DOT/FAA/CT-81/209

Workshop On Mathematical Fire Modeling March 24-27, 1981

Edited by
Oliver K. Foo
Mitre Corporation
McLean, Virginia

August 1981

Proceedings

U.S. Department of Transportation
Federal Aviation Administration
Technical Center
Atlantic City Airport, N.J. 08405

TABLE OF CONTENTS

OPENING REMARKS

Wayne Howell
Chief of Fire Safety Branch
FAA Technical Center

Good morning, my name is Wayne Howell and I am Chief of the Fire Safety Branch here at the Federal Aviation Administration Technical Center. I would like to welcome you to the first aircraft fire mathematical model workshop. As most of you know, the FAA has been involved in aircraft fire math modeling for a few years and has achieved some accomplishments. We thought it would be good to invite some experts in fire modeling, but not necessarily just those involved in the aircraft fire modeling area, to have a technical exchange of information today and tomorrow. We would like to show you what we have accomplished and what we are doing. Hopefully you will learn something on aircraft fire safety R&D work and possibly we will also improve our program as a result of some of your critique and comments. It is a very informal conference and we would like you to relax and enjoy the presentations. When you make a comment, I would like to ask you to please stand up, speak up a little bit louder, and identify yourself so that your comments can be recorded.

I would like to explain to you how the aircraft fire math modeling work relates to the overall activities at the FAA Technical Center. Some of you are familiar with the Technical Center's operations and some are not, so I would like to start off by showing you first of all that the FAA Technical Center (Figure 1) is the most extensive proving ground of aviation safety systems in the United States. The Technical Center's Mission is shown in Figure 2. It also has international recognition because many FAA regulations formed from technical data developed here are used as international standards. Particularly, we are the leaders in the field of aviation safety standards. The research, development, and testing that we do here at the Center evolves into new concepts, new procedures in communications, navigation, air traffic control, and aircraft and airport safety.

FAA - TECHNICAL CENTER

Atlantic City Airport, New Jersey

Figure 1

MISSION

- AIRCRAFT SAFETY R&D
- NAS R&D SUPPORT
- NAS TEST & EVALUATION
- NAS FIELD SUPPORT
- FLIGHT INSPECTION AIRCRAFT SUPPORT

Figure 2

The Technical Center is located about 12 miles from Atlantic City and has approximately 1500 employees (Figure 3). The Center goes back to about 1958. Prior to 1958, there was a technical center in Indianapolis under the old Civil Aeronautics Administration. When the FAA Act was established in 1958, this Center was set up here in New Jersey in place of a former naval air station. The Center has 5,000 acres and about 1,000,000 square feet of building space. The new Technical and Administration Building has 500,000 square feet of floor space and houses close to 1,000 people.

The Center has the most modern airport in the United States with a 10,500 foot long runway. The newest most advanced aviation concepts are being tested here.

In order to test out new concepts in communication/navigation/ aircraft safety and air traffic control, the Center has a complete cross section of aircraft from a helicopter and small propeller type airplane up to a large jet Boeing 727 shown in Figure 4. We are very well equipped here to perform our mission.

The Technical Center organization chart is shown in Figure 5. Mr. Joseph Del Balzo is the Director. There are four divisions which do the actual research/development and test/evaluation work. The Systems Test and Evaluation Division test and evaluate air traffic navigation and communications procedures and facilities. The Systems Simulation and Analysis Division simulates air traffic control pattern or configurations. They can simulate any air traffic control pattern or configuration in the world. They have simulated air traffic patterns of Chicago O'Hare Airport, one of the largest and busiest airports in the world. New procedures and new techniques for more efficiently handling the air traffic at large airports are being developed. The Aircraft Safety Development Division, which I will go into in more detail later, is where the fire modeling work is being done. The Airport Technology Division is looking at approach and runway configurations. The Center also has some tenant organizations. The Flight

LOCATION

12 Miles Inland - Atlantic City

ESTABLISHED

1958 - Airways Modernization Board,
Then Federal Aviation Administration
(Formerly Naval Air Station)

RESOURCES

5,000 Acres - 184 Buildings

1,000,000 Sq.Ft. Floor Space

MODERN AIRPORT

10,500 Ft. Runway and Instrument Landing Systems
Control Tower - Public Use

MODERNIZATION

Hangar, Ramp, Fire/Crash Station - 1968
Technical & Administrative Complex - Scheduled Occupancy 1979

Figure 3

FIGURE 4. TEST BED AIRCRAFT — FAA TECHNICAL CENTER

ORGANIZATION

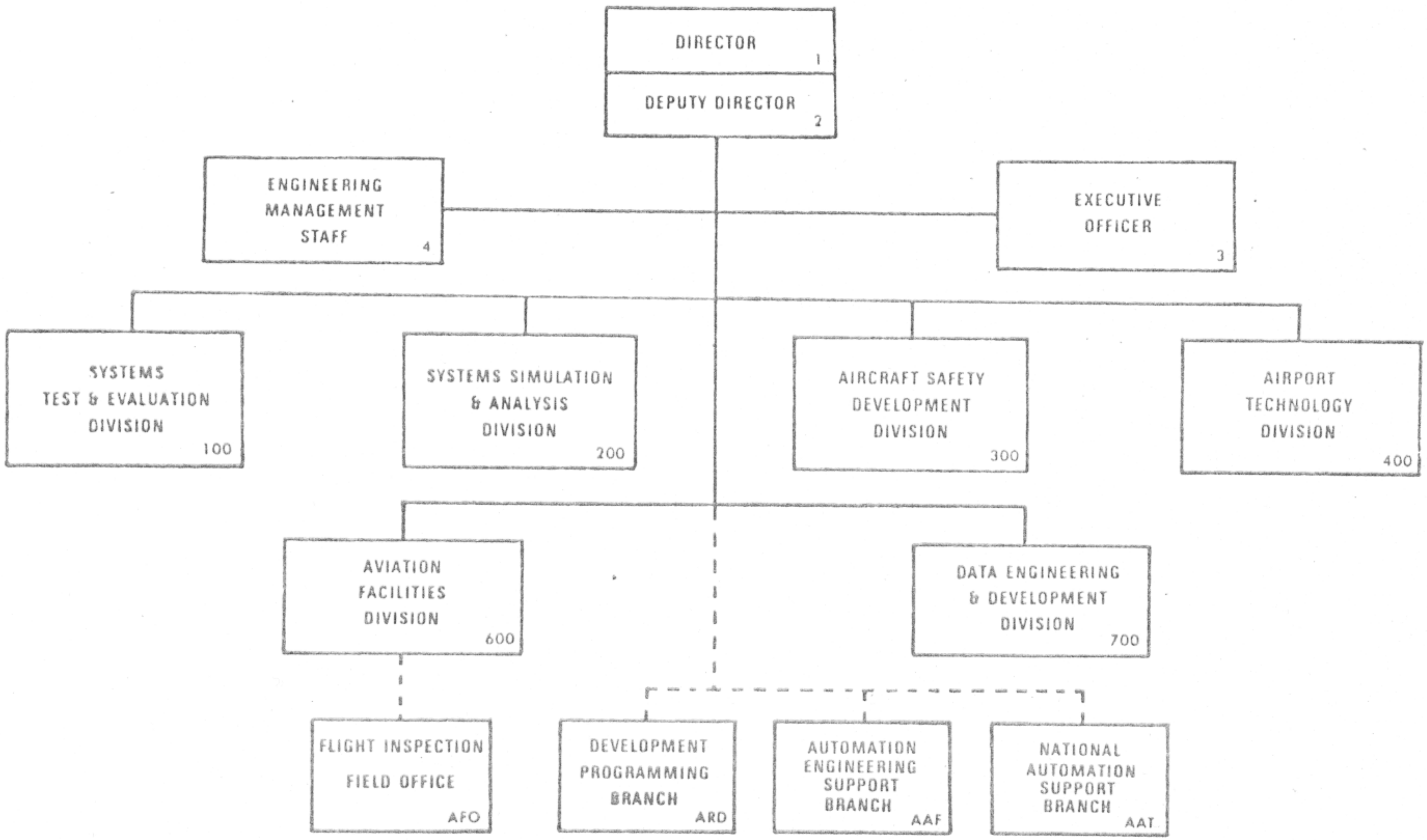


Figure 5

Inspection Division here at the Center has six or seven jet aircraft that flight inspect the communications and navigation facilities in the eastern part of the United States to determine if they are functioning properly and accurately.

Before the systems are implemented, they are tested and evaluated here at the Center, particularly in the air traffic control and communications/navigation areas. In the aircraft safety area, our chief product is technical criteria which are the basis for new regulations or revisions of current regulations.

The Aircraft Safety Development Division is the only division here at the Center which has the complete overall responsibilities for research, development, test, and evaluation. At this point, I would like to introduce Dr. Roy Reichenbach, the Division Chief. The Aircraft Safety R&D Program is shown in Figure 6. If you have any questions concerning this division's operations, Dr. Reichenbach is certainly available to answer those questions. The division consists of a Propulsion and Fuel Safety Branch, Crashworthiness Branch, Operations Branch, and Fire Safety Branch. The Fuel Safety Branch has R&D work going on in antimisting fuel, which is designed to reduce the post-crash fire hazard. Antimisting fuel is a fuel which has been modified by adding a polymer. In a crash situation, the fuel spills out of the fuel tank and atomizes to flammable, small droplets. The polymer added to the fuel prevents it from becoming small droplets and thereby reduces the fire hazard. Another way of trying to prevent a fire, of course, is to design the airplane to withstand a certain crash impact. The Crash Worthiness Branch's program is to develop and strengthen the fuselage and fuel tanks to withstand higher impacts. Under flight safety, the Operation's Branch is looking at the airplane itself, trying to design the airplane to be more compatible with the pilot to reduce pilot error.

