Pool Fire Induced Cockpit Degradation

Anthony San Miguel*
Naval Weapons Center, China Lake, Calif.

It is important to understand the effects of pool fire phenomena on Navy aircraft because of the aircraft carrier fire threat. An interdisciplinary test methodology was used to obtain synergistic data from an unarmed Navy A-4 cockpit engulfed in a pool fire. The study was designed to gather data useful for fire-protection modeling, as well as to identify where emphasis should be placed for design of future laboratory small-scale tests. A description is given of the underground laboratory (located below the pool fire pan) used in this study. Data are presented of the thermal environment within the cockpit, the production of toxic gases, smoke generation, and animal response. A listing is given of quantized events that occurred during the test, together with a number of design recommendations to increase the survival time of fighter aircraft cockpits.

Introduction

A CATASTROPHIC aircraft carrier pool fire will develop when a weapon of either friendly or enemy origin penetrates a fueled weapon-laden aircraft on the flight deck. The fire is then propagated over the flight deck by weapon cookoff[1,2] and fuel spillage. If the fire is not contained within some 5 min, experience shows that it is likely to incapacitate the strike capability of the carrier. Thus, one design goal is to extend pilot survivability within the cockpit to 5 min.

Except for a few critical regions, high-performance military aircraft are not designed for fire survivability during crash-on-takeoff events. Specifications and data for cockpit fire degradation do not exist. To obtain such data, it was necessary to design a test facility and utilize state-of-the-art transducers to generate baseline data. To achieve this goal, fire experience gained from commercial aircraft[3,4] and Army helicopter[5] testing was used as a basis for generating thermal, toxic, smoke, and animal-response data.

The main objective of this study was to obtain synergistic data from an unarmed Navy A-4 cockpit engulfed in a pool fire. An interdisciplinary test methodology was utilized to gather data useful for fire-protection modeling, as well as to identify where emphasis should be placed in designing future laboratory small-scale tests. To achieve this goal, an underground laboratory was constructed below a pool fire pan. An A-4 cockpit was instrumented with an assortment of thermal, mechanical, chemical, and physiological measuring transducers. Data obtained from the test were reviewed, and recommendations were forwarded that could increase the survival time of fighter aircraft cockpits to 5 min.

Underground Fire Facility

The underground fire facility constructed for this study is shown in Fig. 1. The facility features an instrument bunker located 1 m below the fire pan. A 2-m-diam tunnel some 66 m long provides double access to the instrument bunker. Located at one end of the tunnel is a fire control barricade. The other end terminates with an emergency exit. The fire facility is located in a remote desert area of the Naval Weapons Center, China Lake, Calif. Laboratory quality instruments are located in the constant-temperature instrument bunker. During a test, personnel confine themselves to the fire control barricade, which is protected from possible toxic fumes by a positive air pressure. Canaries are used in the tunnel as safety toxic gas detectors. Water, power, and gas are circulated to the test aircraft (shown in Fig. 1) by means of an insulated umbilical tube connected to the instrument bunker.

Instrumented Cockpit

A forward section of a Navy A-4 aircraft was used as the test item. Figure 1 illustrates the portion of the aircraft utilized. The test item was supported on the fire pan by its three landing gear. The aft bulkhead of the fuselage was insulated. The test item was cleaned and fitted with all normal major components, which were of surplus service quality.

The A-4 cockpit was instrumented[6] as illustrated in Fig. 2. Additions to the cockpit were a stainless steel box containing a water-jacketed 16-mm camera with a 3-mm wide-angle lens, a three-dimensional calorimeter, three mutually perpendicular accelerometers, an ice bath for thermocouples, a microphone, conditioning electronics, and a transmitter. Attached to the top of the box was a flight helmet containing a rat (instrumented for EKG and EEG) suspended in a sling. On the instrument panel was attached a smokemeter. A glass treadmill containing a free-running mouse was located on the top of the glare shield. A differential pressure transducer was located on the starboard side of the cockpit. Also protruding through the starboard side of the fuselage was a 7.6-cm-id umbilical tube, housing power, data, and water lines, that was connected to the instrument bunker. Separate 6.4-mm-diam stainless steel lines (some 6 m long) were used to circulate cockpit air between the cockpit and chemical analysis apparatus located in the instrument bunker. A detailed description of the transducers, instrumentation, and installation is given in Ref. 6.

