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Review Article

Specific Technologies of Aviation Rescue and Firefighting Operations over the Years

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Abstract

The twentieth century was a period of rapid development in aviation. It was a time of great progress in the construction of aircraft, the development of ground infrastructure and the improvement of qualifications of aviation personnel. Over the years, aviation has gone from cruise flights in simple aircraft to transatlantic flights, complex aircraft with hundreds of passengers on board. Military aviation can operate at speeds exceeding the speed of sound and in all weather conditions. The infrastructure of large airports has reached the size of cities. Over the past century, the development of aviation has been followed by changes in the organization and equipment of rescue and fire-fighting services. The public does not accept the loss of human life or large-scale material damage and environmental damage. In the search for effective extinguishing agents and methods of administering them, people began to look for ways other than field fire services. Specialized firefighting units have appeared at airports, which are designed for specific rescue and firefighting operations on aircraft and infrastructure. For many years, attempts have been made to select special rescue and firefighting technologies capable of improving the effectiveness and safety of operations. Quite quickly, the car was chosen as the means of transport for airport rescue services. But over time, the need was recognized for it to have different characteristics and equipment than a vehicle for village and town safety units. As a result of various experiments, unusual technical solutions designed to solve basic problems specific to airports were developed. Equally interesting was the path to determining the best fire extinguishing agents and their means of administration. From hand-held fire extinguishers to remote-controlled cannons administering thousands of liters or kilograms of extinguishing agents over a long distance. The publication provides information on the history and development of basic firefighting technologies specific to aviation and some pointers to the future.

Keywords

Aviation, Rescue Equipment, Rescue Vehicles, Firefighting Agents, History

1. Introduction

Since the dawn of time, humans have envied the freedom of birds to move in the air, on the ground and in the water. The desire to fly freely overshadowed all the problems accompanying successive attempts to break away from the ground. The development of aviation was paid for by the suffering and death of many aviation pioneers. Even when the highest price began to be paid by the first users of aircraft, safety was still not paramount.

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Manufacturers of flying apparatus focused mainly on improving the performance of the machines they produced. Airport managers wondered how to reconcile the new activity with the one that brings in funds to maintain airports. Originally, the problems were how to maintain the quality of the pavement, where to position the aircraft and how to build more hangars. As they grew, problems arose with navigation leading to the airports and with fuel supply.

Flight organising companies focused on obtaining suitable aircraft and landing sites and lucrative contracts (e.g. postal services). A great deal of effort was devoted to 'guiding' prospective passengers to the only appropriate mode of travel. The choice of means of transport at the time was not obvious: from ever-better cars, fast and comfortable trains, luxury ships, nostalgic airships to noisy but fastest aircraft. With the development of aviation, the problem of providing passive and active safety became apparent.

As a result of the analysis of the various available materials, an attempt was made to systematise and review specific technical solutions to improve the effectiveness of rescue operations on aircraft. The road to the modern concept of an aerodrome rescue and firefighting vehicle was long and full of many unique technical solutions.

2. The First Problem - The Mode of Transport for Emergency Services

At the beginning of the 20th century, aviation did not have a patron who recognised the importance of safety, and there was no organised air surveillance. In those days, equipment useful for firefighting and rescuing people was mostly stored in hangars or garages. At better organised airports, equipment was transported on handcarts or trailers. It was an evanescence that, even before the First World War, the first typical fire-fighting vehicles were purchased to secure the Berlin-Johannisthal airport. During this period, rescue and firefighting tasks at airports were mainly carried out with hand-held equipment; for example, on 21 May 1919 at Ligescourt, France, the fire on the Handley Page - 0/400 D8314 aircraft and hangar was extinguished with hand-held extinguishers only [1].

Sometimes they were assisted by typical fire vehicles obtained from the nearest fire brigade units, which of course prolonged the rescue operations. The introduction of any fire and rescue vehicles must be considered the first milestone in the organisation of airport fire and rescue services.

In the United States, as early as 1917, for military airfields, the La France company produced a 'Chemical' version of a typical firefighting car with twin generators (probably chemical foam); unfortunately, no detailed information about this vehicle is available [2]. In 1921, the first vehicles adapted for airfield rescue arrived on RAF (Royal Air Force) equipment. These were modernised Crossley 6X6 tankers, which were additionally equipped with a 30-gallon (approx. 114 litre) chemical foam unit and "Fire Snow" hand-held foam extinguishers [1]. The first purpose-built airfield rescue vehicle was delivered to Wroclaw Airport in 1927 [32]. It was built by the Kralig company on a Daimler Benz truck chassis [3]. In 1928, Krupp and Minimax presented a jointly developed airport rescue vehicle, built on a 4-tonne three-axle Krupp chassis. The vehicle was equipped with a Minimax foam system with 2 foam nozzles and a 1600 litre water tank. The equipment also included tetra and foam extinguishers, tools, medical rescue equipment. The first airport rescue and firefighting vehicles differed from typical ones mainly in the size of the water tanks (usually around 2,500 litres) and the size of the fire pump and various solutions for dispensing foam-forming substances. This was the start of a multi-year process of developing technical equipment for airport firefighting and rescue services.

Figure 1. *Platoon of Magirus FLF 25V, FLF 25 S, FLF 25 M rescue and firefighting vehicles, 1957, Montevideo airport [4].*

It has been widely acknowledged that the vehicle is and will continue to be the best way to transport personnel, firefighting assets and emergency equipment at airports. For more than 100 years, tens of thousands of rescue and firefighting vehicles of various sizes and designs have passed through airports. The performance and reliability of these vehicles improved significantly in the late 20th century. Other means of transport have also been introduced for specific rescue applications at airports located among rivers, reservoirs, by the sea or in areas that are difficult to access. These ranged from boats, cutters and ships to hovercraft and special tracked vehicles. Visions of the use of short-range missiles equipped with firefighting warheads, which emerged in the 1980s, should be considered a futuristic curiosity. The main barrier precluding the application of many ideas is the relatively heavy weight of the extinguishing agents required to effectively extinguish an aircraft fire.

Today, in the age of drones and autonomous vehicles, a certain indication, for the future, of airport firefighting and rescue services is the introduction of autonomous cars.

For several years, tests of the use of autonomous vehicles for winter maintenance have been successfully conducted at European airports. Even with the current state of technology, it seems that the tasks of second-row vehicles at airports should be taken over relatively quickly by autonomous cars. The 'braking' role in this project will be played by air traffic control services. However, airport managements will be hard pressed to take this step, due to cost reductions and the increasing problems of recruiting suitable staff for airport fire brigades.

3. Problem - The Search for an Effective Extinguishing Agent

The limited effectiveness of water currents in extinguishing aviation fuel fires was very quickly recognised. In the search for effective extinguishing methods, particular attention was paid to the qualities of carbon dioxide and foam.