The Aircraft Safety Development Division has approximately $15,000,000 worth of facilities at the Center (Figure 7). These

FAA AIRCRAFT SAFETY R&D PROGRAM MANAGEMENT

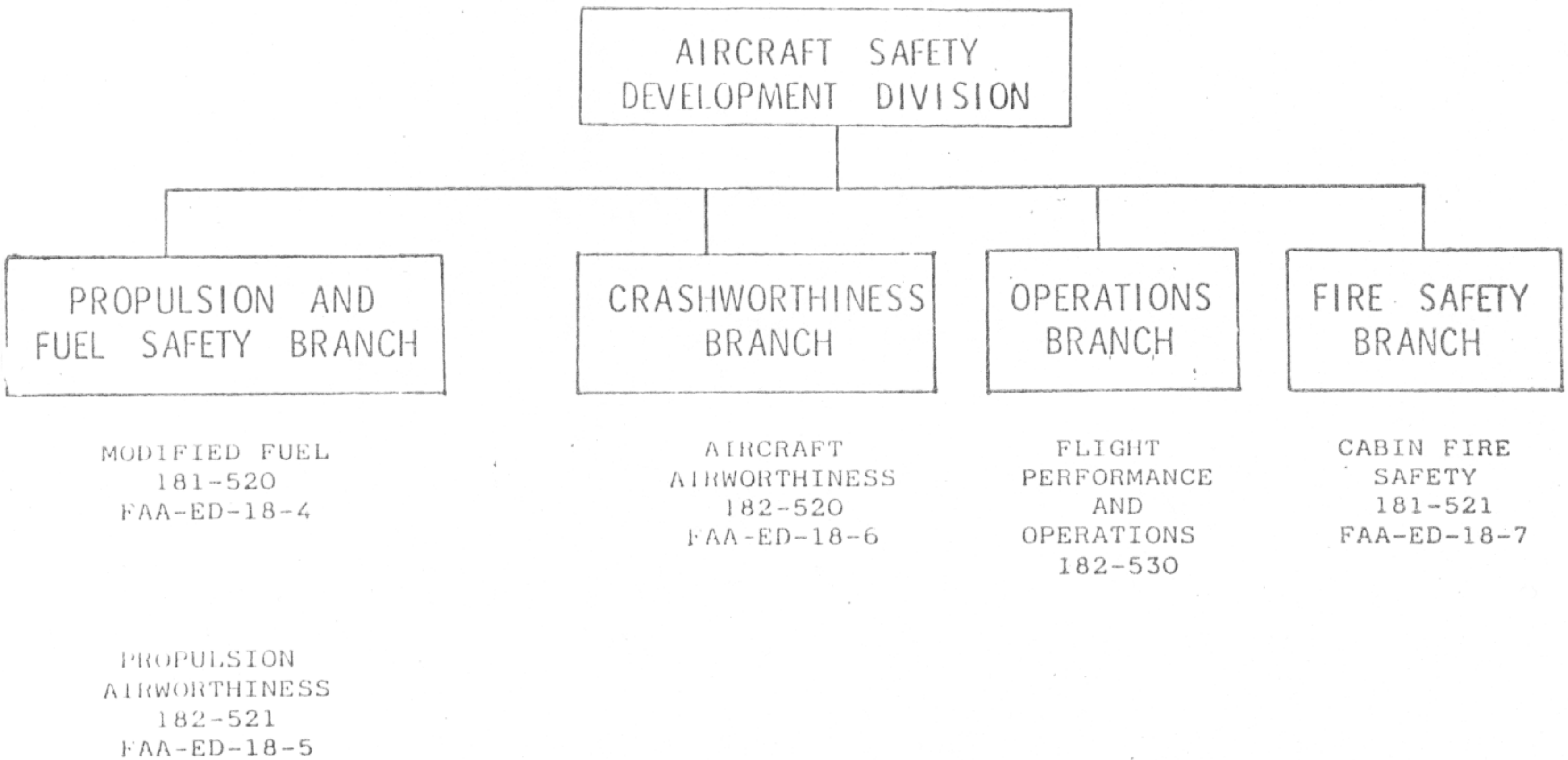


Figure 6

FIGURE 7. AIRCRAFT SAFETY DEVELOPMENT DIVISION TEST FACILITIES

facilities were designed to simulate environmental conditions like post-crash fire, in-flight fire, a crash situation or many of the kind of hazards we are trying to reduce or prevent. We have a five-foot wind tunnel in which we can run tests on small jet engines to determine the fire detection and extinguishing requirements for the engine. We have an engine test facility in which we are able to provide air into the cells to simulate flow through the engine cell itself which simulates airflow conditions while the airplane is in flight. We have a drop test rig in which we can determine ways and means of containing fuel in the wing. We have a catapult and track facility and several fire test facilities. We have a component laboratory in which we do laboratory fire tests.

The Fire Safety Branch's mission is illustrated in Figure 8. The major mission is to improve and develop fire safety standards for aircraft. In addition, the branch is developing fire protection systems for the Air Force.

The aircraft fire safety work covers propulsion systems, fuel systems, airframes, cabin related components, and airport fire fighting systems. I would like to point out the fact that we actually design our own unique fire test facilities. The engineers establish the specifications and work with the architect to insure that the unique requirements for fire testing are included.

A typical example is the full-scale fire test facility which was just completed (Figure 9). This is the largest in-door, full-scale fire facility operated by the federal government. It is 185 feet long, 75 feet wide and 45 feet high. It is capable of housing a wide body jet inside, with the wings and the upper tail cut off. Currently, we use a surplus C-133 fuselage and an 8'x10' pool fire outside the fuselage to simulate a wide body jet postcrash fire situation.

A new chemistry laboratory (Figure 10) is under construction which will be completed by September 1981 and it will be utilized to study

FIRE SAFETY BRANCH

MISSION

A. IMPROVE AND DEVELOP FIRE SAFETY STANDARDS:

- PROPULSION SYSTEMS
- FUEL SYSTEMS
- AIRFRAMES
- CABIN
- RELATED COMPONENTS, MATERIALS, AND EQUIPMENT
- AIRPORT FIREFIGHTING SYSTEMS

B. FUNCTIONAL DESIGN

- SPECIAL/UNIQUE TEST FACILITIES

Figure 8

FIGURE 9. FULL-SCALE FIRE FACILITY

FIGURE 10. CHEMISTRY LABORATORY

AIR FORCE FIRE PROTECTION PROGRAM

- FIRE RESISTANT FUEL LINES
- DYNAMIC ENGINE-BAY FIRE TESTS (F-111)
- ADVANCED FIRE EXTINGUISHANT-HABITABLE COMPARTMENT
- AIR FORCE (GENERAL)
  - EXPERIMENTAL SIMULATION IN-FLIGHT
  - FIRE IGNITION SOURCE STUDIES
  - FUEL TANK FIRE/EXPLOSION SUPPRESSION
- ARMY
  - FULL SCALE COMPONENT FIRE TESTING
  - FIRE HARDENING/PROTECTION ENHANCEMENT
  - ROTARY/FIXED WING

Figure 11

toxicity aspects of the materials in a postcrash fire situation. In the middle of the airport, there is a 200 foot diameter burn pit in which we are able to dump 10,000 gallons of jet fuel, set fire to it and test the effectiveness of different extinguishing systems and foam agents. We have tested both dry chemical and wet foam to extinguish an aircraft fire. A dual agent rapid response system is very effective in putting out the fire in a very short time period and is affordable by small aviation airports.

The Technical Center has been recognized for its expertise and facility capabilities for approximately 35 years in the aircraft fire safety work. As a result of this expertise and facilities, the Aircraft Fire Safety Branch has an active fire protection program for the Air Force. We have solved a lot of fire protection problems in military aircraft. The major efforts are outlined in Figure 11.

The Air Force has lost about six F-111 aircrafts due to in-flight fires and has requested the FAA to investigate the cause. An F-111 fuselage is placed on a fire test pad without the wings and tail surfaces. The airflow supplied from a nearby jet engine compressor bleed air into the engine intake and simulates actual airflow conditions that the F-111 would have during in-flight conditions. A fire is set within the engine bay to test various new fire detection and extinguishing techniques to improve the fire worthiness of this particular aircraft.

The major thrust of the Aircraft Fire Safety Branch is the cabin fire safety program shown in Figure 12. It is a very comprehensive program. There are five different major areas. One major area is Survival and Evacuation, which includes management of people during evacuation and applying survival aids to assist people in getting out of the aircraft. The second major area is laboratory test methodology development. The objective is to use laboratory test methods for material selection. The material selected should be less flammable, produce less smoke and be less toxic. The third major area is fire