Toxic Gas Measuring Apparatus

Toxic effects associated with fires[7] are usually attributed to the presence of chlorine, cyanide, and carbon monoxide, and to the depletion of oxygen. Other toxic gases exist, but standards for acute human survivability have not been universally accepted. The means to measure toxic gases are numerous, each being a compromise of sorts. The system used in this study is shown in Fig. 3 and described in detail elsewhere.[6]

Air was circulated from the vicinity of the helmet rat in the cockpit through 6.4-mm stainless-steel tubing to the tunnel below, where it was sampled by the various transducers. The rate of air circulation was 22,000 cm^3/min. At the first station, water was removed from the gas. Filters were then used to remove particulates. The gas was next cooled to 18°C by means of a water bath. Fifty-cm^3 glass gas samplers were sequentially filled for subsequent analysis. The excess gas was passed through an assortment of toxic gas measuring trans-

Received Nov. 29, 1976; revision received May 3, 1977.
Index categories: Thermal Modeling and Analysis; Cabin Environment, Crew Training, and Life Support; Testing, Flight and Ground.

*Mechanical Engineer. Member AIAA.

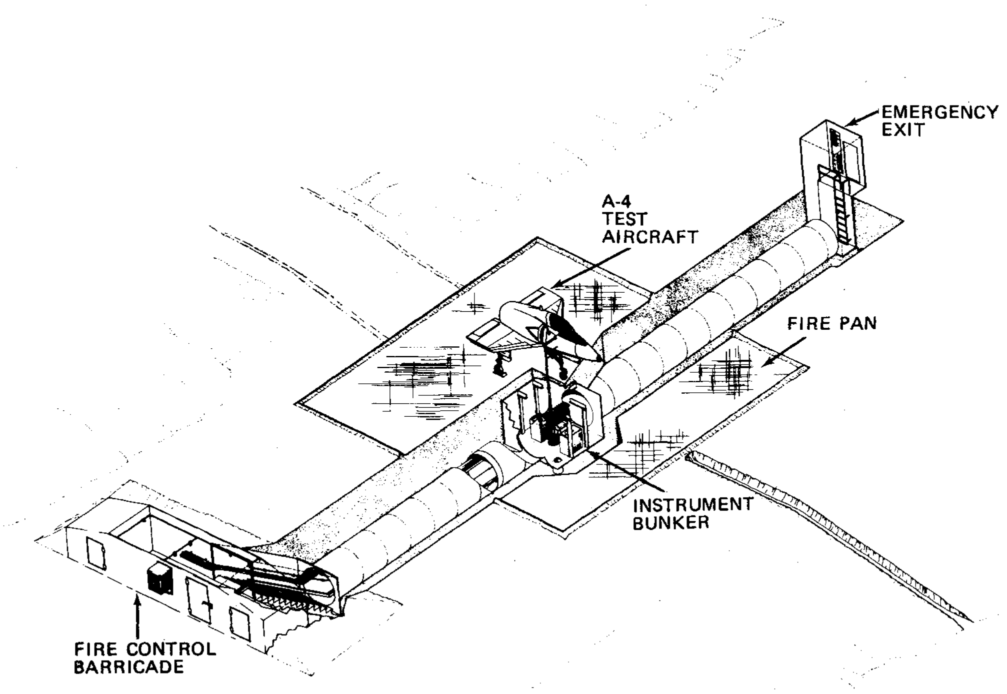

Fig. 1 Fire test facility with A-4 cockpit on fire pan.

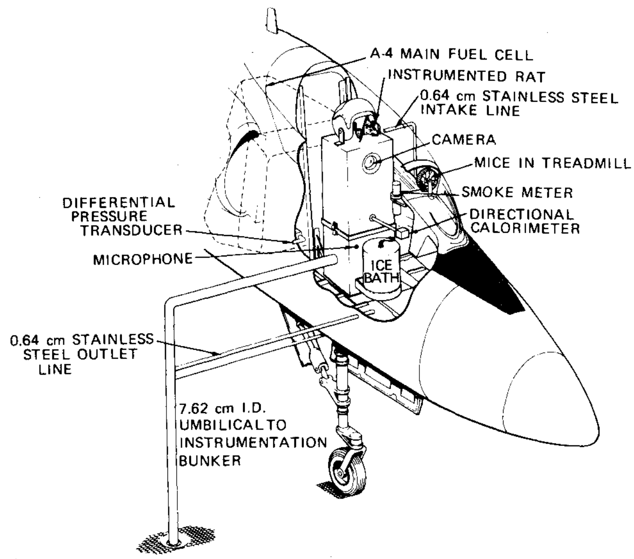

Fig. 2 Cockpit instrumentation systems.

ducers including a glass container with a rat and a glass container enclosing two mice on a glass treadmill. The gas was finally reheated to cockpit ambient temperature and returned to the cockpit in the vicinity of the cockpit floor.

Pool Fire

The pool fire consisted of burning 14,000 liters of JP-5 jet fuel floating over 28,000 liters of water in a fire pan 25 m in diameter. A nominal wind velocity of 10 knots was blowing between the nose and port side of the test item, representative of conditions on a carrier deck.

The fire first developed on the starboard side of the test item. At 224 sec, firemen initiated fire extinguishment, after it had been confirmed that fire had entered the cockpit. Complete fire extinguishment was realized in 16 sec.

