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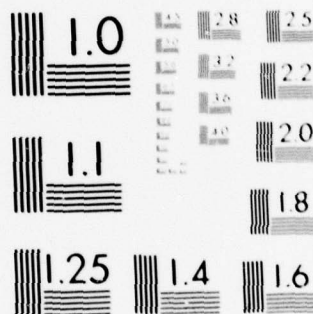
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EDITED TRANSLATION

FTD-ID(RS)T-0963-78 21 July 1978

MICROFICHE NR: *FTD-78-c-000995*

AERONAUTICAL KNOWLEDGE
(Selected Articles)

English pages: 18

Source: Hang K'ung Chih Shih, Number 12, December
1977, pages 12-15; 20-21

Country of origin: China

Translated by: Linguistic Systems, Inc.

F33657-76-D-0389

Jerry K. Chung

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WP-AFB, OHIO.

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Date 21 Jul 1978

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SAFETY AND RESCUE TECHNIQUES IN MANNED SPACEFLIGHTS

by
Hua Bao

This is the second of two parts of an article introducing the subject of spaceflight safety and rescue. Safety and rescue measures employed during various phases of a spaceflight are presented, along with projections on their future developments.

Emergency Rescue in the Powered-Flight Phase (Launch Abort)

Hazards due to the malfunctioning of the booster during the powered-flight phase are generally considered to be conditions to which prime attention should be given. Results from many in-flight tests show that insufficient propulsion, premature shutdown, or even explosion of the booster engines are possible; that the vehicle can lose control and deviate from its pre-determined trajectory due to malfunctioning of the guidance and control system; and that staging cannot be accomplished due to failure of interstage-separators. Under these circumstances, the booster is unable to launch the spacecraft into its pre-determined orbit, and an abort must be initiated to send the spacecraft back to earth. In particular, in the event of engine explosion, where threats to the crew's lives are imminent, means must be provided to enable the crew to escape the catastrophe and be delivered to safety. Of course, boosters designed to carry spacecrafts should be highly reliable so that the above hazards are not allowed to take place, but to fully ensure inflight safety and to avoid the unpredictable, each potential hazard and its corresponding rescue provisions have to be examined individually and in detail.

Working conditions of the boosters are monitored by malfunction detection systems installed in them, so that in case of danger alert can be furnished to the crew and the ground (via

telemetry). Some spacecrafts such as the Mercury spacecrafts have malfunction detection systems that can automatically initiate an abort through direct command of the abort systems.

Different abort methods are adopted at different altitudes in the powered-flight phase. From take-off to altitudes below about 20 kilometers, the spacecraft experiences considerable aerodynamic drag. In case of hazards, power plants on board the spacecraft is incapable of causing it to separate from the booster to escape the catastrophe, so special facilities for escape must be provided. At present, two types are commonly in use, namely, the escape-tower and the ejection-seat.

In the development of the Mercury spacecrafts, the concepts of "pushing" and "pulling" were considered separately. The former consists in installing three solid engines at the aft of the spacecraft. In case of hazards, the three engines would push the spacecraft out of the danger area. This concept was rejected on the grounds that the aerodynamic stability of the booster would be reduced and at the same time the booster would collide with and be damaged by the three engines when they were jettisoned. The design finally adopted was the escape-tower (Fig. 3), which utilized the latter concept, namely, that of "pulling". A steel tower three meters ^{high} were secured by three explosive bolts to the fore of the spacecraft. An escape rocket, capable of generating 23 tons of thrust and burning for 1.2 seconds, was mounted on the forward end of the tower. The rocket had three nozzles slanting outwards at an angle of 19° . The thrust line was offset from the spacecraft's axis to provide lateral displacement from the booster during separation.

The most catastrophic situation occurs when the booster explodes on the launch pad, generating immense fireballs and shock waves. The escape ^{tower} should immediately carry the spacecraft to safety out of the fireballs, and at the same time to a specific height to allow proper operation of the parachute system (Fig. 4).