AIRCRAFT SYSTEMS FIRE SAFETY PROGRAM FUNCTIONAL RELATIONSHIPS AND WORKFLOW

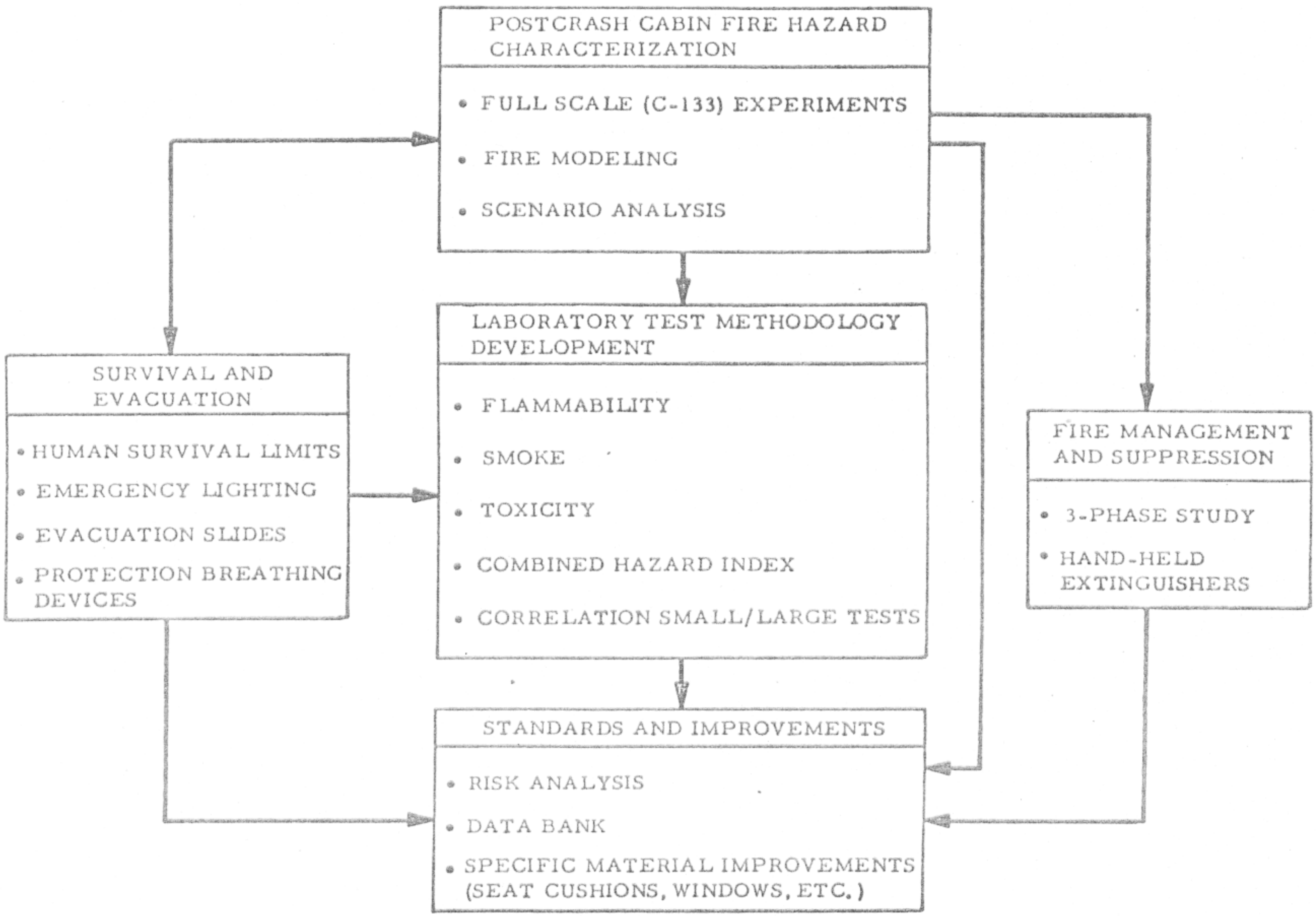


Figure 12

management and suppression which is to develop effective techniques of managing fire. The fourth major area is standards and improvements which includes risk analyses, data bank and specific material improvements. The fifth area is postcrash cabin fire hazard characterization where fire math modeling is being accomplished. It is important to characterize the postcrash fire. The main characteristics measured are fire progression, gas temperatures, radiation, and convective heat fluxes. Full-scale fire tests and math modeling are conducted in parallel to achieve maximum results.

The final recommendations from our fire program are expected to be formalized in August 1983. The standards, improvements, and acceptability criteria will be ready by that time. The aircraft fire safety program is moving fairly well and we hope this symposium today will accelerate it. That briefly gives you the scope and the relevance of the fire math modeling program.

I would like to make a few administrative announcements. Tomorrow morning we will have a tour of our facilities. We realize that some of you have already seen our facilities and probably will not be interested in joining the tour. For those who do not go on the tour, I have reserved two small conference rooms up on the fourth floor in which we can continue our discussions.

The Math Model Advisory Panel will meet in the tower room at Resorts International, Wednesday evening at 7:30-10:00 p.m. The minutes of this symposium will be summarized and there will be a proceedings published.

AIRCRAFT FIRE SCENARIOS

CONSTANTINE SARKOS

Program Manager, Cabin Fire Safety Program, Fire Safety Branch, FAA Technical Center; M.S. Mechanical Engineering, Rutgers. Gus worked for General Electric prior to joining the FAA in 1969.

AIRCRAFT FIRE SCENARIOS

Constantine (Gus) Sarkos
Fire Safety Branch
FAA Technical Center

Thank you very much, Wayne. Good morning. The aircraft safety record has been relatively good over the years, especially compared to other modes of transportation. There have been major fluctuations in the statistical data. For example, last year there was only one fatal accident which resulted in fourteen fatalities, and the record was excellent. Yet several years ago, over 500 died at the Canary Islands during the collision of two 747s, and many of these fatalities were due to fire. The potential exists for fire in a commercial transport due, of course, to the large quantities of jet fuel carried on board and also due to the cabin interior materials which are of interest to the workshop on fire modeling.

The cabin interior of a modern jet transport, in this case a wide-body, is obviously far different from that of a residential room which has been the type of enclosure that has been most often modeled in the past. Typically, the carpet is of wool pile construction. Seats are constructed of a treated urethane foam and wool nylon upholstery fabric. Polycarbonate is used on window dust screens and on passenger service units. The sidewall panels, ceiling and partitions are of composite panel type construction. The length/width ratio of an airplane cabin is on the order of 10 versus one to three for a residential enclosure. The materials found within the home are relatively untreated whereas those used in airplanes are very thermally resistant and are compliant with the FAA flammability regulation which is basically a Bunsen bu type of test. Moreover, the materials are tested by the airplar manufacturers for low smoke emissions and also for firewortht the basis of both small scale and large scale tests. Mar panels have flame spread indices of less than ten.

The multilayer panels constitute most of the surface area within the cabin interior, especially in the upper levels of the cabin. From a fire safety viewpoint, panels are clearly the most important materials system. They are also very complex in terms of geometry and composition. A typical multiple layer panel construction is shown in Figure 1. It has 10 components of various thermal properties within the same panel construction. A composite panel used on the three types of wide body jets typically consists of a polyvinyl fluoride decorative film finish, fiber glass facings impregnated with either epoxy or phenolic resin and a Nomex paper honeycomb core. The behavior of a composite panel under fire almost defies description, especially compared with the type of materials that have been most often studied in the modeling work by many fire researchers. For example, plexiglass is slow burning and well behaved compared to composite panels. In the older airplanes, vinyl on aluminum was used on sidewall panels and vinyl on cloth was used for the upper cabin areas.

There are three types of aircraft cabin fire scenarios, as shown in Figure 2. They are ramp fires (fire occurs usually when the airplane is unattended), in-flight fires, and postcrash fires.

A ramp fire is a smoldering, long duration type of fire which is more like a residential fire. This problem is not addressed in the FAA modeling work.

The in-flight fire is also not of immediate interest to the current FAA mathematical fire modeling program. For in-flight fire safety, we are more concerned with developing an early fire detection system, and [illegible]ffective extinguishing system to contain the fire.

A mathematical fire modeling program focuses on the post-[illegible]re, which accounts for all the fatalities attributable [illegible] carrier accidents.

[illegible]terior arrangement is designed for rapid evacuation. [illegible]atory requirement that complete evacuation be

TYPICAL MULTIPLE LAYER PANEL COMPONENTS

THE MATERIAL DATA BANK FOR DECORATIVE WALL PANELS IN AIRCRAFT INCLUDES BASELINE AND ALTERNATIVE MATERIALS FOR EACH OF THE PANEL COMPONENTS SHOWN

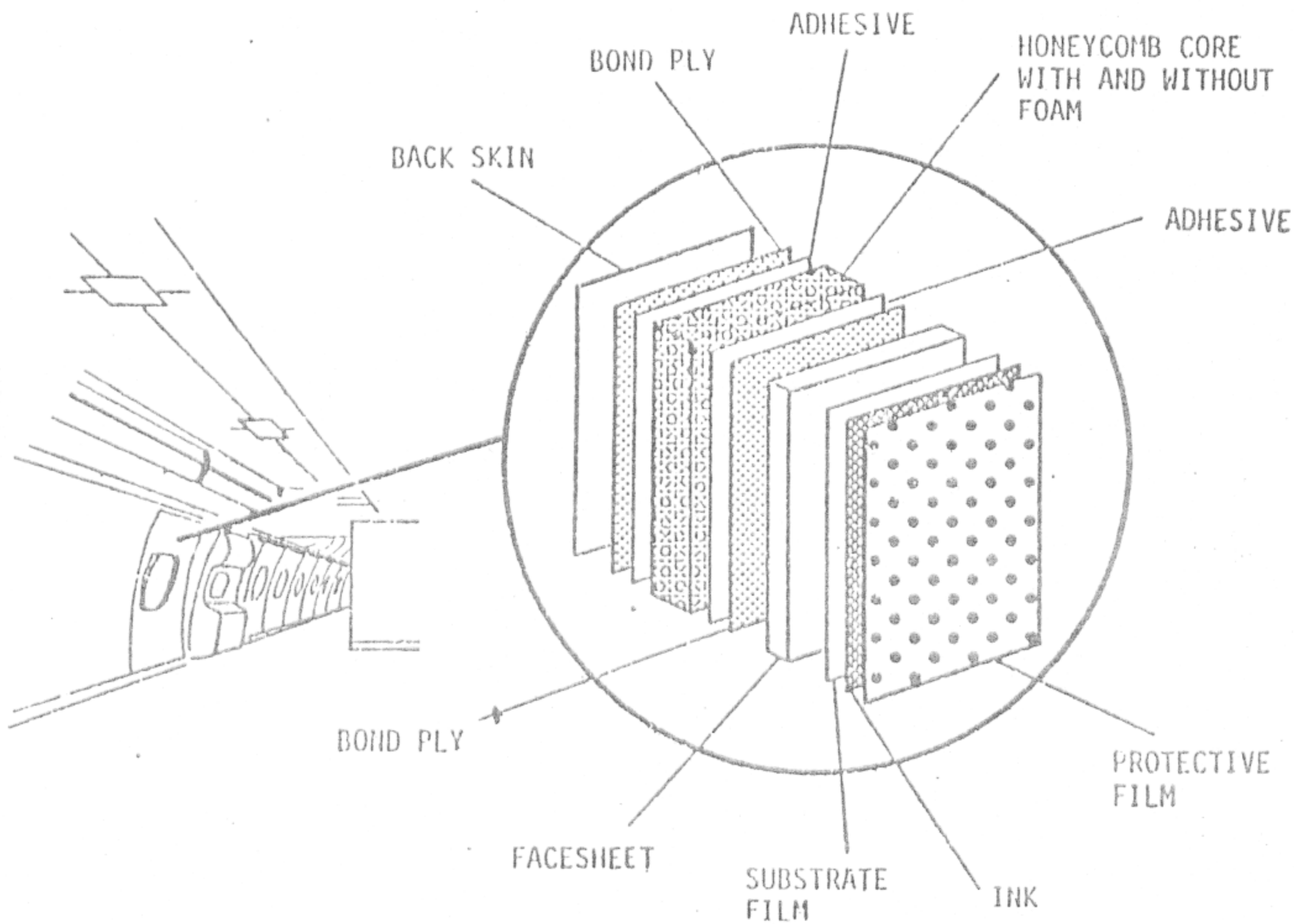


Figure 1

TYPES OF AIRCRAFT CABIN FIRES

- RAMP FIRES
- IN-FLIGHT FIRES
- POSTCRASH FIRES

Figure 2

accomplished within a time period of 90 seconds or less with half of the exit doors open. This is a requirement which must be demonstrated by the airframe manufacturers and airlines during a live evacuation drill. Here exists another major difference between the residential and aircraft fire modeling work. The time of interest in aircraft fires is 0 to 5 minutes while in a residential fire, it is in the neighborhood of an hour or even longer.