Heat Measurements

Slug calorimeters and thermocouples were used to measure cockpit heating. Details of their construction, location, and response during the test are given in Ref. 6. One- and three-dimensional versions of slug calorimeters were used to measure heat flux. Several one-dimensional slug calorimeters and thermocouples were placed in all the major zones within the test item. The cubelike three-dimensional transducer was mounted as shown in Fig. 2.

No response was recorded for the three-dimensional calorimeter until 203 sec. The face of the transducer viewing the forward instrument panel sensed a heat rate of 0.52 W/cm^2 between 213 and 222 sec. The port and starboard faces of the transducer recorded 0.03 W/cm^2 between 211 and 231 sec. The bottom face measured 1.07 W/cm^2 between 208 and 232 sec. The top face measured 0.36 W/cm^2 between 203 and 232 sec. At 232 sec, light water from the firefighting equipment had cooled the interior of the cockpit.

The significance of the levels of heat flux measured by the three-dimensional calorimeter within the cockpit is determined by use of human pain threshold criteria given in Ref. 8. For example, the 1.07 W/cm^2 measured in the cockpit between 208 and 232 sec represents unbearable pain after some 3 sec of exposure time.

Back Side Heating

Post-test inspection of the fuselage fuel tank directly behind the cockpit revealed that the fuel-filled bladder suffered no damage, even though the bottom of the bladder was directly exposed to fire after the bottom exterior aluminum skin melted through. No damage was caused because the fuel-filled bladder behaved as a heat sink protecting the rear of the cockpit. This was confirmed by a slug calorimeter placed on the back of the seat, facing aft. Post-test inspection, confirmed by gas analysis, showed no evidence of fuel leaking into the cockpit during the test.

Nosecone Heating

A thermocouple and a slug calorimeter were placed inside the fiberglass nosecone to measure heating in that section. Initial temperature rise was detected at 7.4 sec after ignition. Heating remained relatively uniform until 162 sec, at which time the thermocouple failed, suggesting that the nosecone was destroyed.

Initial heating by the slug calorimeter was detected at 21 sec. The heating rate was about 0.06 W/cm^2. At 95 sec, the heating rate increased significantly to 5.1 W/cm^2. That rate continued until 99 sec, when the slug calorimeter malfunctioned. It would appear then that the forward bulkhead was directly exposed to fire beginning at 95 sec.

Forward Bulkhead Heating

The forward bulkhead served as an efficient thermal barrier. This was confirmed by a thermocouple attached to the back side of the bulkhead (facing the interior of the cockpit). No appreciable heating was measured during the test until after 222 sec. The light water cooling was not detected. This lack of heating was confirmed by a slug calorimeter facing the floor covering in the proximity of the thermocouple. The heating of the slug calorimeter was negligible. It would appear then that the air in the vicinity of the port floorboard was nearly ambient during the test. This observation was confirmed by post-test inspection in that no significant discoloration, deformation, or melting of plastics was observed.

Port and Starboard Side Heating

The outputs from the thermocouple and slug calorimeters attached to the interior cockpit sides showed that the starboard side of the cockpit was heated more than the port side, due to the wind condition. Initial heating was observed at 11 sec. The starboard fuselage skin reached steady-state conditions at about 113 sec. There was no burnthrough, since the frame and stringers were apparently absorbing the excess heat. This was confirmed by post-test inspection. The heat flux penetrating the starboard side of the cockpit was about 0.1 W/cm^2, compared with about 0.01 W/cm^2 on the port side.

On the basis of the data, no open fire existed in the forward bulkhead region until the canopy failed at 192 sec. This conjecture was substantiated by post-test inspection of the dissected cockpit, in that no charred paint or burned components were found.

Interior cockpit self-heating (material decomposition) behavior was indicated on the port side arm rest between 96 and 161 sec and between 220 and 232 sec. On the starboard side, cockpit material decomposition behavior was indicated between 104 and 135 sec. These peculiar responses occurred in the same time frame that the cockpit toxic gases exhibited unexpected "reversals." Fire was recorded on both sides at 232 sec.

Thermocouples were placed adjacent to the upholstery at the elbow region on both the port and starboard sides. No appreciable heating was recorded. Hence, it is suspected that the heat observed above was due to smoldering material forward of, rather than behind, the pilot's position.

Thermocouples were attached to both the starboard and port sides of the instrument panel facing the pilot's seat. As was confirmed by post-test inspection, no appreciable heating was present until the canopy failed.

Cockpit Ceiling Heating

A thermocouple was attached above the glare shield alongside the exposed glass ferris wheel containing the cockpit mouse. Heating in this location began at 211 sec. Further confirmation of the relative coolness above the glare shield was provided by thermocouples placed near the port and starboard panels. The region above the glare shield remained ambient until after the canopy failed. This was confirmed by post-test inspection of the glare shield.