3.1. Extinguishing Foam

The use of water foaming additives for firefighting purposes dates back to an English patent of 1877. [5]. The first successful tests of (chemical) firefighting foam were carried out in Baku in 1904 by Alexander Loran. The foam formed from mixing in a tank, two solutions, extinguished paraffin burning in a tray [6]. Research began in a number of centres to obtain efficient and stable aggregates producing chemical foam.

In Europe, foam was already recognised as the most promising as the primary extinguishing agent for liquid fuel fires, relegating carbon dioxide to the role of supplementary extinguishing agent. The problem was to produce foam efficiently and cheaply.

The breakthrough year was 1931, and in the UK, the construction of the first firefighting vehicles for military airfields began from scratch. On 6x6 or 6x4 chassis, an open body of wooden construction was built in which there were at least three chemical foam units and hook-ups for multiple portable extinguishers [1]. Foam currents could be administered via fixed hose lines, similar to today's rapid fire lines, terminating in long nozzle-lances. The American pioneer in the production of firefighting vehicles for airports was a company at Camp Holibird in Maryland. Also in 1931, it began building vehicles on 4x4 and then 6x4 chassis. The vehicles had 100-gallon (378 litre) and 300-gallon (1135 litre) tanks, respectively, and a gear pump. Chemical foam was produced using foam-forming powder stored in special hoppers in the upper body. The larger vehicles were also fitted with 4 large carbon dioxide boules and a carbon dioxide feed line terminated with special nozzles.

I Another route was taken in the 1930s with experiments in foam generation using compressed air. In Germany, the design of a portable motor pump with a compressed foam module (CAF) was implemented in 1938. In 1941, the "Royal Engineering Handbook" (a British handbook for engineers) described the compressed foam system and its application in detail. Due to complex and expensive technical solutions, compressed foam technology was 'frozen' until the end of the 20th century. Compressed foam reached airports at the beginning of the next century with the installation of the now-defunct Schmitz Pegasus airport fire and rescue vehicle. Leipzig-Halle Airport gained a number of experiences in the use of CAF in aviation, but the real breakthrough came with the program initiated by Copenhagen-Kastrup Airport, and the Rosenbauer company [7, 22]. Since then, compressed foams have been increasingly chosen by airport fire and rescue services.

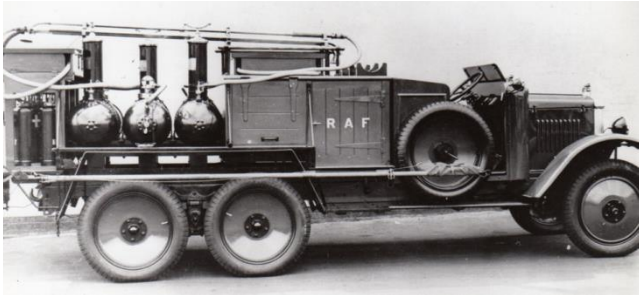

Figure 2. *Morris Commercial (year 1931) with 3 chemical foam units (vertical foam powder hoppers can be seen at the top) vehicle body made of wood [1].*

During the period of research into compressed foam, ways of producing mechanical foam from protein-based solutions using jets were developed very quickly in parallel.

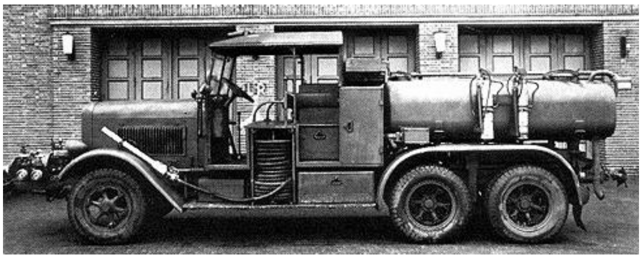

Figure 3. *A Kfz. 343 heavy firefighting vehicle on a Henschel chassis (year 1934) commonly used to secure German airfields and high-risk facilities [8].*

In Germany, as early as the 1930s, a solution resembling the modern heavy foam nozzle became widespread very quickly. The Luftwaffe set the tone for airfield fire protection and introduced a widely used firefighting vehicle, the Kfz. 343, (1934-37), which was equipped with a tank with a capacity of 2,500 litres of water and 300 litres of foam agent [8]. Several hundred vehicles of this type were produced on various chassis. These vehicles used rapid attack lines with foam nozzles of a design similar to contemporary solutions [30].

In the second half of the 1930s, experimentation with the mechanical obtaining of foam also began in the UK. "Streamlined Crossley" 6×4 of 1936, was also the first fire fighting vehicle with a fully enclosed body [1]. Even then, the ease of decontamination of the body surface was taken into account, which is why an ultra-modern body shape was used for the time. The vehicle was equipped with a 200-gallon (approx. 750 litres) water tank and a 75-litre tank of foaming agent. Foam was created by mechanically mixing the solution and air pumped by 2 pumps. The vehicle was also equipped with four CO_2 cylinders, from which the gas could be applied via hose lines fitted with special nozzles.

Figure 4. *The RAF-owned 'Streamlined Crossley' 6×4 of 1936. [1].*

In the early 1940s, Percy Lavon Julian implemented a mechanical foam called “Aerofoam”. He mechanically mixed liquid soy protein concentrate with water and air in a special dispenser. The resulting foam proved to be very stable and the manufacturing method was relatively cheap and simple [9]. Since then, chemists began to devote more time to the search for more stable and efficient foaming agents.

Beginning in the 1960s, the US Navy Research Laboratory, in collaboration with 3M, began researching the use of synthetic chemicals, namely perfluoroalkyl and polyfluoroalkyl substances (PFAS), for use in firefighting foams. 3M's perfluorooctanoic acid (PFOA - used in the production of Teflon) and perfluoro-octane sulfonic acid (PFOS - the main ingredient in Scotch Guard) were also used to develop an aqueous film forming foam (AFFF). This type of foam was another milestone in airport fire protection. The water film flowing out of the foam floated on the surface of lighter-than-water fuels extinguishing fires much faster than earlier types of foam. In addition, the effect of fairly good protection of the surface of the spilled fuel was achieved [26]. Another advantage turned out to be the increased resistance to foam destruction by extinguishing powders. The US Navy received a patent for the AFFF foaming agent in 1966 and entrusted its production to 3M. In the late 1970s, AFFF foam technology took an intricate route, through security operations on aircraft carriers, to military land-based airfields and then to civilian airfields in the US. Within a few years, AFFF foam had become the standard worldwide. Soon, competitors began intensive efforts to produce an AFFF foaming agent bypassing patent claims; the use of the telomere proved to be key. As early as 1974, a US Navy report questioned whether AFFF alternatives should be considered due to 'adverse environmental effects'.