I would like to show a sequence of slides which are perhaps the most detailed ever taken of an aircraft accident. The accident occurred several years ago, following tire blow-out and landing gear collapse. There was penetration of the fuel tank and a major fire erupted. The fire was on the left-hand side of the airplane. The wind which was blowing right to left had a very important bearing on the development of the fire. In this instance, the R-2 slide (evacuation slide) caught fire while the R-1 slide was still being used. The R-1 slide failed later due to radiant heat. This started us on a program to improve the heat resistance of slides. Now the airframe manufacturers are devoting attention to improving the heat resistance of aircraft evacuation slide materials. In this case, the firefighters became aware of the accident even before the airplane came to a halt and were at the accident site within 100 seconds after the initial ignition. It is surprising how severe this fire was yet there were only two fatalities probably caused by disorientation of two elderly passengers. The aircraft fire was extinguished in an estimated time period of about three minutes. The fire was attacked from the right-hand side while the larger fire was actually on the left. The orientation of the airplane and the final landing resulted in an open space beneath the airplane. The fire on the other side can be seen through the opening. From examination of past accidents, we can come up with three major characteristics of a survivable postcrash fire. The first is a large external fuel fire. Practically all crash accidents with fire involve spillage of jet fuel although there are a few exceptions. If there is a major breakage of the fuselage or even a separation, the burning fuel rather than the involvement of interior materials becomes the predominant hazard. Consequently, in a realistic fire test, there should be an opening placed in the vicinity of the fire to allow flames and heat to penetrate and ignite the interior materials. In the experiments performed by the FAA, a typical door opening adjacent to a test fire is used.

The next question is how to treat this large fire adjacent to a long airplane fuselage. A lot of test work has been done on this subject area. One treatment to this problem is to study the fire penetration through one large opening and basically ignore any penetration through the remaining part of the fuselage. This treatment is valid for a short time interval in a wide-body jet which is constructed with highly fire resistant materials. The excellent fire resistance to burn-through penetration of the interior panel construction used in a wide-body jet was demonstrated in a fire accident. After three minutes or longer of exposure to a major fire, there was significant melting of the aluminum skin but no flame penetration to the interior.

Pool fires have been studied extensively over the years. The radiant heat flux is relatively invariant at about 14 Btu ft^2/sec for pool fires of three feet in diameter or greater.

The convective flux is much smaller at 1 to 3 Btu ft^2/sec, and is dependent on the size of the fire. A plot of the radiant flux by a fire plume is shown in Figure 3. Assuming the fire could be treated as a black body radiant sphere, the receiving heat flux at various distances are calculated. An inverse square relationship for the decrease in radiation versus distance is obtained. The practical deduction here is that in order to have any smoldering or flaming combustion on the cabin interior, the fire has to be adjacent to the fuselage. A fire adjacent to an opening will produce very intense radiant heat and ignite the cabin inside materials. The flame penetration through the opening depends on wind speed and direction and location of other openings.

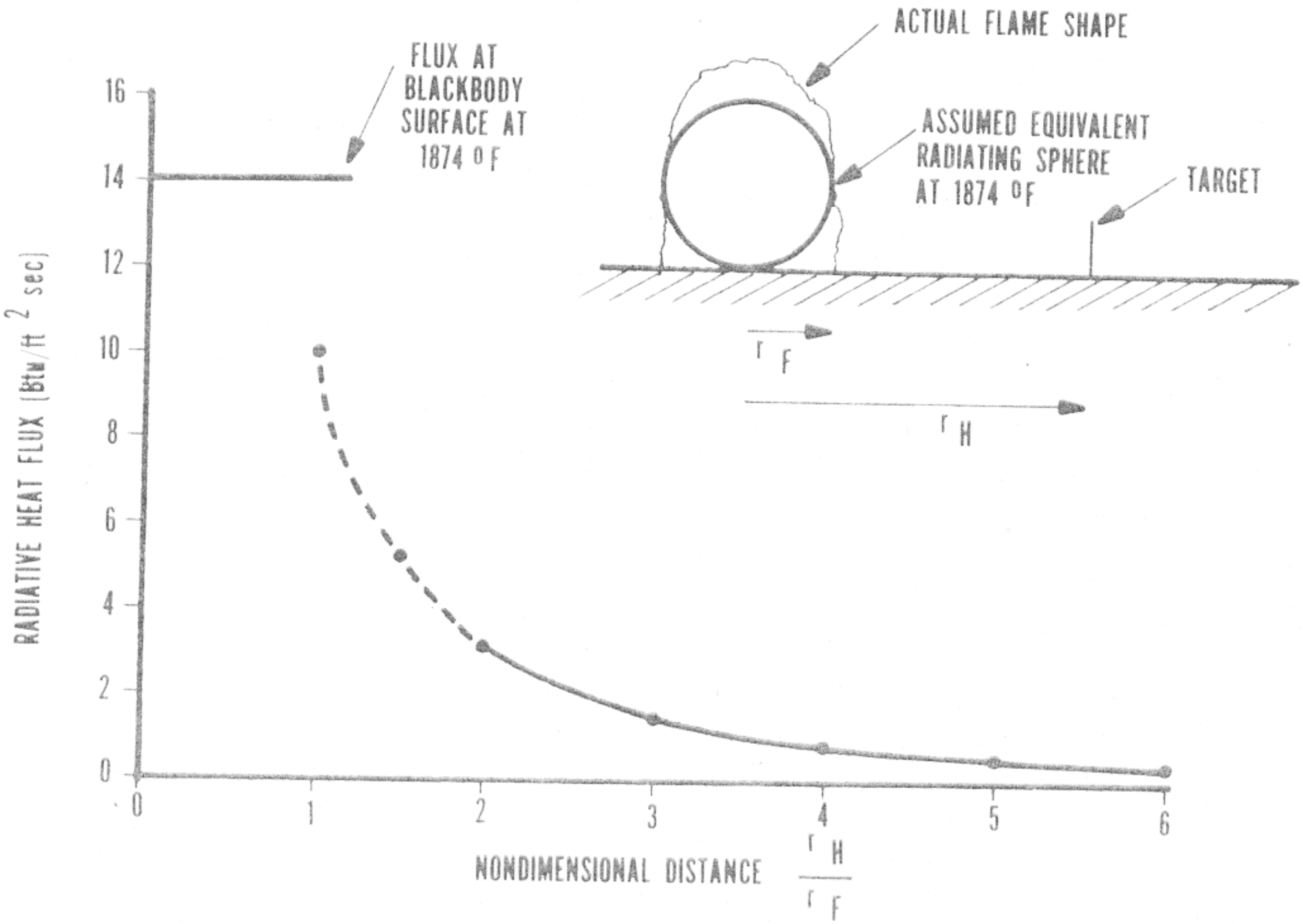


FIGURE 3. POOL FIRE HEAT FLUX VERSUS NONDIMENSIONAL DISTANCE

The FAA has studied the penetration of fire through fuselage openings using subscale models as well as surplus airplanes. A four-foot diameter fuselage model was made from an open-ended cylinder and an opening was placed on the side. A fuel pan was placed adjacent to the opening to simulate the postcrash fire scenario.

The FAA also studied fire penetration using a surplus DC-7 adjacent to a 20-foot square fuel fire. There was a fire penetrating through the opening. The amount of the penetration is dependent upon the wind velocity vector as well as the placement of openings away from the fire.

The ceiling temperatures inside the DC-7 fuselage versus time for a number of high wind cases are shown in Figure 4; fire was upstream of the fuselage. The worst condition (high temperature in a short time) occurred when the downwind door was open and the upstream door was closed. This apparently was due to the low pressure area created by the wind flow over the aircraft cylinder creating a draft which induced flame penetration into the cabin. Contrast this with a case where the upwind door was open and the downwind door was closed. A very moderate penetration of flame and resultant low build-up of heat inside the interior was measured.

Wind in the aircraft postcrash fire can be a detrimental factor to hazard development. Wind induced flame penetration will also increase radiant heat flux. This is illustrated in Figure 5. Radiant heat flux on the symmetry plane against time was measured for the calm wind and mild wind cases. A reasonable agreement on heat fluxes was achieved between the modeling and calm wind results with all doors closed. For a fluctuating wind, shown by the dashed curve, the radiant heat fluctuated above the calm wind pattern. As a result of flame penetration, the radiant and convective heat fluxes, smoke and gases inside the cabin increased as the fire penetrated further into the interior.