Thermocouples were placed on both sides of the helmet housing the instrumented rat. The temperature rise on either side of the helmet was insignificant until the canopy failed. Note that significant EEG postictal rat activity occurred at 133 sec, suggesting that the rat was beginning to sense heat through the canopy.

A slug calorimeter and a thermocouple were placed on top of the seat frame (behind the helmet) directed toward the sky. No appreciable heating was recorded before the canopy failed. Thermocouples were also placed inside the canopy

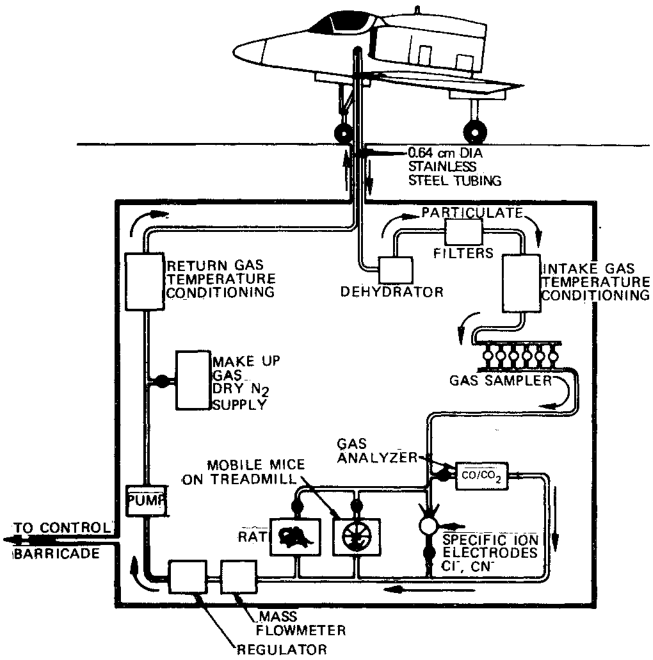

Fig. 3 Schematic of gas measurement system.

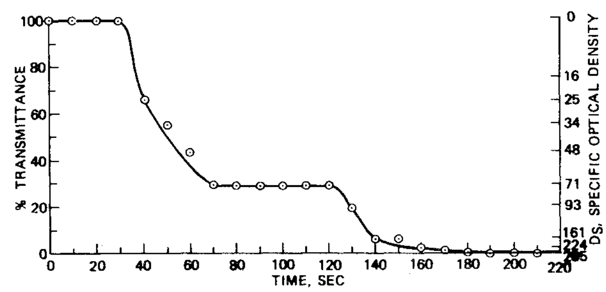

Fig. 4 Smoke transducer data produced during burn test.

along the periphery—one on the port side, one on the starboard, and one at the top. Insignificant heat transmitted through the canopy to the pilot before the canopy failed.

Cockpit Floor Heating

The output of a slug calorimeter attached to the starboard floorboard forward of the pilot's position recorded no appreciable heating penetrating the forward starboard floorboard.

A thermocouple was placed on the pilot's seat separated from the aft floorboard. Its temperature began to rise at 59 sec. The heating was due to fire in the wheel well eventually penetrating the floorboard and heating the seat from below. Post-test inspection revealed that the floorboard under the seat had melted and burned through. It is possible that this event contributed to or caused the anomaly in the development of toxic gases between 120 and 150 sec.

Smoke Production

Smoke production was measured in the cockpit. Measured data were expressed in terms of the specific optical density, D_s.[9] The smoke transducer was placed vertically in a holder in front of the instrument panel as shown in Fig. 2.

The output of the smoke transducer is shown in Fig. 4. No smoke was recorded until after 30 sec into the test. At that time, the transmittance began to decrease uniformly from 100 to 29% (from $D_s = 0$ to $D_s = 71$) at 70 sec. The materials producing this smoke apparently were then expended, because the transducer output remained uniform between 70 and 120 sec. New smoke generation began at 120 sec, causing the transducer output to increase to $D_s = 161$ at 140 sec. Complete smoke obscuration ($D_s = 200$) was measured by 155 sec.

Gas Analysis

The results obtained from the analysis of 15 gas samples are plotted in Fig. 5. The concentrations of oxygen, carbon dioxide, and carbon monoxide are shown, along with the concentrations of Cl and CN ions as indicated by the output from the specific ion electrodes. Note that the initial production of carbon dioxide and carbon monoxide correspond with the initial depletion of oxygen at about 55 sec. At about 120 sec, a peculiar reversal occurs, suggesting that air entered the cockpit. Then at 150 sec, the depletion of oxygen and the production of carbon dioxide, carbon monoxide, Cl^-, and CN^- resumed. The data from a gas chromatograph confirmed the peculiar reversal (see Table 1). The cause of the phenomenon is open to subjective interpretation.