The weight of a Mercury spacecraft in orbit was 1360 kilograms,

and that of the escape tower 580 kilograms. Owing to the very limited carrying capacity of the Atlas booster, the escape tower had to be discarded when the spacecraft had reached a certain height and when the power supplies on board (e.g. retrograde rockets) could cope with an abort mission. For this purpose, three jettison rockets, each of which could provide 160 kilograms of thrust, were installed adjacent to the three nozzles of the escape rocket. Under normal launch conditions the escape tower was discarded by means of the jettison rockets at an altitude above 6.5 kilometers.

Similar escape-tower abort system (Fig. 5) were also adopted for the Apollo and Soyuz spacecrafts except that under normal launch conditions the escape towers were not jettisoned until an altitude of about 80 to 90 kilometers had been attained.

In case of hazards the escape tower can only abort the spacecraft as a whole to escape the catastrophe, but is incapable of coping with accidents on board the spacecraft itself. On January 27, 1967, when three astronauts were sitting on board the Apollo IV spacecraft mounted on top of the Saturn booster at the launch pad undergoing simulated tests (two members of the crew were very experienced astronauts), a spark inside the oxygen-filled cabin set the whole cabin ablaze. The hatch could not be opened in time from either inside or outside, and the three astronauts were burned to death.

The ejection seat mode of escape was developed based on that used in present-day aircraft. The Command Module of a Gemini spacecraft was equipped with two ejection seats inclining $8^{\circ}20'$ upwards and making an angle of 24° with each other. In the range from the launch pad to an altitude of 14 kilometers, and under the conditions that the Mach number was less than 2 and the maximum dynamic pressure did not exceed 4000 kg/m^2 , the ejection seats were capable of ejecting two astronauts out of the Command Module simultaneously to land safely on ground. However, in practice, they were restricted to operate below an altitude of 5 kilometers. In case of booster

explosion on the launch pad, the ejection seats were capable of enabling the crew to escape the catastrophe and to attain a specific height for proper performance of the parachute system.

The ejection-seat abort system is also used in the Orient spacecrafts (Fig. 6). In case of hazards due to malfunctioning of the booster at high altitudes, on-board propulsion (such as retrograde rockets) can be used to separate the spacecraft from the booster, and then working procedures similar to ^{those for} normal reentry are followed to return to earth. Abort reentry trajectories at various altitudes should be calculated in advance and suitable reentry angles adjusted to prevent overloading of the reaction control system during reentry.

On April 5, 1975, shortly after the ignition of the final-stage rocket engines, which was a few minutes after take-off, malfunctioning of the Soyuz 18 guidance and control system caused the booster to deviate from its pre-determined trajectory. The ground control hurriedly issued an abort instruction. The booster engines were immediately shut down, and the spacecraft separated from the booster. At that time, the spacecraft had travelled beyond the dense atmosphere, and the escape rocket and adaptor had been jettisoned, so trajectory-adjustment engines inside the Service Module had to be activated to separate the spacecraft from the booster. Procedures akin to those for normal reentry were then followed. The spacecraft finally landed southwest of Gorno-Altajsk in a mountainous area in western Siberia, 1600 kilometers ^{away} from its take-off point.

Emergency Rescue in the Orbit (Orbit Abort)

Existing American and Russian spacecrafts are not equipped with specially tailored emergency devices, and in-orbit flight safety is only guaranteed by the reliability of commercially available products. Redundancy for important systems is provided as much as possible. For key areas without redundancy, ample safety margins are allowed for in design. In case of hazards, an abort has

to be made.

On March 16, 1966, the orbiting Gemini VIII spacecraft lost control of its attitudes as the crew erroneously turned on an attitude-control and trajectory-adjustment engine, and kept tumbling in space. Then it was also found that the engine circuits were shorted so that now even manual control was not possible. As the saying goes: Misfortunes do not come singly! The spacecraft had been planned to orbit for three days, but now only after 10½ hours in flight, it had to return to earth earlier than scheduled. Events like this are too many to enumerate.