Since 2002, there has been a worldwide campaign to phase out AFFF foams altogether and replace them with 'fluorine-free' products. In the 2000s, this process gained momentum with the emergence of a number of safe and effective alternatives.

In the background of the battle for AFFF, top foam agent manufacturers have been conducting research into improving the extinguishing effectiveness of existing foams meeting the International Civil Aviation Organisation (ICAO) Level B requirements [9]. For several years now, foaming agents meeting the much more stringent extinguishing effectiveness tests referred to as 'ICAO level C' have been present on the market [22]. In the near future, it is expected that the range of these agents will be expanded to include products that are completely safe for people and the environment and that can be used in lower concentrations (0.5-1%) [24].

Chemical companies are carrying out a number of research efforts to improve firefighting foams for extinguishing liquid fuels. Unfortunately, these efforts are shrouded in great secrecy. On the basis of traces of information, one can only speculate that a completely new generation of chemical foams is being worked on again.

3.2. Carbon Dioxide

In the USA, high hopes were placed on the use of carbon dioxide for many years. A very important step for airfield rescue was the introduction of relatively large and heavy vehicles with Cardox snow units to secure US Air Force airfields. Designated Crash Class 150, the vehicles were built on Reo and Sterling Class 7t chassis, with a 6x6 drive train [2]. The stock of extinguishing agents was approximately 2720 kg of CO_2 and 1136 litres of foam agent solution. The extinguishing agents could be administered separately or in combination. The vehicle was equipped with a hydraulically operated firefighting arm with a special nozzle and an adjustable front head located above the bumper. The vehicle was equipped with 4 hose lines; 2 lines approx. 30 m long with a diameter of approx. 25 mm, located on large diameter reels mounted just behind the cab. The other 2 lines of similar length but with a diameter of approx. 15 mm were coiled in a special recess located on the rear axles. The vehicle did not have an auto pump; the driving medium for ejecting foam was carbon dioxide. These vehicles incorporated unique solutions to maximise the extinguishing capabilities of carbon dioxide. As a result, successive generations of C 150 vehicles were used on US military airfields until the 1960s.

Today, carbon dioxide is not recognised as an effective extinguishing agent and some aircraft manufacturers even advise against its use. Despite this, rescue and firefighting vehicles with 'snow' units are still being ordered in some European countries. By design, these are to be used to extinguish on-board avionics compartments. These are usually cylinder units containing 60-120 kg of carbon dioxide.

Figure 5. *C 150 Cardox vehicle on Sterling chassis year of manufacture 1943 [2].*

3.3. Fire Extinguishing Powders

In 1928 in Budapest, Szilvay patented a car for 'dry' fire extinguishing. The powder, which was a mixture of sodium carbonate and diatomaceous earth, was fed using the energy of combustion gases [10]. In 1929, the professional fire brigade in Frankfurt received a car with a large powder unit from Total. The popularity of firefighting powders returned in the second half of the 1970s. Manufacturers began to experiment with different powder delivery systems. The most popular was the solution using compressed gases: nitrogen or carbon dioxide, but powder units were also built using compressed air as the driving gas. Rival manufacturers promoted different ways of fluffing powder. In the 1980s, fire extinguishing powder changed considerably. Dedicated varieties for extinguishing BC or D fire groups and universal versions for extinguishing ABCD fires began to emerge. Following the appearance of giant vehicles with water tanks of 18,000-20,000 litres at major European airports, powder extinguishing vehicles with units of 6,000-12,000 kg were also supplied. Vehicles with aggregates of 750 to 3,000 kg of powder were a common solution. Experiences from large fires extinguished with powder verified the fascination with the extinguishing capabilities of powder. Taking into account the widespread use of modern powders, after many tests the ICAO has set the minimum powder quantities and capacities for medium-sized airports (6, 7 category) at 225 kg. For the largest airports (8-10 category), the minimum powder capacity was set at just 450 kg. This has resulted in the twilight of specialised powder cars at airports, in place of enriching water and foam car equipment with 250-500 kg powder units. The tactical premise for the use of firefighting powder currents has also changed, from extinguishing D fires to extinguishing pressurised liquid fuel fires. In recent years, so-called high-pressure powder units have emerged. The genesis of this name is the raising of the internal pressure in the powder genset tank by about 100%. Manufacturers suggest that such units better meet the requirements of pulse extinguishing.

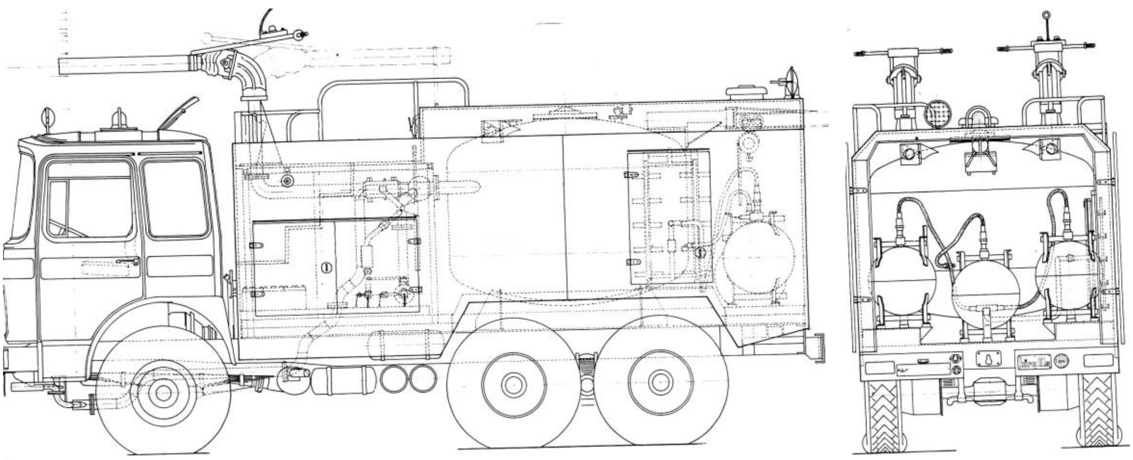

Figure 6. *Biocarbo 5000 one of the most extensive airport powder vans, carrying approximately 5,000 kg of powder [23].*

Gas fire extinguishing agents.

At the end of the 1970s, halon extinguishers and units began to find their way into the equipment of airport fire services. Halon seemed the ideal agent for nipping small avionics and engine fires in the bud. Unfortunately, these substances were found to contribute significantly to the destruction of the ozone layer. In Montreal, on 16 September 1987, an international commitment was signed to limit and phase out the use of, among other things, halons for firefighting.