The quantitative values shown in Fig. 5 are reasonable on the basis of measured carboxyhemoglobin (CO-Hb) levels in the rats. The measured CO-Hb level in the cockpit rat was about 49%. This concentration is reached in minutes for rats exposed to CO concentrations of 5,000 ppm. The maximum CO concentration in Fig. 6 was about 4,400 ppm at 171 sec. This correlation is considered good in the context of synergistic phenomena.

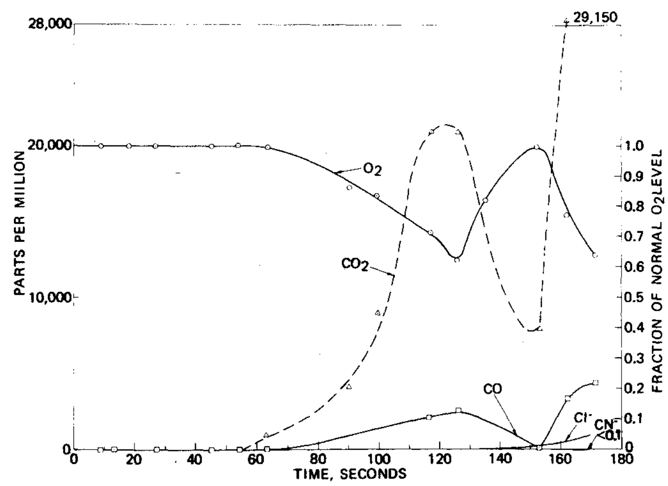

Fig. 5 Toxic gas production within the cockpit.

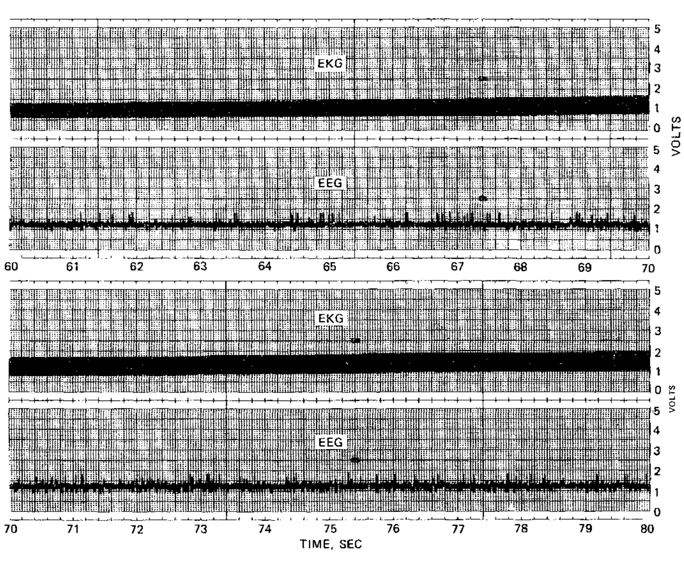

Fig. 6 Typical "apparent" EKG and EEG voltage signals from the cockpit rat.

Table 1 Gases identified by gas chromatograph—mass spectrometer, produced within Navy A-4 cockpit

Compound	Relative concentrations (electronic integrator responses)				
	Time after ignition, sec				
	36	72	108	144	180
Air + CO	114 003	141 024	140 809	85 086	149 957
Carbon dioxide (CO_2)	122	131	77	85	1771
Ethylene (C_2H_4)	-	-	-	1	66
Acetylene (C_2H_2)	-	-	-	Tr	24
Ethane (C_2H_6)	-	-	-	-	5
Propene	-	-	-	-	500
Water	4444	30 694	3361	3234	14 169
Acetaldehyde (C_2H_4O)	Tr	Tr	13	-	22
Acetone (C_3H_6O)	-	-	9	8	Tr
Benzene	-	-	-	Tr	73
Toluene	5	6	8	14	33
Xylene	-	Tr	-	Tr	Tr
Xylene + styrene + phenyl acetylene	-	Tr	-	Tr	Tr
Not identified	200	10	9	20	421

Physiological Effects

Rats and mice were used to obtain data on the physiological effects produced by smoke, heat, and toxic gases. The resulting data, although not statistically significant, can be used, together with that obtained with physical transducers, to roughly estimate pilot functionability. A rat placed in a helmet sling (Fig. 2) had electrodes implanted in the head and chest so that electroencephalographic (EEG) and electrocardiographic (EKG) data could be recorded during the test. EEG and EKG leads ran from the rat to the telemetry unit in the lower part of the manikin.

Another rat was placed in a glass container in the instrumentation bunker to serve as a control. The control rat was trained before the test to perform an electric shock avoidance leg flexion to provide a test of physiological functioning during the fire test. After the test, blood samples were taken from both rats to measure the CO-Hb level in the blood.

A less complex animal experiment involved the use of mice on a treadmill. Basically this method involves measuring the time a mouse can adequately function on a glass treadmill. The only data obtained is from a 16-mm movie camera monitoring the activity of the mouse while it is being exposed to potentially toxic gases.