Even though the Soyuz spacecraft claimed to be able to accommodate three passengers, its capacity was actually so limited that three astronauts donned with heavy space suits could hardly squeeze inside. Therefore, the crew had to wear ordinary flight suits in order to ride in it, which was extremely dangerous, for should a leakage develop in the cabin, the result would be disastrous. In 1964, the Russians once took such a risk with their Voskhod I spacecraft, and by luck won the honor of "sending three men to space for the first time". With this, they were even ready to push their luck further with the Soyuz spacecraft.

On June 29, 1971, prior to reentry, a sealed plug leaked as the Command Module of the Soyuz XI was decoupled from the Orbit Module. Air inside the Command Module escaped through this opening, and the crew wearing no space suits were killed because of the explosive reduction in pressure. From then on, no astronaut would dare to ride in the Soyuz spacecraft without a space suit. The so-called three-passenger Soyuz spacecraft now has to be changed to accommodate two passengers only. From this, it is clear that taking chances with safety in spaceflight can lead to very serious mistakes.

Emergency Rescue during Reentry

Before a spacecraft returns to earth from orbit, it is first re-oriented, and then retrograde rockets are fired, whereupon the

the spacecraft departs from its orbit around the earth , re-enters the atmosphere, and finally deploys its parachute system at an altitude below 20 kilometers for safe landing.

A spacecraft is generally equipped with two attitude modulation systems for reentry, one of which is an inertial-type automatic system, whereas the other is an optical-type manual system, the former being pre-dominantly used. Many incidents have actually occurred in which the automatic systems developed malfunctions and had to be replaced by the manual systems. On March 19, 1965, when reentry of the Voskhod II was initiated, the automatic reentry system failed. The spacecraft had to execute one more revolution before the crew could switch to the manual system. It finally landed in a snow-covered forest on the western slope of the Urals, 800 kilometers from the scheduled recovery point. The recovery forces had to spend three hours to locate the spacecraft, and one day to enter this remote forest to carry the astronauts^{out} on sledges.

In the incipient stages of manned spaceflight, people were not very confident of the performance of retrograde rockets, so in the design of orbits perigees were often chosen rather low. For example, the perigee of the first American Mercury spacecraft was only 140 kilometers above ground, so that in case the retrograde rockets should misfire, the spacecraft could follow the decaying of the orbit to naturally return to earth in $1\frac{1}{2}$ days' time without having to tumble in space for a long period, although the landing point could not be accurately predicted. Besides, the spacecraft was specifically designed. For example, the retrograde rocket was composed of several engines so that in case one of them failed the rest could still enable the spacecraft to return to earth in time, although deviation from the pre-determined landing site could be large.

People were also quite concerned about the performance of the parachute systems during the final landing stage of a spacecraft, for in case the parachutes should fail to be deployed or should get torn by air currents, all earlier efforts would be in vain. Therefore, spacecrafts were often equipped with multiple

parachute systems or with reserve parachute systems. On August 7, 1971, prior to retropackage jettison, one of the 3 main parachutes of the Apollo XV spacecraft was burned. Fortunately, the remaining two could be deployed properly to permit safe landing of the spacecraft. On April 24, 1967, prior to the landing of the Soyuz I, deployment of the main parachute failed due to entanglement of the parachute ropes, and the experienced astronaut Komarov was killed as the spacecraft crushed to ground. It was reported that thereafter all the Soyuz spacecrafts were equipped with reserves for the main parachutes. For spacecrafts equipped with ejection-seats such as the Orient and the Gemini, these seats can be used for abort in case of malfunctioning of the parachutes.

On July 21, 1961, as a Mercury spacecraft was performing splash-landing during a sub-orbital flight test, the explosive bolts on the hatch of the Command Module suddenly exploded and the hatch was opened prematurely. The crew hurriedly ^{swam} ~~swam~~ out of the Command Module and drifted in the sea, and was subsequently picked up by helicopters, while the spacecraft sank to the bottom of the sea. From this it is clear that at every link of the mission, from take-off to landing, there are always possibilities for hazards.