Despite the radical commitments, halons still remained in aircraft fixed firefighting systems on board. 'Ground' firefighting equipment using halon was replaced after a short period by its safer substitutes. Particularly at North American airports, gas fire extinguishing units generally referred to as 'clean extinguishing agent' have become very popular. The extinguishing agent is a variety of liquefied gases that are relatively effective extinguishers and quite safe environmentally. Most often, these are the same substances used in fixed fire extinguishing systems protecting large server rooms and computer centres.

3.4. Other Firefighting Measures

In 1937, under the auspices of the US Army Corps of Engineers, the Peter Pirsch truck was modified for the US Air Force. It had an auto-pump with a capacity of 750 gallons (2835 l) per minute and a 250-gallon (945 l) water tank. Innovative was the water and foam system using a high-pressure 'Bean' nozzle used by citrus growers in Florida for spraying. The Bean nozzle was also the first adjustable nozzle to produce high-pressure water mist [2]. Water mist technology did not gain acceptance at the time due to its high cost and limited effectiveness.

New technologies bring enormous benefits but also new risks. An example of this is the fire of the 'invisible' B-2 bomber at Guam airbase. It turned out that the super-secret coating on the surface of the flying wing, giving it a 'stealth' characteristic, severely hampered firefighting and structural cooling. Following this incident, the US Air Force accelerated the deployment of the UHP technology, which had been under development since 2002. The main feature of the UHP system is the delivery of water at a pressure of 100-150 bar. Trials have also been conducted to mix water at this pressure with other agents such as carbon dioxide [11]. The technology is very effective but is unfortunately associated with high costs and secondary hazards. Interestingly, the Russians had similar problems with extinguishing the outer lining of the soundproofing and reducing signatures in April 2015, when the nuclear submarine K-266 caught fire in the repair dock. Nothing is known about the introduction of new extinguishing technologies in Russia [12].

4. Problem- Application Methods for Firefighting and Rescue Agents

Until the ICAO officially defined the minimum expenditure of foam-forming solution in the early 1980s, depending on the category (fuselage size) of the aircraft, manufacturers of airport rescue and firefighting vehicles were quite free to choose their extinguishing agent delivery equipment [32].

4.1. Rapid-Response Devices

Historically, the first devices for administering fire extinguishing agents, after hand-held fire extinguishers of course, were various types of lances or nozzles connected to a section of hose with a fixed cross-section. This combination of equipment corresponded to today's rapid-response devices. The classic prototype of today's solutions is the equipment distributed by German manufacturers in the 1930s. The biggest difference is the way the axle of the fixed hose reel is oriented and the lack of a remote return reel. Over the years, rapid attack devices with a fixed cross-section hose reel have developed considerably. Designs adapted to high-pressure and UHP equipment have been implemented. Hose reel lengths have reached up to 100 m. In the last decade, hoses with a Kevlar backing structure were also implemented in place of the classic multi-layered rubber ones. A significant reduction in the weight of the unwound hose has been achieved. Manufacturers offer a variety of reel-back and blow-back systems.

Figure 7 *Two-line rapid attack device on a Kfz.343 Henshel car (1936) [8].*

Figure 8. *A contemporary dual-function foam-powder device from Attac - One.*

The solution dedicated to the parallel feeding of foam and powder proved to be a kind of dead end. The dual-hose reels (for solution and for powder) looked beautiful on advertising materials. Unfortunately, the weight and design of the combined hoses caused very big problems with effective line unwinding. US manufacturers even proposed the use of a special bar connecting the two nozzles to act as a 'snake' to facilitate unrolling.

4.2. Bumper Turrets

For many years, hand-held foam nozzles were considered completely sufficient to effectively extinguish an aircraft fire. With the increase in the size of aircraft and the amount of fuel carried, there was a need to find a way to deliver foam over a greater distance and with greater intensity. Even greater problems had to be overcome by proponents of carbon dioxide extinguishing. The throwing ranges were much smaller than those of foam and over-intensive delivery often resulted in the formation of ice build-ups around the discharge nozzles.

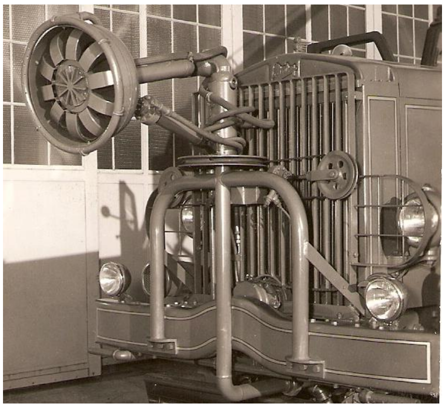

Figure 9. *Left, adjustable carbon dioxide delivery head of a C 150 Cardox car prototype bumper turret [2].*

Figure 10. *Contemporary Rosenbauer bumper turret.*

Dozens of trials resulted in the design of a special multi-mode head. Obviously, such a device was not suitable for manual operation and therefore had to be linked to the vehicle design. The idea of the designers of the C 150 Cardox car was a breakthrough. The adjustable multi-barrel head met the tactical objectives for carbon dioxide and, at the same time, became a model for contemporary bumper turret designs. The warhead was fully controllable from the driver's cab. An additional innovation was the inclusion of directional nozzles under the bumper to protect the approach zone.

4.3. Main Turret (on the Roof of the Cabin)

Remote-controlled turrets on the roof of the cabin are today the most popular device for administering firefighting currents at airports. In 1947, fire tests were carried out on eight B-17 bombers at Eglin Field in the USA, burning almost 95,000 litres of fuel. A C 155 class water and foam vehicle with a tank capacity of approximately 3,780 litres was used for the tests [13]. Among other things, the series of tests proved that firefighters did not have a method of administering foam with adequate output and throwing range.

As early as 1948, the Australian Department of Civil Aviation (DCA) began an ambitious programme to identify future solutions. Post-war surplus bomber aircraft were used for trials. Based on specifications developed by DCA engineer Marshall Fordham, a unique test vehicle was built on an REO bus chassis with the engine located at the rear [14].

Figure 11. *Turret on the roof of the cabin of the experimental vehicle of the Monegeett Monster project, 1948 [14].*

The vehicle concept was highly advanced and incorporated a number of innovative features. "Armoured" aluminium bodywork was designed to allow the vehicle to approach a burning aircraft directly, while protecting the operators inside. A roof-mounted, manually operated turret had the ability to deliver foam over a distance, while sprinklers mounted under the bumper delivered foam to the ground directly in front of the vehicle. The turret operator sat on a raised motorcycle-type saddle and, with the blinds down, looked through a slit in the armoured dome located on the front corner of the vehicle's roof. The Australian design can be considered the prototype of today's cab roof-mounted turrets, controlled from the interior.