The results of the animal behavior experiments were derived from inspection of the test animals, blood samples taken from both rats, movie coverage of both the cockpit mouse and the control mouse on treadmills during the fire, an avoidance response test of the control rat, and observation of the control mice in the ensuing weeks after the fire.

Immediately after the fire was extinguished, the cockpit rat was found to be alive, but with third-degree burns. The animal was immediately anesthetized with nembutal, and a heart puncture technique was used to secure a blood sample. This sample, taken 30 min after the end of the test, showed a 49% level of CO-Hb in the blood.

The typical electrical signals recorded from the cockpit rat are shown in Fig. 6. Such data were obtained for the entire test time of 243 sec and are found in Ref. 6.

The significant changes in "apparent EEG" signals occurred at about 41 sec, when both amplitude and frequency bursts (spindle incidence) decreased. At 93 sec, the signal amplitude and spindle incidence increased. At about 133 sec, apparent activity of the kind that follows a sudden attack or seizure was indicated by low-voltage amplitude. At about 150 sec, animal revival was indicated. At about 161 sec, animal hyperexcitability ended with the signal moving off-scale. At about 238 sec, the signal returned to near normal, suggesting that the animal was still alive.

At about 34 sec, the "apparent EKG" amplitude decreased and the frequency increased. At 51 sec, the amplitude increased. The reference level initiated a shift (perhaps due to animal movement). At 69 sec, the amplitude stabilized and its frequency increased. At about 93 sec, the reference voltage increased dramatically (perhaps due to animal movement). At about 97 sec, the reference voltage peaked and started to decrease (perhaps due to the animal slowing down its movement). At about 120 sec, the reference voltage stabilized. At about 128 sec, the reference voltage increased again. At about 133 sec, a low-voltage amplitude was recorded. Animal revival occurred at about 153 sec. From there on the signal was off-scale until the end of the test. However, at about 238 sec, the signal returned to reference level to suggest that the animal was still alive.

The control rat in the instrumentation bunker was observed to be alive and functioning when personnel entered the bunker after the test. At 5 min after completion of the burn test, this animal was administered the electric shock flexion response test and was observed to perform the avoidance response without difficulty. From all gross observations of the animal, it appeared normal.

At 15 minutes after the completion of the fire test, two blood samples from the control rat were taken. One of these samples indicated a 50% CO-Hb level in the blood and the other indicated 36%. A mean of these two values, 43%, is the best estimate of the actual CO-Hb level.

The activity of the cockpit mouse was recorded on movie film[2] until it could no longer be observed at 71 sec. By the time the firefighters reached the cockpit after the fire, the mouse had expired.

The two mice in the instrumentation bunker survived the test with no apparent toxic effects. Both mice continued to live normally during the next 6 months of observation.

No Response Measurements

There were no significant responses from the microphone, the differential pressure transducer, or any of the three accelerometers during the test. Hence, fire entering the cockpit was not accompanied by an explosion/implosion.

Structural Damage Assessment

Cockpit damage was caused by a combination of heat and firefighting. Significant structural damage was evident for the canopy (polymethyl methacrylate), the nosecone (fiberglass), and the sheet metal (aluminum) in the regions where the floorboard met the forward bulkhead, and under the pilot's seat. The instrument panel and interior side panels were not significantly damaged. In general, aluminum skin that did not melt was buckled. A combination of buckling and melting was manifested in large skin-to-stringer separation at the juncture of the floorboard and forward bulkhead. These separations could admit flames through holes with a cross-sectional area of about 230 cm^2 on either side. No other structural failures were found on either of the two sides, the forward or aft bulkheads, or on the top (other than the canopy).

The understructure of the aircraft was severely melted. Flames had direct access to the fuselage fuel bladder, the engine bay, the gun bays, and all hydraulic and electrical lines exposed below the cockpit floor. The aluminum flooring directly below the cockpit seat melted away, with only the cross-ribbing remaining. Of significance is the fact that the aircraft remained on its landing gear and did not collapse. The