Escape Modules and Space Relief Vessels

As an additional step to ensure the lives and safety of the crew, the idea of installing ^{escape} ~~abort~~ modules on board the spacecrafts or in the space stations are proposed. Escape Modules are also called Escape Vessels. In the event of hazards when the spacecrafts cannot return to earth, the crew can ride the Escape Module out of its parent spacecraft to return to earth alone (Fig. 7). As the loading capacity of a booster is increased, especially in the development of space shuttles, it is possible to incorporate such an ^{escape} ~~abort~~ module compatible with the weight and volume of the spacecraft on board.

An escape module should be compact and at the same time should contain all the vital equipments. In particular, it should include

attitude control, retrograde rockets, heat protection system for reentry, life protection provisions, parachute systems, and mandatory help-request communication and signal facilities, for successful departure from its orbit around the earth and for safe reentry and landing.

Escape modules, according to their structures, can be classified into two types: rigid and expandable(collapsable).

One kind of rigid escape module design consists in remodelling the command module of an Apollo spacecraft to incorporate a system of solid-propellent retrograde rocket at the aft end. It can ~~accommodate~~ ^{accommodate} two to six passengers for use in large space stations in case of an abort.

Figure 8 shows a single-passenger escape module based on the encapsulated ejection-seat as used in the B-58⁸ bombers. A circular collapsable heat shield is added to the back of the seat to sustain aerodynamic heating in reentry. Also included are a hydrogen-peroxide manual attitude-control system, an environment-control system, a wide-angle telescope, a help-request communication and signal system, a parachute system for landing, a retrograde rocket, an ejection barrel, and jettison rockets. Such an escape module weighs 320 kilograms, and can be used for abort throughout all phases of the mission, from take-off to landing.

A rigid escape module occupies considerable space inside the spacecraft, and is difficult to maneuver, so various kinds of expandable escape modules are proposed. Under normal flight conditions, an expandable escape module is stored folded inside an emergency pouch or emergency box, and is pulled out and expanded in time of needs.

Figure 9 shows a single-passenger expandable escape module. On the surface of its metallic-shingled envelop is coated a soft refractory material to sustain aerodynamic heating. It is folded under normal flight conditions, and is expelled out of the spacecraft and inflated to a circular cone measuring 2 meters in dia-

meter and weighing 215 kilograms when in use. The living conditions of the astronaut is guaranteed by the space-suit.

Figure 10 shows a three-passenger collapsable escape module. Its structural shape is ensured by rigid ribs that can be folded. It weighs 660 kilograms. When expanded it measures 2.4 meters in diameter and 1.5 meters in height.

Finally, we shall briefly describe the space relief vessel.

On May 14, 1973, the United States launched the first space station, the Sky Lab, into space. At the time when it was experiencing maximum dynamic pressure, the micrometeoroid protection shield (made of aluminum and coated with a refractory layer) that was situated on the surface of the Orbital Workshop opened prematurely, and was torn away by strong currents. One of the two wing-shaped solar cell panels folded on the two sides of the Orbital Workshop was swept away together with the torn shield, while the other was entangled by the remaining fragments of the shield and consequently could not be opened. Thus the power supply of the space station was reduced by one half. Having lost the shield, the temperature of the Workshop rose to 55°C under direct sunlight, making it impossible for the astronauts to work there.

The Ground Control immediately examined all possible avenues for repair, for otherwise this 86 ton, 25 billion dollar space station would be ruined completely.

Eleven days later, three astronauts on board an Apollo spacecraft carrying repair gears and material supplies were sent to the Sky Lab. After docking, the repair crew entered the space station. A canopy expandable to the shape of an umbrella was extended from an opening at the Science Cabin. The canopy opened automatically to form a sunshade 6.7 meters wide and 7.3 meters long on the sunward side of the Orbital Workshop. The temperature of the Workshop consequently dropped and stabilized at about 27°C. Then two astronauts climbed out of the Workshop, and spent three hours

cutting the shield fragments off the solar cell panel with an automatically extendable, 3 meter long cutter, much like gardeners trimming branches off a tree. The solar cell panel could finally be opened, and part of the power supply was thus recovered.

It is evident from the Sky Lab experience that when spacecrafts or space stations encounter serious problems, it is possible to dispatch rescue crew on board a relief vessel carrying emergency equipments from earth to the troubled area. In the future when the development of space shuttles ~~has been~~^{is} successfully completed, it is possible to construct vessels expressly used for relief purposes.