In 1950, in Washington, D. C., J. K. Schmidt, Roscoe Bell and Ray Smith demonstrated, before a gathering of congressmen and senators, a prototype of the new vehicle, designated 0-10.

Figure 12. *Type 0-10 fire and rescue truck (1950) probably the first mass-produced vehicle with a roof-mounted turret [13].*

Unfortunately, during the demonstration, the 0-10 vehicle's operator collapsed and died. The US legislators present were 'dampened with foam'; nevertheless, they were impressed with the vehicle's tactical capabilities and allocated funds to American La France for mass production of the 0-10 [13]. The negative experience from the earlier 0-07 and 0-08 prototypes, in which the turrets were mounted on the cab mudguard, was obliterated.

Over the years, turret designs have undergone many changes, which also resulted in a division between classic designs aspirated nozzle with foam barrel and modern non-aspirated nozzle.

Figure 13. Modern European water and foam turrets Ziegler Z 8000 with classic aspirated nozzle.

Figure 14. Modern European water and foam turrets Rosenbauer RM 60 with non-aspirated nozzle.

Akron Brass has developed an “aerospace” gun head design with a dispersing mushroom nozzle. Thanks to its unique internal design, this nozzle allows the delivery of a current of water or foam just as with a mechanical deflector. A very original way of mounting the water and foam turrets can be found on the Oshkosh P-15 vehicle. The turrets are mounted in the front and rear of the vehicle. Due to the solutions used, the operators operate the water and foam turrets in a similar way to how mariners operate anti-aircraft cannons on warships.

Figure 15. One of the 80 Oshkosh P-15 fire and rescue vehicles produced in 1978 [13].

4.4. Coaxial Application of Foam and Powder

One of the biggest problems in both the petrochemical industry and airports was extinguishing pressurised fuel fires. Impressed by the problems in extinguishing the Magpetco tank farm fire (in January 1974), Dwight Williams began to look for effective solutions. The result of his intensive work was the development of a nozzle design for nozzles and guns, through which powder and foam could be applied simultaneously. An innovation in relation to earlier solutions was the application of agents coaxially; the jet of extinguishing powder was surrounded by a jet of water or foam [16].

Figure 16. The classic solution foam – powder (from 1963).

Figure 17. The revolutionary Williams foam and powder coaxial application nozzle (1980).

The method of coaxial application of powder and foam currents has proved very effective in extinguishing spill fires, but especially in extinguishing pressurised fuel fires. Nowadays, it is available as hand-held nozzles as well as turrets [15].

4.5. Extinguishing Arms

Conducting firefighting operations using fire turrets mounted on firefighting vehicles also has disadvantages. Often the extinguishing agent jet obstructs the operator's view of the fire area, making precise extinguishing impossible. In many cases, the extinguishing agent jet cannot reach the desired location, e.g. through holes in the structure or behind an element shielding the combustion zone. Even moving the vehicle to another location is not sufficient to avoid losses due to reflection and dispersion of the jet. In many centres, projects have been initiated to increase the manoeuvrability of the guns by 'inserting' a movable arm between the gun and the vehicle structure. The rotating arm used in the CC 150 Cardox firefighting vehicle can be considered the prototype of modern firefighting arms.

As part of the innovative Nimbus project, Walter Baiker of the Swiss company Hydrokran proposed mounting 2 short horizontally rotating arms terminating in cannons on the roof of the body. The idea was that during the application of the extinguishing currents, the operator had a good view of the area between the extinguishing agent jets. The ability of the extinguishing currents to reach behind obstacles was also improved. Unfortunately, the project did not go beyond the construction phase of 1 prototype [17].

One of the forerunners in the development of firefighting arms was the American company Snozzle (now part of the Oshkosh Corporation), which has been developing the HRET (long distance extendable cannon) design since 1987 [18]. The HRET design is 2 arms (the upper of which is telescopic) mounted pendulously on a rotating base mounted in the upper body of the vehicle.

Figure 18. *The prototype, the firefighting arm of the CC 150 Cardox car on a Mack chassis (1947) [2].*

Figure 19. *The modern version of the HRET arm on the Oshkosh Strker 6x6 car (2023).*

Over more than 30 years, the concept has evolved considerably to reach a working height of more than 20 m, suitable for Boenig 747 or Airbus 380 aircraft. Several manufacturers offer different mutations of the original idea proposing different working fields, different sized firefighting turrets and auxiliary equipment. Firefighting arms have become a global standard and the Oshkosh Corporation boasts hundreds of different vehicles sold with HRET arms.

Much attempt has also been made by the US company Colet to improve the manoeuvrability of firefighting turrets on vehicles. The designers of this company used slightly different arm mechanics. The largest design used a hydraulically lifted giant A-shaped frame, fixed, to be built into the rear corners. The disadvantage of the solution is the lack of rotation. On top of the massive frame is a pivoting two-part turret arm. When the second arm is straightened out, the cannon "overtakes" the body of the vehicle by a small distance, while when lowered the turret can function as a bumper turret.

Figure 20. *Colet vehicles with firefighting arm - highest position.*

Figure 21. Colet vehicles with firefighting arm - lowest position.

Nowadays, firefighting arms are manufactured by many companies. Years later, the design has also found favour with units protecting large chemical plants. The more affluent American and Canadian off-road fire services are also beginning to reach for this solution.

A completely different solution is the short drop arms with mounted cannons to extinguish fuel spills using the 'low attack' method. Here, too, the forerunner was Snozzle with its Rhino solution.

Figure 22. American designs of short drop arms with turrets, by Oskosh.

Figure 23. American designs of short drop arms with turrets E-One.

4.6. Piercing

An analysis of the course of firefighting operations carried out on transport (cargo) aircraft indicated the extremely low effectiveness of internal operations. It is practically impossible to carry out safe and effective operations when the holds are cluttered "up to the ceiling" with cargo containers. In order to be able to carry out internal operations in such cases, the concept (known from the early days of airport rescue) of piercing the hull plating was revisited. With the first HRET firefighting arms, a new generation of piercers was delivered, in which the piercing lance was pressed against the fuselage skin while the arm was telescoped. After a few years, a modification was introduced with additional actuators pushing the lance into the hull. The ability to apply a dispersed fire extinguishing current of 500-1000 litres per minute through the hull plating, into the hull, increased the effectiveness of internal operations significantly. Under the right conditions, the punch lance can penetrate, even into the interior of an aircraft transport container. Of course, various types of handheld punchers with a water output of 50-300 l/min are still in use.

Figure 24. Classic Oshkosh punch with a forced arm movement.

Figure 25. Rosenbauer punch with an additional forcing actuator.