Table 2 Chronology of significant events occurring during A-4 burn test

Time, sec	Event
0	Fuel ignition
7.4	Initial temperature change recorded on inside bottom of nose cone
11	Initial heat recorded on starboard side of cockpit
21	Initial heat flux recorded on bulkhead between nose cone and cockpit
27	Initial heat recorded on port side of cockpit
30	Initial smoke recorded by smoke transducer
34	EKG amplitude reduction, frequency increase
37	Smoke measurement, D_s = 16
41	EEG amplitude decrease, spindle incidence decreasing
51	EKG amplitude increasing, reference shifting initiated
59	Initial heating of lower pilot seat
63	Initial oxygen depletion & presence of CO and CO_2 measured
69	EKG amplitude stabilizes, frequency increases
71 - 120	Smoke measurement, D_s = 71
93	EKG reference voltage increases dramatically,
	EEG amplitude increases, spindle incidence increases
95	Fire enters nose cone, impinges on forward cockpit bulkhead
96 - 161	Exothermic behavior in vicinity of port armrest
97	EKG reference voltage peaks, starts decreasing
103	Camera records total initial darkness in cockpit
104 - 135	Exothermic behavior in vicinity of starboard armrest
109	EEG amplitude decreasing
113	Starboard fuselage skin reaches steady state
120	Flux transducers indicate asymmetric heating of cockpit,
	EKG reference voltage stabilizes
123	Steady-state heating reached on starboard side of cockpit
126	Maximum depletion of O_2, production of CO and CO_2
128	EKG reference increases again
131	EEG reference drops, lower amplitude
132	Initial Cl^- production
133	EEG postictal activity, EKG low voltage amplitude
134	Initial heat flux through canopy recorded
150	EEG signal indicates animal revival
153	O_2 returns to normal, CO returns to normal, CO_2 decreases,
	partial recovery of EEG and EKG
155	Smoke measurement, D_s = 200
161	Animal hyperexcitability ends, EEG and EKG signals off scale,
	possible destruction or detachment of nose cone
171	End of gas sampling
192	Camera recorded initial fire flick in cockpit
203	Top of directional calorimeter sensing initial heating from canopy
205	Camera and flux transducers facing canopy record initial fire in cockpit
208	Directional calorimeter measures initial heating from bottom
210	Flux transducer recorded significant heat entering through floor
221	Sides of directional calorimeter sensing initial heating
222	Cockpit thermocouples record sustained fire
224	Fire trucks take position and firefighting begins
232	Light water observed by cockpit camera
231 - 232	Cooling of directional calorimeter
238	EKG amplitude lowers to reference, EEG activity suggests that animal is alive
240	Fire extinguished
243	Recording equipment turned off

tires, immersed some 18 cm in water and fuel, did not blow out.

Discussion

A chronological listing of the major events occurring during the test is given in Table 2 (see Ref. 6 for all the data). The first heating that was recorded occurred at 7.4 sec at the inside of the bottom of the nosecone. The starboard skin began warming at 11 sec, some 16 sec before the port skin. This time lag was due to the prevailing wind. The forward bulkhead began to heat at 21 sec, suggesting that the nosecone was quickly degrading.

Within the cockpit, smoke generation began at 30 sec. The cockpit rat initiated unusual response at 34 sec. By 37 sec, the smoke reached $D_s = 16$. Rat reactions were pronounced by 41 sec. The skin below the pilot seat probably melted and vented by 59 sec. Oxygen depletion and the presence of CO and CO_2 were initially measured at 63 sec. Rat behavior stabilized at 69 sec. Smoke production ceased between 71 and 120 sec.

Rat activity returned at 93 sec, peaking at 97 sec. Short-term heating from apparant exothermic cockpit material decomposition was recorded in the vicinity of the port armrest between 96 and 161 sec, and of the starboard armrest between 104 and 135 sec. This material decomposition may account for the smoke production after 120 sec. The cockpit camera recorded total darkness at 103 sec. Hence optical transmission degradation of the canopy was due to chemical degradation of the canopy and not due to cockpit smoke. The darkness problem accounts for the reduced animal activity. At 120 sec, asymmetric heating of the cockpit was confirmed. Steady-state heating was reached at 123 sec. The maximum depletion of O_2 and the production of CO and CO_2 were reached at 126 sec. This too correlates with decreased animal activity. Animal revival after 128 sec correlates with the O_2 increase and decrease of CO and CO_2.

Heat flux from the canopy to the helmet was detected at 134 sec. Smoke production continued and reached $D_s = 200$ at 155 sec. The cockpit camera recorded an initial flick of flame at 192 sec. This flame occurred at about 2 o'clock facing forward, in front of the helmet.

Heat from the fire entering the canopy was detected by the three-dimensional calorimeter at 203 sec, which corresponds with the cockpit camera data. At 208 sec, heat was detected by the three-dimensional calorimeter from the bottom. The sides of the three-dimensional calorimeter recorded heat at 221 sec. This suggests flame effluent was passing through the canopy from the holes near the lower forward bulkhead and under the seat, in a chimney-like flow.

Light water was recorded[2] by the camera and the three-dimensional calorimeter at 232 sec. The rat voltage returned to its reference level at 238 sec, signifiying that it was still alive.

The data show that the cockpit remained relatively ambient up to the time the canopy failed, which is consistent with the data in Refs. 3 and 5. Although the measured temperatures would cause discomfort, they could readily be tolerated by a pilot until canopy failure. The data also shows that heat rather than toxicity is critical to pilot survivability. This was quite apparent since none of the animals died of, or even demonstrated, toxic effects. It follows then that since canopy degradation leads to cockpit degradation, the canopy is the critical component that must be made more fire-resistant in order to meet the 5-min pilot survivability requirement.