Rendezvous and docking techniques of space vehicles are very essential to rescue in space. Although at present preliminary success is obtained, many problems have yet to be solved. In the event when a spacecraft loses control of its attitudes and tumbles in space, intricate techniques are required for the relief vessel to approach and dock with the troubled spacecraft.

Conclusions

In the foregoing paragraphs, emergency rescue techniques for spaceflights around the earth have been briefly presented from an engineering point of view, but none of the pertinent biomedical problems has been touched on. In the future when man travels to other planets (such as Mars), problems on the subject of rescue will be much more complicated. At present space rescue techniques are still at the developmental stage; much hard work has yet to be done.

Explanation of figures(in original Chinese script) by: Zu Shao Xian

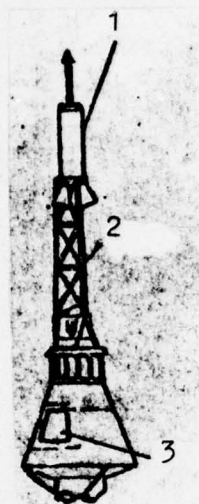


Fig. 3 Project Mercury launch escape system

- 1 escape rocket
- 2 escape tower
- 3 hatch



Fig. 6 Ejection seat on board the Orient spacecraft

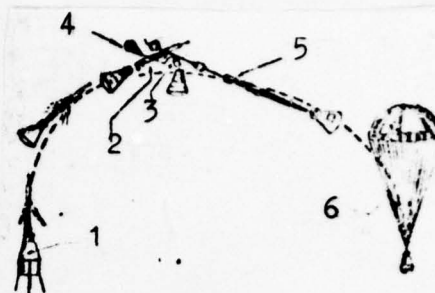


Fig. 4 Mercury landing system, launch-pad abort sequence

- 1 on launch-pad
- 2 escape tower separation
- 3 antenna canister jettison
- 4 drogue deployment
- 5 main parachute deployment bag
- 6 main parachute deployment



Fig. 5 Soyuz launch escape system (for use from launch-pad to 80 km altitude)

- 1 jettison rocket
- 2 adapter (airing)
- 3 pitch-control rocket
- 4 escape rocket nozzle
- 5 escape rocket



Fig. 7 Escape module reentry sequence

- 1 orbit
- 2 escape module departs from parent spacecraft
- 3 re-orientation and firing of retrograde rockets
- 4 reenters the atmosphere
- 5 drogue deployment
- 6 main parachute deployment
- 7 landing



Fig. 9 A single-passenger expandable escape module

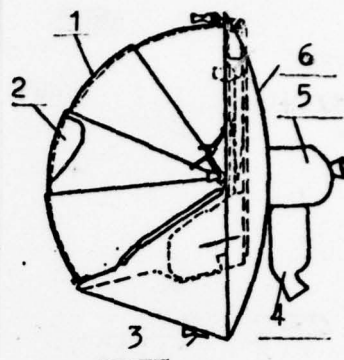


Fig. 8 An escape module based on encapsulated ejection-seat used in aircrafts

- 1 hatch
- 2 window
- 3 attitude-control nozzle
- 4 jettison rocket
- 5 retrograde rocket
- 6 heat protection shield



Fig. 10 An expandable 3-passenger escape module

- 1 life protection system
- 2 retrograde rocket
- 3 astronaut
- 4 structure
- 5 communication and guidance devices
- 6 parachute landing system
- 7 flight control system

A BRIEF INTRODUCTION TO THE MILITARY SPEY ENGINE

Mr. Chang-Gong, a reader from Chengtu, wrote: "According to a foreign magazine report, two American firms are going to replace the original engines in the Russian made MIG-21 jet planes for Egypt by the Spey engines made by the British Rolls-Royce Company. What are the main features of a Spey engine? Kindly explain." The following is a reply to the reader's question.