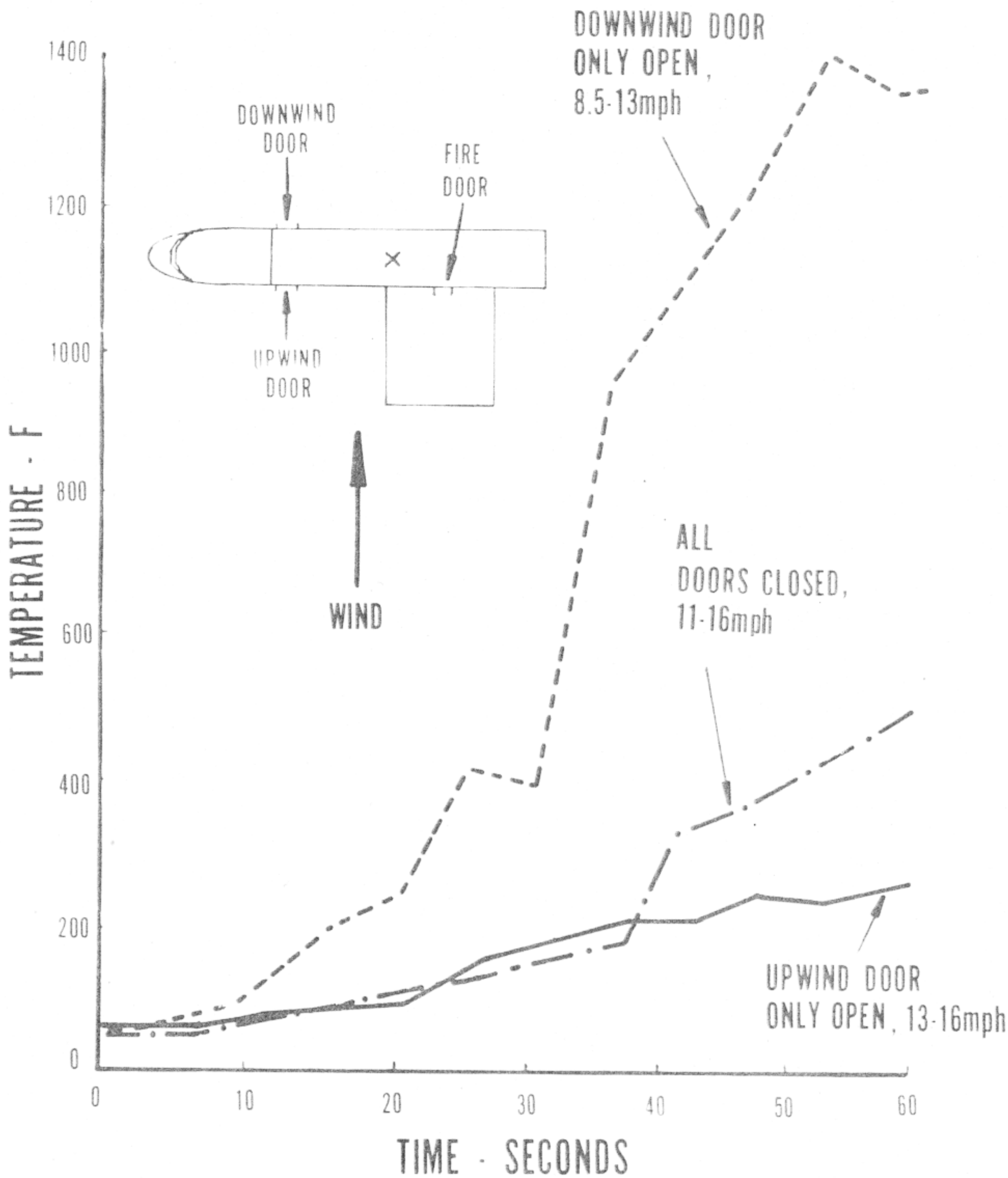


FIGURE 4. DC7 CEILING TEMPERATURE HISTORIES

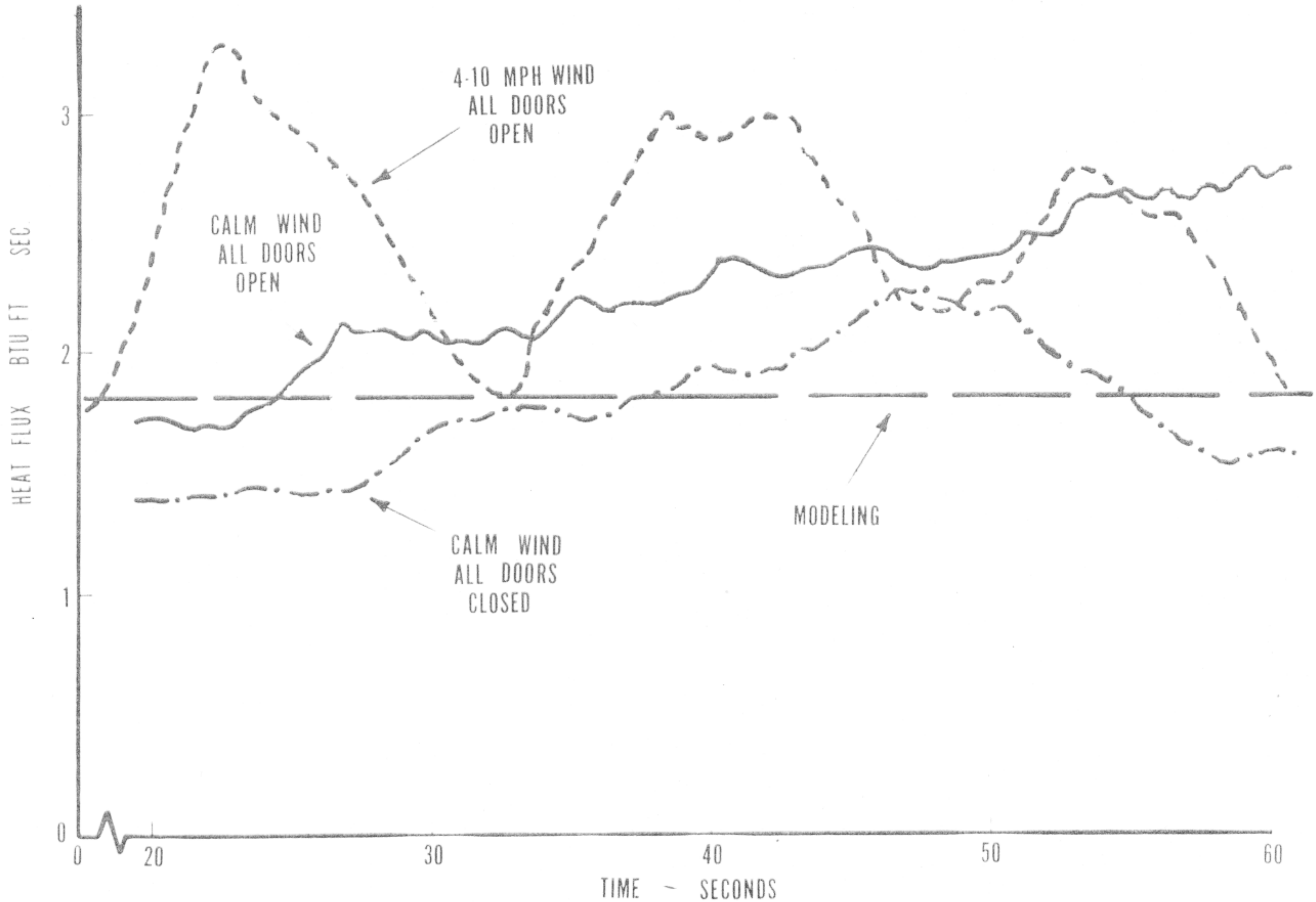


FIGURE 5. DC7 SYMMETRY PLANE HEAT FLUX

The bulk of the FAA full-scale test work is now conducted with a C-133 wide body test vehicle. An 8'x10' fuel pan which produces approximately 70 or 80 percent of the radiant heat from a very large pool fire is placed adjacent to a door opening. The initial tests in the C-133 were baseline tests to determine the hazards from the fuel fire alone. The cabin interior was bare. We found out that from an external fuel fire, heat and smoke were much more hazardous than carbon monoxide. We did not measure much carbon monoxide inside the airplane from a fuel fire.

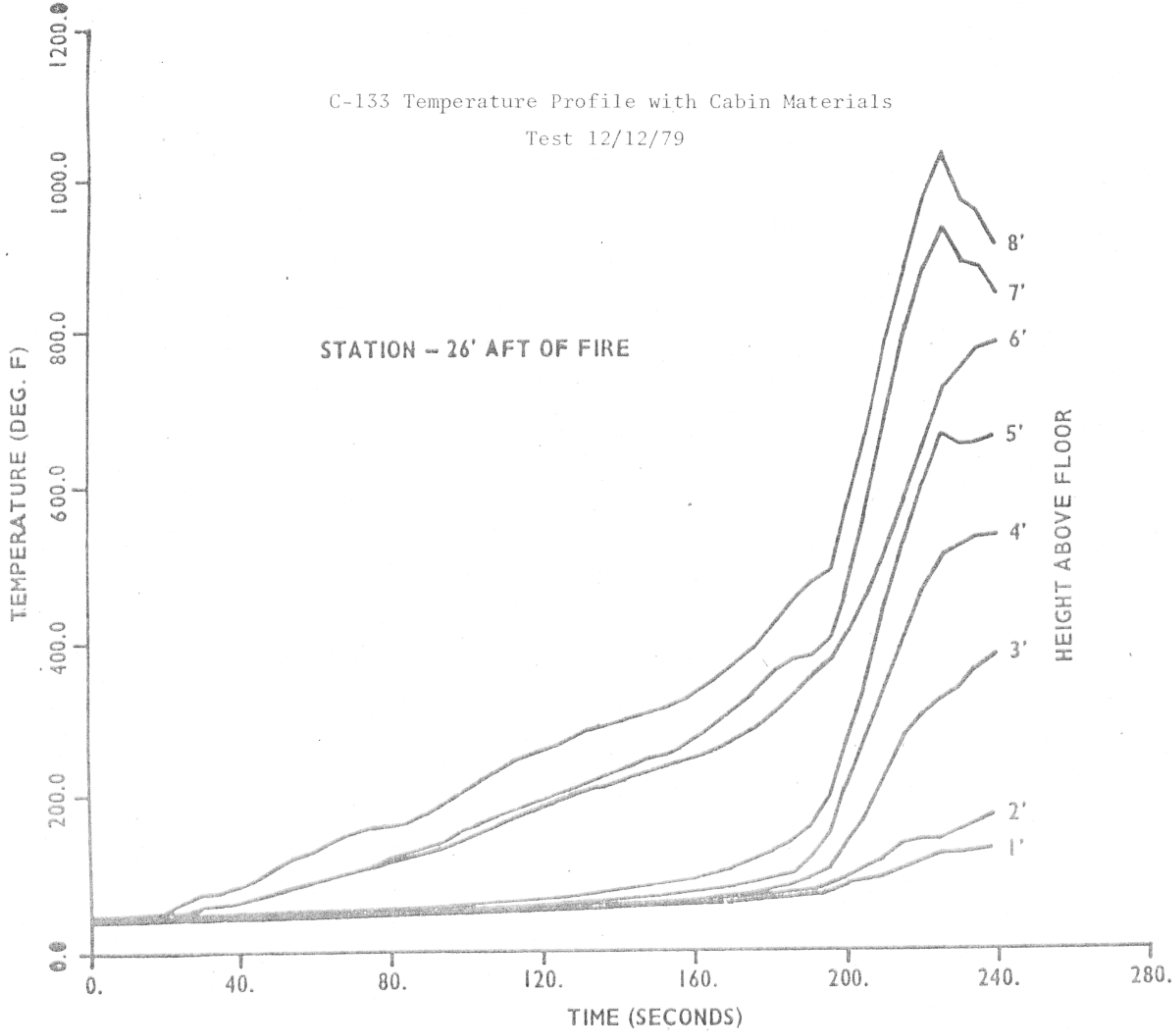
The impact of the external fuel fire on the cabin interior materials is of greatest concern to the FAA fire safety program. Seat materials are chosen as initial candidates for the study. We are studying seat fires resulting from ignition by a large pool fire penetrating through an opening. We are looking at improved cushion materials which will be a viable replacement for the currently treated urethane. However, about a year or more ago, we did run one test in the C-133 with a 20-foot section furnished and lined with seats and materials (used in a wide-body jet) that were provided by airframe manufacturers and various suppliers. Coincidentally, we are running a test similar to this today. It is our first test of this nature inside our new fire test facility. The seat cushions are protected by a fire blocking layer.

