss of alertness, memory loss, moroseness, overconfidence, and belligerence, hypoxia leads to death. They strongly recommended equipping the oxygen mask or airtightness and pressurization to avoid hypoxia.

Pilot illusions are also a serious cause of fatal accidents. Combined with darkness or adverse weather, serious illusions can occur, including spatial disorientation, vestibular illusions, or somatosensory illusions in circumstances of total darkness or white out.

Another case of nighttime illusion is the confusion of starlight, the light of high buildings, other airplanes, etc. An illusion of stopping or moving light sometimes occurs as well. In the most serious cases, an illusion can result in a pilot viewing a dark smooth lake surface and perceiving it to be the runway of an airport. Wilson et al. also noted the possibility of hypoxia during night flight within the marginal safe altitude airspace because the corneas of the eyes consume more oxygen during flight in dark conditions.

Even during daytime flights, pilots experience various spatial illusions such as length, width, depth, angle, distance, and size. Wilson et al. recommend the active utilization of instruments and control tower guidance information.

When a pilot experiences spatial disorientation, vestibular illusions, or somatosensory illusions, an acceleration of the engine results in the lower back pulling strongly because of the combined force of inertia and gravity. In this case, the control stick being rapidly pulled up causes a stall.

Wilson et al. repeatedly recommended the use of instruments and the guidance of the control tower, and they also strongly warned against flying into the IMC using VFR.

Accidents due to CFIT

Wilson et al. reported that controlled flight into terrain（CFIT）was the worst cause of fatal accidents in commercial airplanes. The total number of deaths due to CFIT was 9,000 between 1950 to 1990, and 3,735 between 1987 to 2005. This means that CFIT devices have had many problems. Accidents have decreased through technological innovations, improvements, and pilot training. CFIT is usually utilized in adverse weather conditions such as thick clouds, thick fog, and total darkness at night. Therefore, the condition of the CFIT is already dangerous. However, the high rate of CFIT accidents indicates the difficulty of human-machine cooperation.

Improvements to both sides, such as the technological engineering improvement of the CFIT system, and the human side that considers the pilot's training for utilizing CFIT systems, jointly contributed to the decrease in accidents. Wilson et al. recommend the full utilization of various instruments, guidance from the control tower, and a checklist. They also repeat the importance of identifying the plane's location, paying attention to altitude, standard manuals, and multiple reconfirmations.

These recommendations are also useful for other industries that manipulate large equipment. In the case of large-scale industries, a minor incident sometimes causes fatal mishaps.

Environmental impact is a serious problem in the nuclear industry. For example, a tsunami after an earthquake, similar to the case of the Fukushima nuclear accident, and inundation due to river flooding after heavy rain at French nuclear centers, are demonstrative of the negative environmental impact of the nuclear industry. Overcoming such impacts on the environment is also a fundamental security policy for the nuclear industry.

5. Conclusion and Implications

In this article, we focused on the development process of the aviation industry. We have identified trial and error cases in the fluid stage of jet engine breakthrough. The development stage of the nuclear power industry can be understood based on the aviation industry analogy. We can also use an analogical case of the automobile industry and fined some important concepts related to the development of novel technologies. For example, through the development process of automobiles, we learned the concepts of design hierarchy, fluid stage, and dominant design from Abernathy's theory.[32]

The most fundamental thesis is the paradox between ignorance and civilization, which means that limited human rationality created civilization through innumerable ad hoc trial and error.[33] We can find countless historical cases of trial and error that have managed to construct a certain level of practical products. We utilize the analogy of preceding industries to predict the future of the nuclear power industry.

The automobile industry is now familiar to every person, and the aviation industry is also popular today. Moreover, as mentioned at the beginning of this article, the aviation industry is exposed to severe social surveillance regarding its security, as is the nuclear industry.

We can confirm that there exists a common trend in the development process of any new technology, after examining two kinds of analogies from the automobile and aviation industries. After the breakthrough, countless cases of trial and error were required to overcome many types of serious accidents in the fluid stage for both industries. Once, the first satisfactory model is found, referred to as the dominant design, relatively minor technological improvements and human factors are emphasized.

In the most difficult portion of the fluid stage, innumerable trial and error attempts are executed, and many new technologies become dead-end technologies, because of the lack of effective improvement methods or the emergence of other promising breakthrough technologies.

For example, airships seemed to have reached a dead-end as an authentic transport industry. The Hindenburg disaster on May 6, 1937, was a critical trigger. However, notably, what led airships to become a dead-end technology was a promising breakthrough technology for airplanes. As a technological device, changing the floating gas from hydrogen to helium completely overcomes the risk of explosion of air ships. However, airships have never been utilized for transport; they were instead used for advertising instruments.

Therefore, these finding may have implications for the nuclear industry. From the analogy of the automobile and aviation industries, we can infer the life cycle of the nuclear industry. It may be proposed that we are currently in the end of the fluid stage or the beginning of the growing stage, because some dominant designs are being fixed gradually. After fixing the dominant design, the number of serious accidents decreased dramatically.

If we had abandoned the breakthrough technologies of automobiles or aircrafts in the difficult fluid stage of the technologies, we could not live as we do our modern lives. We should continue to make efforts to improve the security and efficiency of the nuclear power generation industry to realize our successors' high quality of life in the future, as our predecessors did.

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