The Spey engine is a turbofan designed and made in England. It was first conceived in 1959 for the propulsion of Trident passenger airplanes. Ever since its debut in the aviation industry in 1964, it was found to exhibit excellent properties, such as large take-off thrust, low fuel consumption, low noise, and so on. Consequently, based on the civilian model, a military model was developed, which was first used as propulsion plants for the British Buccaneer, Hunter, and Phantom F-4E combat aircrafts in 1968.

A turbofan is also a jet engine. It differs from the common turbojet chiefly in that the turbofan includes an extra fan and an associated air channel. The air entering the turbofan is split into two streams. One of the streams, called the interior duct current, flows downstream into the heart of the engine, where it works in a way similar to that in a turbojet. The fan increases the pressure of the other stream, called the exterior duct current, which flows downstream through an outlet around the periphery of the interior duct. These two streams can either pass through the engine separately and be discharged through the exit nozzle, or be mixed prior to discharge. Now the thrust of a jet engine increases as a function of the amount of gas discharged. Since the turbofan has an additional exterior duct current, the thrust produced is more than that produced by a common turbojet having similar size and interior parts; at the same time, fuel consumption is also lowered.

A combat aircraft engine is usually equipped with an afterburner to satisfy combat requirements. It is imperative to increase thrust in a short time for take-off, climb, occupation of strategic altitude, surmounting of sonic barrier, and pursuit of enemy aircrafts. An additional thrust of about 70% is obtained for military models modified from civilian turbofan models. However, the modification does not simply consists in adding an afterburner; the structure and control system of the engine have to be improved too.

The thrust and fuel consumption of a military Spey engine are as follows.

Take-off Thrust: the thrust that is produced by a single engine during take-off. The bigger the thrust, the better the take-off acceleration is. When the afterburner is off, the thrust of the Spey engine is 5560 kilograms. When the afterburner is on, thrust can be increased to 9300 kilograms.

Fuel Consumption Rate: an index of fuel consumption usually expressed in units of amount of fuel consumed per hour per kilogram of thrust generated. Fuel consumption of the Spey engine is lower when the afterburner is off, the rate being 0.68 kg/kg thrust/hour. Fuel consumption increases when the afterburner is on, at which time the rate is 2.4kg/kg thrust/hour.

In the following paragraphs we shall briefly describe the components of the military Spey engine (see Figures).

Fan: also known as low pressure compressor. Its operational principle is similar to that of an axial-flow compressor. The fan is composed of five stages for use in increasing the air pressure. Air having passed through the fan is split into two streams. The portion of the air that is close to the central portion of the engine flows into the high pressure compressor and its pressure is continued to be increased. The outer ring of

air flows downstream through an annular pipe around the periphery of the interior duct.

High pressure compressor: It consists of 12 stages to further increase the pressure of the compressed air entering the interior duct.

Main combustor: It consists of 10 flame tubes and 10 fuel injection nozzles. Air leaving the high pressure compressor enters the combustor. It is then mixed with the fuel ejected from the fuel injection nozzles, and quickly burned. Temperature of the combusted gas can reach approximately 1300°C.

High pressure turbine: It consists of two stages. Hot compressed air flows into the high pressure turbine from the combustor and rotates the turbine, which then drives the high pressure compressor.

Low pressure turbine: It consists of two stages. Air leaving the high pressure turbine continues to flow into the low pressure turbine, which is then rotated and in turns drives the fan.

Mixer: It is used to conduct the exterior duct current to flow into the afterburner to be mixed evenly with the interior duct current.

Afterburner: It is housed inside a right circular cylindrical shell of large diameter. In the middle are three arrays of flame stabilizers and ~~augmented-thrust~~^{augmentation} fuel injection nozzles. When the engine is required to produce extra thrust, fuel is injected from the nozzles to intermingle with the evenly mixed interior duct and exterior duct currents, which are then combusted again. The temperature of the afterburner is very high, reaching about 1630°C. The higher the temperature, the more the thrust will be generated by the engine.

Exit nozzle: Current leaving the afterburner is ejected to the outside atmosphere at high speed through the exit nozzle. The nozzle area can be adjusted: when extra thrust is needed, the nozzle area will ^{be} ~~be~~ adjusted to a maximum; otherwise, it will be reduced.