At the beginning of the 21st century, firefighters at Koln-Bonn Airport experimented with the use of Cobra extinguishing technology on the firefighting arm. Despite promising tests, the solution did not catch on in the airport environment. A puncture device mounted at the end of the firefighting arm appears to be a promising solution for operations at modern large-volume facilities. Unfortunately, there has been no fire service in Europe that has undertaken to investigate the practicality of such solutions.

4.7. Access Devices

One of the problems encountered during rescue and firefighting operations on an aircraft is rescuers' access to the interior [25]. Already in the early 1950s, a special saw for cutting large holes in the fuselage skin was tested as part of the Australian Monegeeta Monster programme mentioned earlier [14, 27]. The size of the hole not only allowed firefighting currents to access the interior. It was also possible to evacuate casualties through such an opening. Admittedly, tests carried out on decommissioned bombers confirmed the short time required to make a rescue hole (usually less than a minute). Unfortunately, other aspects were assessed negatively and the idea was consigned to the archives.

Figure 26. *Testing of a special hole saw as part of the Monegeeta Monster programme (1948-1950 [14]).*

Figure 27. *The result of use a special hole saw (1948-1950 [14]).*

The conversion of the mobile staircases used for passenger service was seen as the simplest way to improve firefighter access to aircraft interiors. Vehicles could be fitted with a range of equipment such as rapid deployment reels, dry risers, fire pumps and water tanks, generators and smoke extractors. An interesting concept was the use of a modified elevated cabin used for on-board food deliveries.

The Italian company BAI adapted the scissor-lifted cabin for rescue purposes. The capabilities of the vehicle were very high, but the barrier was the complexity and low capacity of the fold-out auxiliary ladder.

At military airfields, evacuation of injured pilots from fighter aircraft was a problem. Any operation, once the fairing is opened, in a cramped cabin is very difficult and carries the risk of activating the catapult system.

The firefighters had to carry out operations from an appendage ladder or by standing, or basically balancing, on streamlined sections of the cabin skin. To improve safety and efficiency, the rescuers asked for folding platforms to be fitted to the front of the vehicles. One of the first minimalist solutions was proposed by the now defunct Dutch company Saval-Kronenburg.

Figure 28. *Modern staircase on a vehicle chassis, adapted for rescue purposes by Rosenbauer.*

Figure 29. *A simple platform on a MAC 6 Saval-Kronenburg (2001).*

Figure 30. *A modern but large platform on Panther 8x8 Rosenbauer vehicles (2022).*

One of the leading manufacturers of airport rescue and firefighting vehicles proposes a very robust design based on lifting columns (similar to those used in garages). The solution unfortunately has significant drawbacks such as reduced visibility, weight, reduced angle of attack. Adopting such a concept is a difficult decision for those seeking a solution to improve access. A solution that lies in between the above structures is a Polish solution, made by WISS on behalf of Wroclaw Airport.

Figure 31. *The fold-out platform on the WISS Felix II car (2012).*

Figure 32. *The simplest solution - a Thornycroft Nubian 6X6 (1968) with a bonnet adapted to the function of a support platform [28].*

5. Off-road Bravery, Driving Dynamics and Safety

In the second half of the twentieth century, the International Civil Aviation Organisation (ICAO) took the issue of the field capacity of airport rescue and firefighting vehicles very seriously. During this period, airports began to be relocated further away from urban centres into areas that were less urbanised and saturated with suitable roads. Problems with moving heavy vehicles occurred not only in the close-in area but also in the airport areas [33].

"The American way" resulting in the construction of airport vehicles on special chassis with increased off-road capability was recognised by the ICAO authorities. The approach and departure angles of airport vehicles defined at the time, the requirement for single tyres and all-wheel drive have become canonical to the present day.

Figure 33. *Prototype vehicle 0-12 on a special 8x8 chassis, like the earlier 0-10 and 0-11 were the inspiration for many US manufacturers [13].*

European manufacturers only started to abandon commercial chassis in the late 1970s.

Figure 34. *One of the first European special chassis vehicles, Faun LF 1412/52V12 8x8, GTLF 20000 Magirus [19].*

Leading players in the aviation world also expected a dramatic improvement in the off-road capability of the vehicles of selected airport fire stations. Two avenues for improving terrain performance were recognised. The first was the use of tracked vehicles. As early as the 1950s, the Americans experimented with the firefighting use of an adapted Nodwell Arctic tractor [20]. The subject was revisited during the Vietnam War. An impoverished version of the then state-of-the-art M 113 tracked armoured personnel carrier was used as a fire fighting vehicle. Among other things, the vehicle was fitted with a fixed boom with a large medium foam generator. Despite its many advantages, none of the solutions lived to see wider implementation due to the cost and limited versatility of the traction.

Figure 35. *A fire version of the Vietnam War-era M 113 transporter.*

Figure 36. *A contemporary fire version of the Bv 206 [21].*

Manufacturers in the Russian Federation also have considerable experience in this field, but they have oriented themselves mainly towards forest firefighting.

Nowadays, some airport units use various versions of articulated tracked vehicles, derived from the Hägglund Bv 206 design, which have proven their usefulness on many occasions and have also found their way to field firefighting units in the Czech Republic, for example.

Another way to increase off-road ability was to use wheeled articulated vehicles. This solution was considered more promising because it guaranteed good handling characteristics on paved roads and in moderately difficult terrain. The first attempts were made after the Vietnamese experience with the M 520 Goer articulated vehicle. Unfortunately, no detailed information is available from this period. For many years the programme was abandoned returning to it at the end of the 20th century. The fruit of Oshkosh and Rosenbauer's collaboration was the DA 1500 vehicle, which was distributed in relatively large numbers to military and civilian fire services. The vehicle, which consisted of two articulated sections with an 8x8 drive train, featured much greater terrain capability while retaining good high-speed road driving capabilities.