A test was set up to illustrate that a major fuel fire, external to the airplane, would ignite internal materials that in turn would affect the passengers survivability. Basically, information pertaining to the development of fire, the mechanisms of fire development inside the aircraft cabin, and the buildup of hazards were collected.

The results were quite obvious. There was extensive damage near the fire door. The fuel fire did ignite the interior materials. There was fire development which preceded very gradually in the beginning but then became much more intense. The estimated time for survivability in the cabin in this particular test was about three minutes. There would have been virtually no hazards from the fuel fire alone. The hazards were strictly due to the involvement of the interior materials.

During the fire test, the seat next to the door ignited very early and burned rapidly. However, there was very little ignition of other materials in the airplane at that time. One minute later the seats immediately forward and aft of the seat in the opening ignited. These were the only materials which were burning for most of the test. The heat produced by the seat was rising and hot gas was building up at the ceiling. This caused the ceiling panels to pyrolyze and distort. When these distorted ceiling panels collapsed onto the remaining seats away from the door, a very rapid growth in the fire was observed. In Figure 6, temperature measurements versus time at 26 feet aft of the fire on the symmetry plane for a series of thermocouples one-foot apart from the floor to the ceiling were plotted.

It is very interesting and perhaps reassuring that there is a very pronounced two-zone environment based on temperature measurement. A hot zone up at the ceiling is two to three feet thick. The hot gases are recorded by the thermocouples at 8, 7 and 6 feet. Temperatures recorded by the remaining thermocouples in the lower portion of the cabin during the first three minutes deviated very little from the ambient temperature. When the fire developed rapidly due to the collapse of the panels which caused burning of the remaining seats, the two temperature zones were no longer apparent. However, there was still a large difference in temperatures between the floor and the ceiling. The temperature at one-foot and two-foot levels were less than 200 degrees, whereas the temperature at the ceiling approached 1000 degrees. This difference in temperature was reflected by the damage of the interior materials. The materials in the upper cabin were virtually destroyed, whereas those near the floor, especially the carpet, were practically undamaged. The carpet, except near the fire door opening, showed very little damage.



C-133 Temperature Profile with Cabin Materials
Test 12/12/79
STATION – 26' AFT OF FIRE
TEMPERATURE (DEG. F)
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
TIME (SECONDS)
0.
40.
80.
120.
160.
200.
240.
280.
HEIGHT ABOVE FLOOR
8'
7'
6'
5'
4'
3'
2'
1'

Figure 6

Figure 7 shows the hazard development. Instruments were installed inside the airplane for measuring various hazardous components, such as smoke, CO, HCN, temperature and O_2 depletion. Smoke increased early into the test; the oxygen depletion was small because it was a ventilated cabin. The predominant hazards were CO and high temperature. At three minutes, the CO level was at 3000 parts per million, HCN level was relatively low at 10 parts per million, and the gas temperature was about 250°F and rising.

This concludes my presentation. I hope I have been able to convey to you the major characteristics of a postcrash aircraft cabin fire and some of the contrasting features with residential fires which you are most familiar with.

QUESTION:

Len Cooper, National Bureau of Standards. You have very much downplayed the pool fire aspect of a hazard and I wonder if you could clarify that a little bit. During all this time, you saw the pool fire going. Earlier you showed that pool fire was a very great hazard in and of itself. Why is it downplayed in this scenario and what would the pool fire have done?

GUS SARKOS:

The ultimate goal of our program is improved test methods for cabin materials. Therefore, we are just trying to develop a realistic fire scenario which uses a pool fire but allows the interior materials to be the predominant factor. We are forcing the interior materials to be the predominate factor in hazard development because that is what we are interested in. We do not want to mask the results of the hazards developed by the interior materials by the fuel fire hazards.

QUESTION:

Len Cooper, National Bureau of Standards. Why do you believe this to be such a significant scenario?

GUS SARKOS:

We are focusing the scenario to come out that way because we are interested in the materials. The accident record provides very meager statistics to derive patterns in aircraft accidents. It is very difficult to come up with a typical fire scenario. You probably could not define a typical fire. We derived this particular scenario

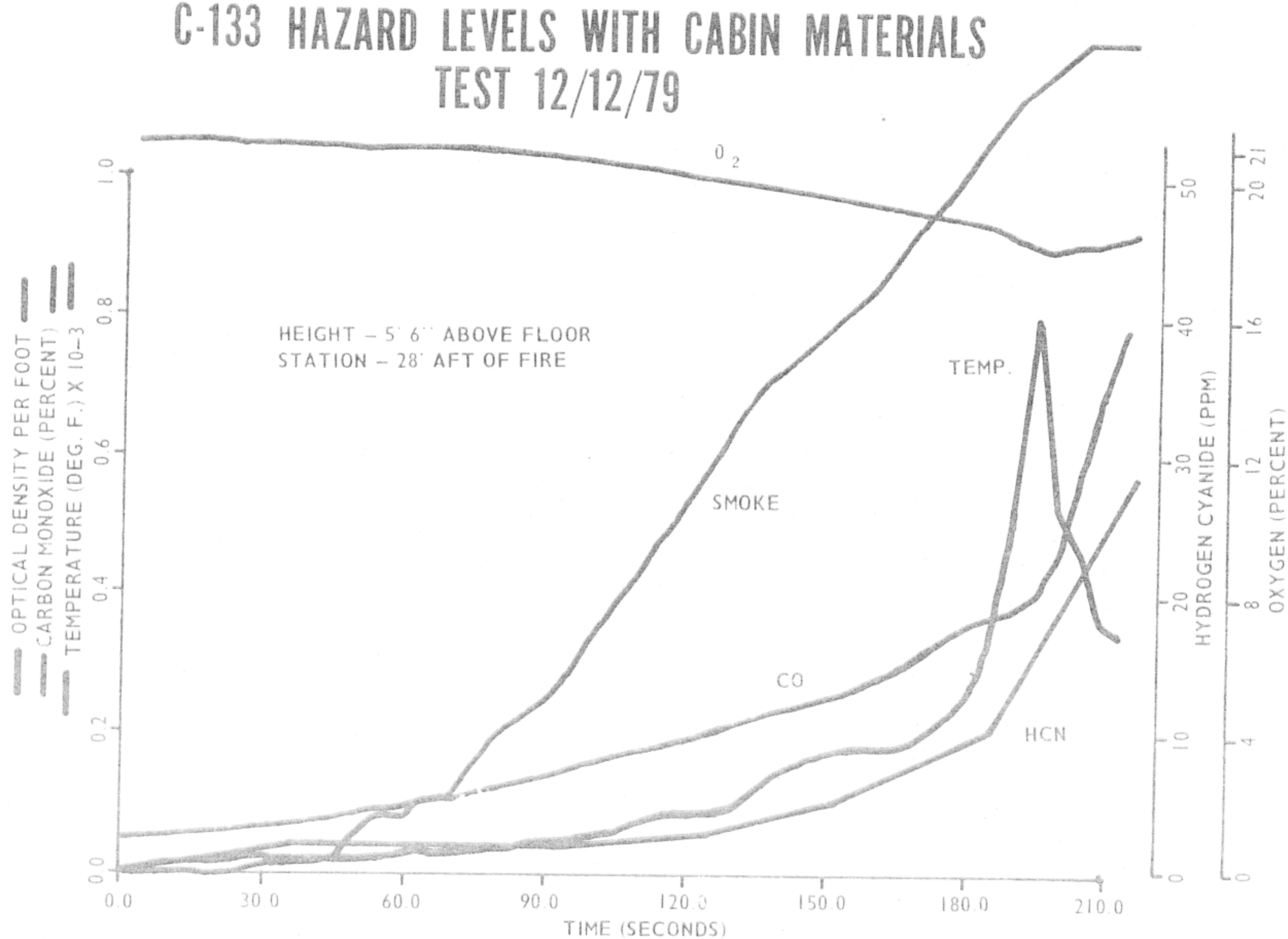


FIGURE 7. C-133 HAZARD LEVELS WITH CABIN MATERIALS TEST 12/12/79

which corroborated to a great degree the actual postcrash accident that I have just talked about. There was an intact fuselage with door openings adjacent to the fire. I am not sure I have answered your questions. Perhaps we can get together later on.

QUESTION:

Charles Troha, Consultant. I think it is a scenario which happens in a real aircraft fire. The question is what effect does the material have on the total involvement? In other words, you developed the scenario for a pool fire and were you able to subtract any of that affect to show the real affect of the material?

GUS SARKOS:

If I didn't mention it, I meant to say that under that particular test condition, there would have been virtually zero, if any, hazard at all from the fuel fire. When you have a zero wind case, with a large fuel fire next to the opening, you get very little accumulation of hazards from the fuel fire. It is hazardous only when you have flame penetration. That particular test was a zero wind test. The fuel fire hazards were minimal. The only hazard through that door opening was significant radiant heat. A flame licking in randomly would ignite the seat as it was being cooked, but there were virtually no hazards from the fuel fire in that particular test. We designed it that way. We did not want to mask the fuel fire hazards from those of the interior materials.