Auxillary systems: They include fuel-adjustment system, lubrication system, starter system, electrical system, control system, etc. These systems are used to ensure proper functioning of the engine under different flight conditions.

Engines originally installed in the American Phantom F-4E and the MIG-21 combat aircrafts are the J79-GE-17 and the P-110-300 respectively. Listed on the following page are some important parameters of these engines and the Spey engine also, and the maximum attainable cruise speeds for these aircrafts.

Here we illustrate the advantages brought about by the installation of the Spey engine into the Phantom aircraft. The geometrical size and weights of the original engine and the Spey engine are basically similar, so replacement of the engine is greatly facilitated. However, the increase in air current necessitates a change in the air intake passage. Improvement in performance of the modified Phantom aircraft are essentially as follows.

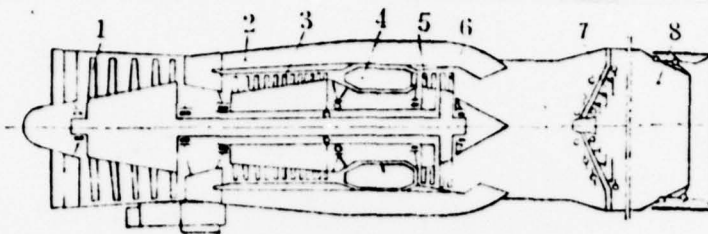
Owing to the increase in thrust, performance in take-off, climb, and acceleration is improved. The time taken to start from ground to a height of 12000 meters is reduced by 20%; in the acceleration from $M=1$ to $M=2$, flight time is reduced by 30%.

Flight ascent limit is raised to 21.3 kilometers, an increase of 1 kilometer. The maximum cruise speed is raised from $M=2.2$ to $M=2.4$.

Fuel consumption during sub-sonic flight is considerably lowered, so flight journey and uninterrupted flight time are increased by 30%, whilst combat radius is increased by 10%.

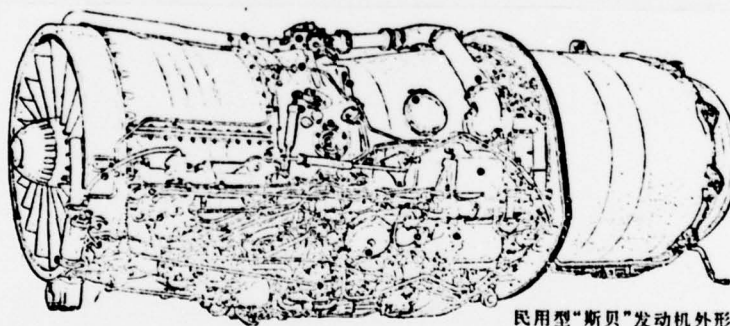
Comparisons of the Properties between the
Military Spey Engine and the Original Engines
Installed in the Phantom F-4E and the MIG-21
Aircrafts

Model	J79-GE-17 Engine (For Phantom F-4E)	P-110-300 Engine (for MIG-21)	Spey MK202 Engine
Structural features	Adjustable-stator, single-rotor jet engine	Double rotor turbojet	Double rotor turbofan
Compressor stages	17	3 + 3	5 + 12
Pressure increment ratio	12.5	8.85	20
Total air flow	75kg/sec	63.7kg/sec	92.5kg/sec
Thrust(kg):			
afterburner on	8120	5750	9305
afterburner off	5385	3900	5556
Thrust/Weight	4.66	5.0	5.05
Fuel consumption rate:			
afterburner on	1.97	2.3	2.1
afterburner off	0.84	0.94	0.68
Maximum attainable cruise speed (M)	2.2	2.0	2.4



Schematic diagram of the military
Spey engine

1. Fan 2. Exterior (By-pass) duct 3. High pressure compressor (through which interior-duct current passes)
4. Combuster 5. High pressure turbine 6. Low pressure turbine 7. Afterburner 8. Exit nozzle



民用型“斯贝”发动机外形

Appearance of the civilian Spey Engine



Trident passenger aircraft

Explanation by: Si Lin Wu
Figures by: Wen Cheng Cheng

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