Figure 37. *An experimental vehicle probably based on the M 520 Goer.*

Figure 38. *A modern vehicle Oshkosh DA 1500 car.*

Another major problem proved to be ensuring adequate driving dynamics and safety. The statistical size of the water tanks in airport rescue and fire-fighting vehicles has doubled over the decades. On top of this, the maximum actual weight was increased by constantly expanding special equipment and devices (e.g. HRET). In order to achieve acceptable accelerations and speeds (which found their way into the official regulations), it was inevitable that the power output of the power units was increased. While engines of 500-600 hp were standard in the 1980s, vehicles with engines of around 1,000 hp began to become widespread by the turn of the century. Previously, such combined power units were only characteristic of extremely large vehicles, e.g. those built on Faun LF 1412/52V12 chassis. After the Second World War, it was common practice to use components from wartime production for civilian applications. Years later, very large, old engines from military equipment began to be taken out of production. Very often, a system of 2 smaller propulsion engines was used to achieve adequate power. Many companies are credited with having taken the lead in implementing such solutions, which now seem to have no future. Today's vehicles on 8x8 chassis have powertrains with power outputs in excess of 1,500 hp. As a result, vehicles weighing 48-52 tonnes have dynamics worthy of rapid intervention vehicles. Acceleration times in the 0-80 km/h range of less than 20 s have become possible; top speeds of 130-135 km/h are possible. Very good dynamics also have serious drawbacks. Extreme operating conditions adversely affect the durability and reliability of the powertrains. The biggest problem, however, proved to be a safety hazard. Large and heavy vehicles were easy to accelerate but increasingly difficult to brake effectively and ensure stable driving on curves. At airports in the United States of America, the number of accidents resulting in a car tipping over on its side or on its roof increased. The perception of overloading in heavy and fast airport vehicles has been diminished by improved ride comfort. Independent suspension, well-silenced cabins and powerful engines have become an unwanted recipe for loss of grip during curved driving. Similar problems were also experienced by Polish drivers who switched from old Stars and Jelcz to the relatively comfortable and 'powerful' CAS 32 vehicles on the Tatra 815 chassis. The US aviation authority implemented a research programme that resulted in a number of measures to prevent cars from tipping over during curved driving.

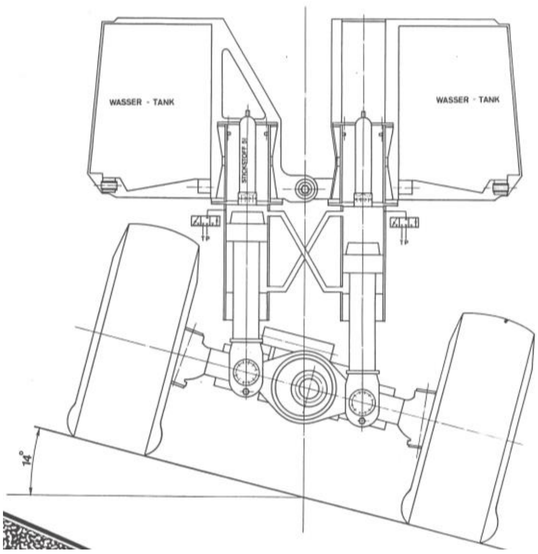

Figure 39. *Active hydraulic suspension system and of the experimental Nimbus vehicle's.*

In these realities, the ideas implemented in the experimental Nimbus project must be considered well ahead of the era [17]. The rescue and firefighting vehicle had the features expected by the users. The combined power of the 2 drive trains slightly exceeded 1,000 hp, the capacity of the water tanks was greater than 10,000 litres and the wheels of both drive axles could be steered. Despite the lack of modern electronic driving safety aids, the vehicle was characterised by outstanding stability, safety and dynamics typical of rapid intervention vehicles.

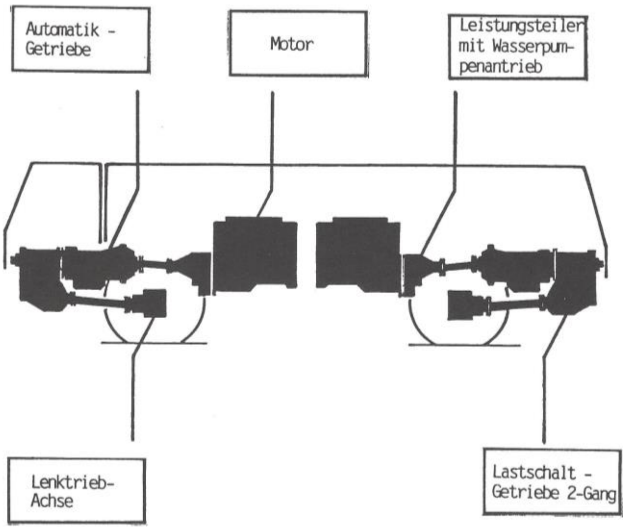

Figure 40. *Layout of the experimental Nimbus vehicle's propulsion system components.*

The Nimbus was able to correct lateral tilt up to 14^{o} and featured a low centre of gravity.

The use of active suspension in airport vehicles was attempted without much success by the American Colet and the European Terberg. A 6x6 airport rescue and firefighting vehicle built by the German company Lentner on a Terberg chassis was delivered to a Polish airport. Unfortunately, it was not a great success. Innovative but not thoroughly tested technology, combined with traditional driver and service training, proved to be the generator of many problems.

The use of electric drive units in airport vehicles has become a reality. One of the first was a Portuguese manufacturer, unknown in Poland, with its prototype vehicle Jacinto Lucitano. Current trends include the path of full electric propulsion created mainly by Rosenbauer. Another environmentally friendly solution is the hybrid version, which consists of supporting the traditional propulsion system with an electric system. Such solutions are proposed by Ziegler and Oshkosh, among others. Although the proposed hybrid solutions appear to be 'safer' for firefighters their innovation is limited. The complete replacement of the mechanical transmission between the internal combustion engine and the drive wheels could be considered a true new quality. Such solutions were already promoted by Ferdinand Porsche at the beginning of the 20th century in passenger cars and special heavy artillery tractors [35]. The exclusion of mechanical transmission offers greater freedom of vehicle design and control.

For several years, leading airport vehicle manufacturers have been offering systems to support active and passive safety. The best offerings include ABS, ASR, ESR or other systems known from cars and trucks with similar effects. Complementing the 3-point seatbelts, front and side airbags are beginning to be used, although these are not the most popular choices of future users. Perhaps the explanation is the nature of airport operations. In order to maintain the required response time, airport firefighters have to dress and don BA gear while on the move. They have a time of 1- 1.5 minutes to do this. There is a lot going on in the cabin during an emergency drive and more straps to fasten safely in such a short time is a big problem. It is high time that manufacturers came up with a safety solution dedicated to this style of operation. Crew cabs complying with the ECE R 29 standard have become the norm, although a collision between a fire truck and an aircraft taking off has shown that there are no completely safe cabs.

An absolutely virgin area in airport construction is the provision of a 'clean cabin'. A federal study conducted at a number of large fire garrisons in the US, put forward the thesis that the dramatic increase in cancer mortality among firefighters is due to poisoning resulting not during rescue operations but during the return from those operations. Firefighters in contaminated uniforms get into the cab of a vehicle. As they return to the unit, they inhale a mixture of many unstable carcinogenic substances from the fire, released from their protective clothing. In the small volume of the cabin, very high concentrations of substances hazardous to health can be formed. For this reason, many units have begun to introduce the principle of returning from action in barracks clothing. Potentially contaminated protective clothing, helmets, BA equipment are returned to the unit in a dedicated separate locker. They then go for decontamination and maintenance. Until now, no such 'dirty' lockers have been set aside in airfield vehicles - it is high time this changed.