FAA MODELING EFFORTS

THOR EKLUND

Fire Safety Branch, FAA Technical Center.
B.S. AeroEngineering, Princeton University;
M.S. and Ph.D. in Fluid-Dynamics from Brown
University. Thor worked for Esso Corporation, Naval Air Propulsion Test Center in
Philadelphia, and Arthur D. Little Company
prior to joining the FAA in 1975.

FAA MODELING EFFORTS

Thor Eklund
Fire Safety Branch
FAA Technical Center

First of all, I hope the weather turns out mild. For many of you it will be a long week here. Bob Levine and Oliver Foo felt that this would be a good way to combine a number of different efforts and would give people an opportunity to see this area and cover a number of topics. There will be ad hoc fire mathematical modeling meetings. We are also committed to have a workshop on the DACFIR model developed by Charles MacArthur under FAA contracts. Because our efforts in this area blossomed over the last year, we wanted very much to bring in the people who will be working under FAA sponsorship. It will give them an opportunity to learn the previous work, to know what a postcrash aircraft fire scenario is, and to distinguish an aircraft fire from a home or dwelling or even a corridor fire.

In 1973 the UDRI contract was started. This was the FAA pioneer effort in this fire modeling area. Over the years, the University of Dayton Research Institute (UDRI) people worked closely with Boeing, NASA-Houston, and us here at the FAA Technical Center. Until the fall of 1979, this was under sponsorship of the Systems Research and Development Services (SRDS) in FAA Headquarters in Washington. The project was moved under our sponsorship in 1979. We felt that the SRDS had been running a very good project and we wanted to continue their philosophy. It was really at the suggestion of Chuck Troha that we started an interagency agreement with the National Bureau of Standards (NBS) to further go into the field modeling as well as zone modeling. We also suggested redirecting the Dayton work more to a postcrash fire scenario, and Dick Kirsch requested our involvement in material burning at Jet Propulsion Laboratory (JPL) under Dr. Kumar Ramohalli. FAA math modeling is a continuous program going back to 1974. Our philosophy on modeling is very much the same. It just happens that as we learn more, we do things somewhat differently.

There are five tasks that concern us this year. First of all, we are interested in detailed input into a zone model like DACFIR. A zone model is like a bathtub upside down filling up. The aircraft cabin is like a long pipe and the hot layer spreads along the ceiling. There are considerable heat losses and changes as the hot layer from a fire moves along the cabin. We are interested in further development of smoke layer motion at the ceiling, and the gas dynamics in detail.

The second point we are very much interested in is thermal impact at openings. This has been fairly well described in what you saw earlier. The major threat from the external pool fire to an intact fuselage is through an opening. The equivalent surface temperature of fire is of the order of 1800 or 1900 degrees F and the radiative heat flux to any materials inside is spectacular. We want ultimately to get more understanding on what possibilities we would have of hardening the doorway. We also want to know at what rate the material fire is developed in that area from such huge heat fluxes.

The third point we are very much interested in, based on experimental work here at the Technical Center over the last three years, is the effect of wind on fire plume. Given an external pool fire, the wind and door opening configuration is the predominant factor regardless of the material involved. We have asked NBS to look into the pressure distribution around the fuselage next to a pool fire. If the wind is blowing over a fuselage with one door behind the fire and the other door facing the wind, the wind will drive through the aircraft and blow everything back out into the fire. We would like to get some quantitative analyses on this phenomenon. Clearly, when a fire burns at a door, the stagnation point there will be lost. We don't have any idea of the magnitude or why this is, but this controls the ventilation within the aircraft during the fire. We feel that this is a very important point.

Item number four that we are working closely with NBS on is correlation. We do a lot of small-scale testing and we do a lot of large-scale testing. Like everybody else, we have problems with correlating small-scale tests to large-scale tests. This is on our mind very much right now.

The fifth item that we are looking at and are very interested in is actually the mechanisms of burning and flame spreading over aircraft type materials. We are working through NASA and with NBS on this topic. It is hard enough to study the flame spread and burning mechanism with a simple and uniform material like plexiglass. The aircraft materials have fire retardants and are often laminated one way or another. The existing data and test methods are insufficient for aircraft materials. It is mandatory that we get some answers soon in this area.

Those are the five areas that we are interested in at this time in math modeling. I would like to reinforce some things that Gus Sarkos presented to you. We are spending something on the order of 15 to 20 percent of our cabin fire safety budget on math modeling because it is important. We have a lot of other high priority obligations. An aircraft cabin has the shape of a long tube and is packed with plastic materials (side walls, ceiling, carpet, and seats). Furthermore, it is densely populated with people. A huge heat source is an external pool fire. I will give you an example of how severe this pool fire can be. When we did small-scale tests, we ignited a pan with around five gallons of fuel. I could not get close to that pan. A 747 taking off with its total fuel has close to 50,000 gallons. I can't in my mind imagine what kind of fire you could make with that amount of fuel. That is something we want to hammer in. It is a very serious heat source. We do know wind and door openings are important but we are not too comfortable with our understanding of the relationships to fire.

There are two different aircraft fires. The in-flight fire problem is to put it out before it gets severe. But if it gets severe, nobody can get out. The postcrash fire is a very rapid developing fire and everybody has to get out very quickly.

I would also like to say a few things about the aircraft materials burning phenomena. The composite panels do not burn so well. They may cook out and disintegrate and fall. Other than the panel outer layer, the rest of the panel components do not burn heavily. The carpet, as long as the fire is not coming from underneath the aircraft or from the cargo area, is generally pretty flame resistant. The urethane seats with various coverings right now seem to be the big factor in a fire. The materials which are placed in different orientations suffer from different exposure conditions. Their behaviors are quite different even under the same overall test conditions.

There are two final remarks about the aircraft configuration. The cabin is a longitudinal one. Great buoyancy forces are difficult to be generated, as compared to that from an enclosure fire. Also, it is pressurized for the in-flight fire. These can have effects on an analysis.

I would like to say a few words now about what we are ultimately looking for. Like everybody else, we would like to have perfect math models which would predict everything. We really don't believe that will be the case. Right now we are interested in separately looking at gas dynamic development and material burning phenomena. In the future, we would like those to be bridged. That is, once you know what is happening within the fuselage, you can start saying what you know about materials behaviors under various exposures. That is a little further downstream.

We are interested now in whatever test models are available and use them in our test programs. We want to know that we are making the right measurements in the right places. The FAA wants to develop new standards, which have to be very defensible. Our C-133 test represents only one scenario. One way or another the validity of that scenario has to be demonstrated either by mathematical solutions/small-scale tests or by logical arguments. We need mathematical modeling to give us a better handle on the type of situations that can occur and possibly what we can do about them.

We are interested in mechanical type countermeasures. For instance, in the case of the wind caused pressure distribution, we could have ventilation countermeasures. In the case of better elucidation of fire in the doorway, we might be able to give a rational basis for fire hardening procedures. If we can get a better handle on the mechanisms of burning, we might be able to design better material. There is one effort we are involved in now that might lead to such a solution.

In summary, we need the modeling to expand our scenarios, to find the key test parameters that we should be looking at, and to correlate small- and full-scale tests. I would like to say aircraft materials are very good now. It is the magnitude of the postcrash fuel fire and also the lack of egress capability in an in-flight situation that makes the aircraft fire still a terrifying situation to think about. Any kind of elucidation we can get theoretically or experimentally I hope we can put to good use.

DACFIR MODEL WORKSHOP

CHARLES MacARTHUR

Research Physicist, University of Dayton Research Institute; M.S. Physics, Ohio State University, 1969; M.S. Engineering, University of Dayton, 1973; Currently working on Ph.D. dissertation. Joined University of Dayton Research Institute in 1970.

DACFIR MODEL WORKSHOP

Charles MacArthur
University of Dayton Research Institute
Dayton, Ohio

The DACFIR Model, Dayton Aircraft Fire Model, is in its third version. Even though this program has been going on for some time, this third and final version was just developed within the last three months. It still has some testing and perhaps debugging to be done, but the results to date are very encouraging. The handout packages contain equations, assumptions, results, etc., all pertaining to this third version.

The computer program at this point is in good condition and can be distributed for those who wish to get a copy of it. I believe that FAA will make these available in a very short time. The report on this third version of the program and the computer listing, in a tabular form, will be available within a month or a month and one-half after the FAA review is completed.

At the very start of this program, the specifications for a computer model on aircraft cabin fires were laid out in the statement of work. The objective of the model (Figure 1) was to assess the smoke and toxic gas accumulation in the cabin resulting from an exterior fire. As you have heard earlier, the situation has changed. The FAA is more interested in the exterior fire and its effect on the interior materials. When we started the program, the emissions scenario was an interior ignition which might be a ruptured fuel line through the floor or a spilled flammable liquid in the interior, and the effect of the interior material on survivability. We did not formulate the problems by starting with the first principles of thermodynamics. It was not possible then and still may not be possible now. We were looking for a practical first-cut engineering solution to predicting the survivability of the cabin. The emphasis was on the practical method and the method that could be used for safety decision making.