No critical significance is given to the other competing failure modes since the data was obtained from only one test. It is premature, at this time, to derive generalized statements without the aid of a systems model. On the other hand, the data should serve as a basis to compare future data, for systems modeling confirmation, and also for scaling laboratory tests with respect to smoke, toxicity, heat, and animal behavior.

Recommendations

Based on the events given in Table 2, future emphasis should be placed on reducing the smoke production potential of cockpit materials. Once the pilot's visibility is impaired (smoke, toxic gas), his normal instinct would be to abandon the aircraft, and he may perhaps inadvertently fail to shut down all systems prior to escape. Future laboratory tests addressing the smoke problem could be pursued with smoke chamber studies[9] utilizing the measurable quantity, D_s. Such tests, in conjunction with animal response to toxic gas, would eventually lead to the development of reasonable material specification standards.

Another important synergistic laboratory small-scale test that should be developed in the context of the subject matter of this paper is EEG/EKG responses from rat subjects. Table 2 demonstrates that the instrumented rat was the only transducer used to respond to all the environmental effects. Figure 6, which is representative data, has not been exercised by frequency spectrum analysis. However, it is apparent that if the rat was "calibrated prior to test," then approximate quantitative data could have been generated.

The canopy can be fire-hardened to achieve a 5-min survivability time by any or all of the following: 1) construct canopies of high-temperature-resistant polymers, e.g., polycarbonate; 2) coat methacrylate canopies with high-temperature-resistant polymers; and 3) incorporate a fire-extinguishing protection system in canopy design.

Wheel-well doors should be insulated and modified/designed to be shut at all times when the aircraft is not being serviced. Such doors would open only to retract/extend landing gear (the deck crew would possess a service key). An emergency fireproof ladder is needed to enable the pilot to escape and to allow firefighters to reach the pilot. A fire-sensing signal should be provided to warn the pilot of a pool fire so that he could take immediate appropriate action. The use of a "wrinkled" steel foil between the aluminum skin and upholstery would serve to block fire entry into the cockpit.

Conclusions

The conclusions that follow are made in the context of "baseline" information obtained from a single full-scale experiment.

Heat-transfer mechanisms are more critical to pilot survivability than those of toxic gas production. The influence of smoke in reducing visibility for the pilot, and thereby jeopardizing his chances for survival, is significant. The levels of toxic gases measured during the test are not great enough to produce serious short-term effects in the pilot. It is not known what influence the pilot's clothing, parachute, or unofficial paraphernalia would have on these "baseline" conclusions.

The cockpit did not get "hot" until the canopy failed. At that time, flame effluent penetrated through the cockpit from the holes (from melted aluminum) in the floorboard. The time to canopy failure was 192 sec. This time would have been shorter had the pool fire developed quicker, as in an unrealistic no-wind condition. Under ideal conditions a pool fire can develop fully in 20 sec. Thus, it is conceivable that the canopy could have failed at 110 sec.

References

[1] San Miguel, A. and McQuaide, P., "Shrike and Sparrow Missile Baseline Cookoff Tests," Naval Weapons Center, China Lake, Calif., NWC TP-5672, Oct. 1974.

[2] "Aircraft Fire Survivability," Naval Weapons Center, China Lake, Calif., Technical Motion Picture 413, 1976 (10 1/2 min., color, sound).

[3] Brenneman, J.J. and Heine, D.A., "The Cleveland Aircraft Fire Tests," *Fire Technology*, Vol. 4, Feb. 1968, pp. 5–16.

[4] Kourtides, D.A., Parker, J.A., and Gilwee, W.J., "Thermochemical Characterization of Aircraft Interior Panel Materials," *Journal of Fire and Flammability*, Vol. 6, July 1975, pp. 373–391.

[5]Atallah, S. and Buccigross, H., "Investigation and Evaluation of Nonflammable Fire-Retardant Materials," U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Va., Tech. Rept. 72-52, Nov. 1972.

[6]San Miguel, A., "Baseline Test of A-4 Cockpit in Simulated Carrier Deck Fire," Naval Weapons Center, China Lake, Calif., NWC TP-5812, Aug. 1976.

[7]Longelle, G. and Verdier, C., "Gas Sampling and Analysis in Combustion Phenomena," North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development, Hartford House, London, AGAR Vugraph No. 168, July 1973.

[8]Buettner, K., "Effects of Extreme Heat on Man," *Journal of the American Medical Association*, Vol. 144, Oct. 28, 1950, pp. 732-738.

[9]San Miguel, A. and Rieger, J., "Construction and Use of a Smoke-Measuring Transducer," *Fire Technology*, Vol. 12, Nov. 1976, pp. 303-310.