6. Problem - Durability and Reliability

Over the years, airfield rescue and firefighting vehicles have become very complex to build. In the second half of the 20th century, manufacturers were very bold in introducing many new developments. Unfortunately, performance was often achieved at the expense of reliability. A classic example is the water and foam cannon, known from the Barracuda vehicles. To balance the cannon, the elastic energy of special springs was used. Control required the cooperation of an electrical, pneumatic and hydraulic system. Such an elaborate control system is a natural source of faults.

The reliability of airport vehicles began to decline with the wider introduction of electro-pneumatic control and electronics. Of course, CAN-standard control installations offer digital quality, but the huge number of sensors and actuators can generate many problems. The proportion of sensitive and fault-prone electronic components is steadily increasing. This is happening because of the trend towards the automation of many processes (the hassle of providing a sufficiently numerous service) and the duplication of many circuits in order to increase reliability.

In the 1960s, the challenge of increasing the reliability of airport vehicles was addressed. One of the reasons for exploring avenues for such a vehicle solution was the very unfavourable observations from the USA. Following the widespread introduction of vehicles built on unitised or small batch production special chassis, it became apparent that these were very unreliable. Existing users had habits corresponding to standards suitable for simpler mass-produced commercial chassis. A glaring drop in the efficiency of the new vehicles was observed, which was explained by their technical characteristics and the lack of an adequate technical operating support system. In Italy and France, the search for a way to simplify the design of airport rescue and firefighting vehicles began. In Europe, special chassis are used much less frequently for airport vehicle development than in the United States, so the focus was on a different problem. It was recognised that complex water and foam systems and foaming agents caused many problems.

Figure 41. Airport rescue and firefighting vehicles without an auto-pump, Italian Sirmac Rampini 524D 4x4 Rambo [31].

Figure 42. Airport rescue and firefighting vehicles without an auto-pump, French Birocarbo 5500.

Problems with the precise metering of the foaming agents, the durability of the auto-pumps and the stability of the foaming agents were recognised as obvious. In order to exclude the consequences of sedimentation, viscosity changes and biological decomposition of the foaming agents, it was proposed that ready working solutions be carried on the vehicles [29]. This resulted in the simplification of the water and foam system; metering systems were unnecessary. At a time of dynamic development in the design of powder units, it became natural to dispense with the auto-pump in place of a design with a pressurised tank containing the appropriate amount of solution [34]. Vehicles built on the basis of this concept were mainly deployed in units protecting military airfields.

7. Summary - Conclusions

As a result of a multi-directional analysis of the available material and observations from operations to date, an attempt has been made to systematise conclusions and expectations for the coming years.

7.1. Means of Transport

Undoubtedly, the motor vehicle will continue to be the primary means of transport for airport rescue and firefighting services, but many changes are expected in this area.

1. The state of the art and the experience gained indicate that autonomous vehicles should be implemented relatively quickly to support airport rescue and firefighting operations, the delivery of fire extinguishing agents and specialised equipment or the evacuation of casualties are the first applications for such vehicles.
2. It is advisable to change the concept of equipping airports with rescue and firefighting vehicles, a reduction in the off-road capacity of basic vehicles is expected in exchange for the introduction of supporting lighter vehicles with high off-road capacity.
3. The introduction of lighter vehicles with high off-road capability is expected to simplify design, improve ergonomics and operational efficiency and reduce production costs and increase supply.
4. In lighter vehicles, with water tanks of up to 6,000 litres, it is worth considering a return to the concept of vehicles with pressurised units in place of the fire pump, this could be a step towards lower operating costs and increased reliability;
5. Modernisation of classic drive systems is necessary; especially the introduction of direct electric drive of wheels, auto-pumps and other working components is expected. This will facilitate the proper installation of airport rescue and firefighting vehicles, significantly improve the control method and reduce the environmental load.

7.2. The Methods of Application

The methods of application of fire extinguishing agents can be considered quite effective but it is worth seriously considering new solutions that should improve the effectiveness and safety of operations, especially with the decreasing personnel capacity of rescue units.

1. it is natural to boldly introduce specialised land-based drones, i.e. remotely controlled (with elements of artificial intelligence) platforms capable of developing hose lines, application of fire extinguishing agents and transport support, in areas with increased risk to people or limited terrain accessibility.
2. it is worth modernising attack technologies through hull plating/structures; the concept of internal operations carried out in parallel through several punch lances left in the hull is promising.

7.3. Fire Extinguishing Agents

Fire extinguishing agents must be continuously modernised in line with aviation technology.

1. In the group of classic extinguishing agents, i.e. foams, it is mainly expected to offer a full range of products with the highest effectiveness (ICAO level C) safe for people and the environment, applied in low concentrations, durable and easy to store.
2. Fire extinguishing agents highly effective in extinguishing lithium battery fires, various modifications of which will increasingly find their way into aircraft designs, are urgently awaited.
3. The provision of effective extinguishing agents suitable for the new propulsion technologies (hydrogen, modern biofuels, fuel cells) will become a certain challenge in the near future.

7.4. The Personal Protection

The personal protection used by airport fire and rescue services has so far not deviated from the standards commonly used by all fire services. Expectations for change in the field of personal protection are increasingly being articulated.

1. There is an expectation of the implementation of clothing and equipment designed for the aviation environment, taking into account the specific hazards and operating conditions (e.g. cramped aircraft interiors).
2. The introduction of technical solutions for increasing the physical fitness of rescuers, such as special exoskeletons, at airports will be a very important, even historic, moment.

7.5. Reconnaissance and Emergency Management

Reconnaissance and emergency management appear to be the areas where, with the current state of technology, major advances will be easiest to achieve.

1. The use of safe drones (e.g. buoyancy drones) for external reconnaissance is obvious but it is worth extending their functions to include surveillance of environmental contamination in CBRN conventions.
2. Miniature cameras, including thermal imaging, with image transmission and 'on line' information on the status of firefighting agents in vehicles superimposed on aircraft technical data, could become the basis of a major decision support tool for the rescue and firefighting manager.

Abbreviations

AFFF	Aqueous Film Forming Foam
BA	Breathing Apparatus
CAF	Compressed Air Foam
CAN	Controller Area Network (CAN bus)
CBRN	Chemical, Biological, Radiological, Nuclear
HRET	High Reach Extendable Turret
ICAO	International Civil Aviation Organization
PFOS	Perfluoro Octane Sulfonic Acid
PFOA	Perfluoro Octanoic Acid
UHP	Ultra-High Pressure

Author Contributions

Andrzej Marzęda is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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