OBJECTIVE OF THE CABIN FIRE MODEL

- Develop an Analytic/Numerical Technique to Assess the Smoke and Toxic Gas Accumulation within an Aircraft Cabin Resulting from an Interior Fire

  - Method Should be Practical in Terms of Computer Time and Storage Requirements and Amount of Input
  - Method Should Produce Results Directly Applicable to Safety Decision Making

- Starting Information (Input Data) is Obtained from Laboratory Scale Flammability and Toxicity Test Data on Cabin Interior Materials

Figure 1

DAYTON AIRCRAFT CABIN FIRE MODEL

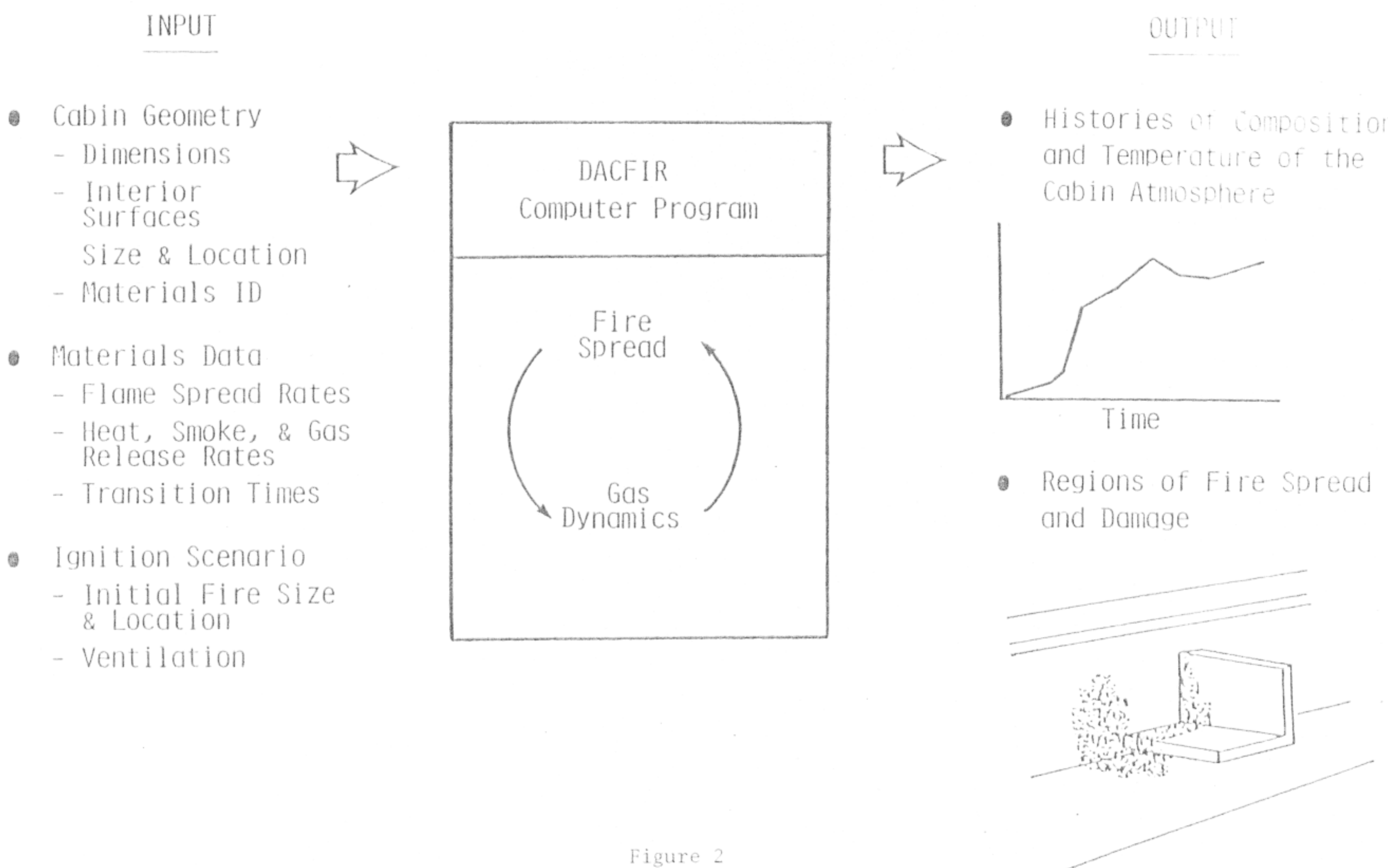
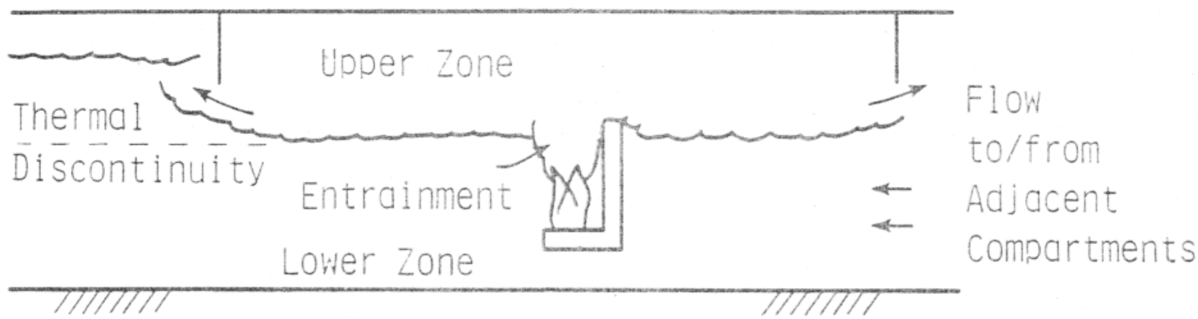
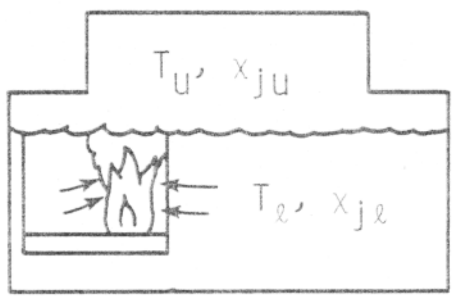


Figure 2





Zone Model of the Compartment Atmosphere

Figure 3

code and run time. Also, in most of the situations when the interior materials are involved, the flame will not spread over the materials beyond two or three seat row sections from the origin of the fire before the interior of the cabin is really not inhabitable at all. We are not trying to predict the development of the fire up to flash-over or a fully developed compartment fire, but only that first three, five or maybe ten minutes during which people may still be able to escape and conditions haven't become intolerable yet. It is the objective of the model to predict the time at which the cabin becomes unsurvivable.

Figure 4 shows a very crude, but effective, presentation of the cabin interior. The seats consist of horizontal and vertical planes in L-shape. The surface of these planes is divided into square regions which are named fuel elements. The method of computing fire spread in the program is through a method of tracking these elements from the undisturbed state into a flaming state or a smoldering state then into a burned out state, etc. It is a discrete step-by-step description of fire behavior from the materials. It is an oversimplification, but a good first cut, in handling the very complex geometry of a cabin interior with furnishings.

The cabin interior surfaces were divided into square regions. The dimension of these squares was one-half foot, mainly because it was a convenient length scale for the interior of the cabin and also it did not really create an excessive amount of computer storage. The program could be refined to have smaller element sizes to predict areas more precisely, but one-half foot is a good practical compromise right now.

Figure 5 shows how the development of the fire is tracked in the computer model by adding the shaded squares which are regarded as being on fire and being a source of heat and smoke and gas emissions. These elements (burning or burned out) are determined by the particular material data supplied to the program inputs. These geometric regions

DACFIR REPRESENTATION OF CABIN INTERIOR

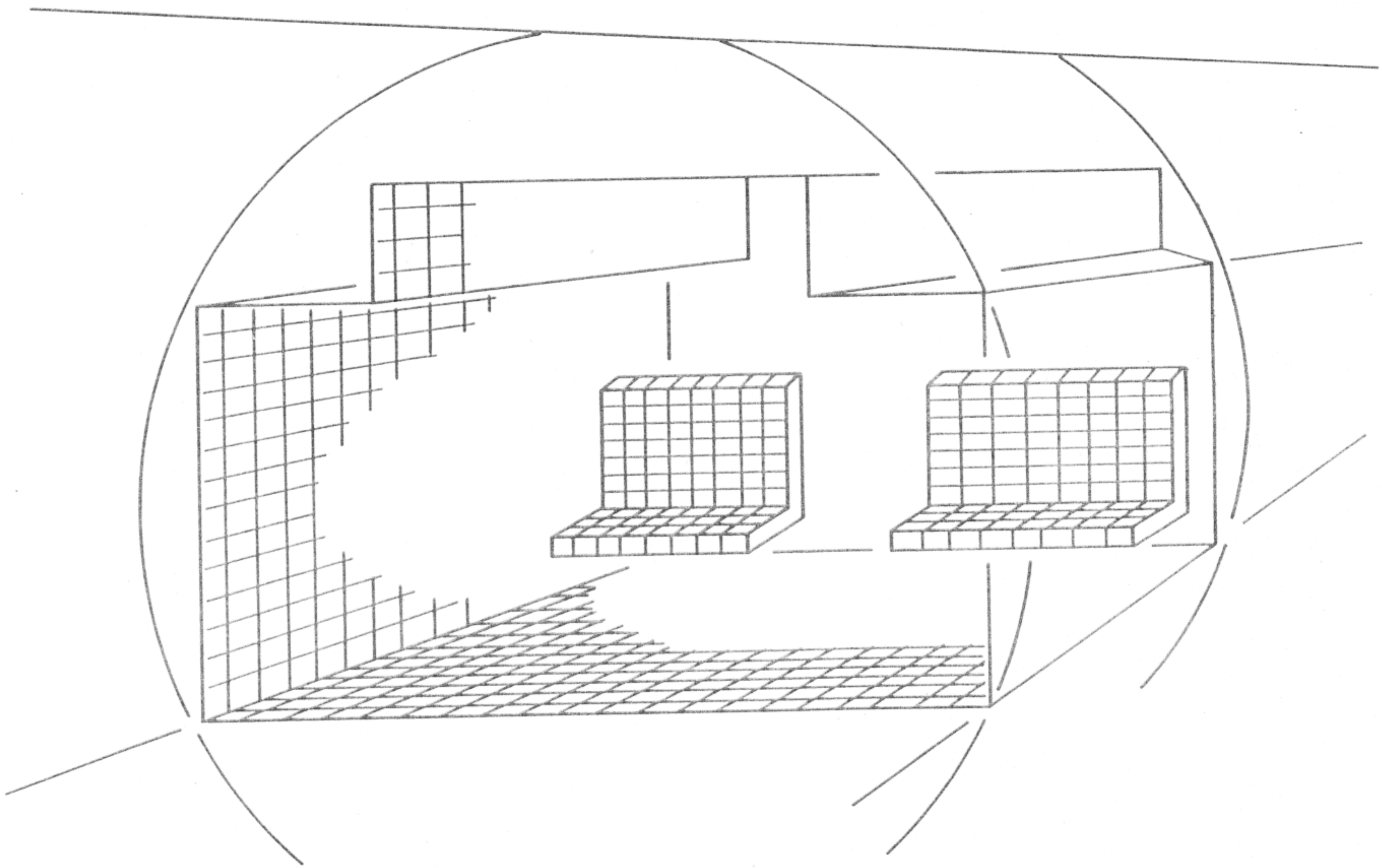


Figure 4

TRACKING THE FIRE SPREAD

Groups of Flaming Elements form Fire Bases

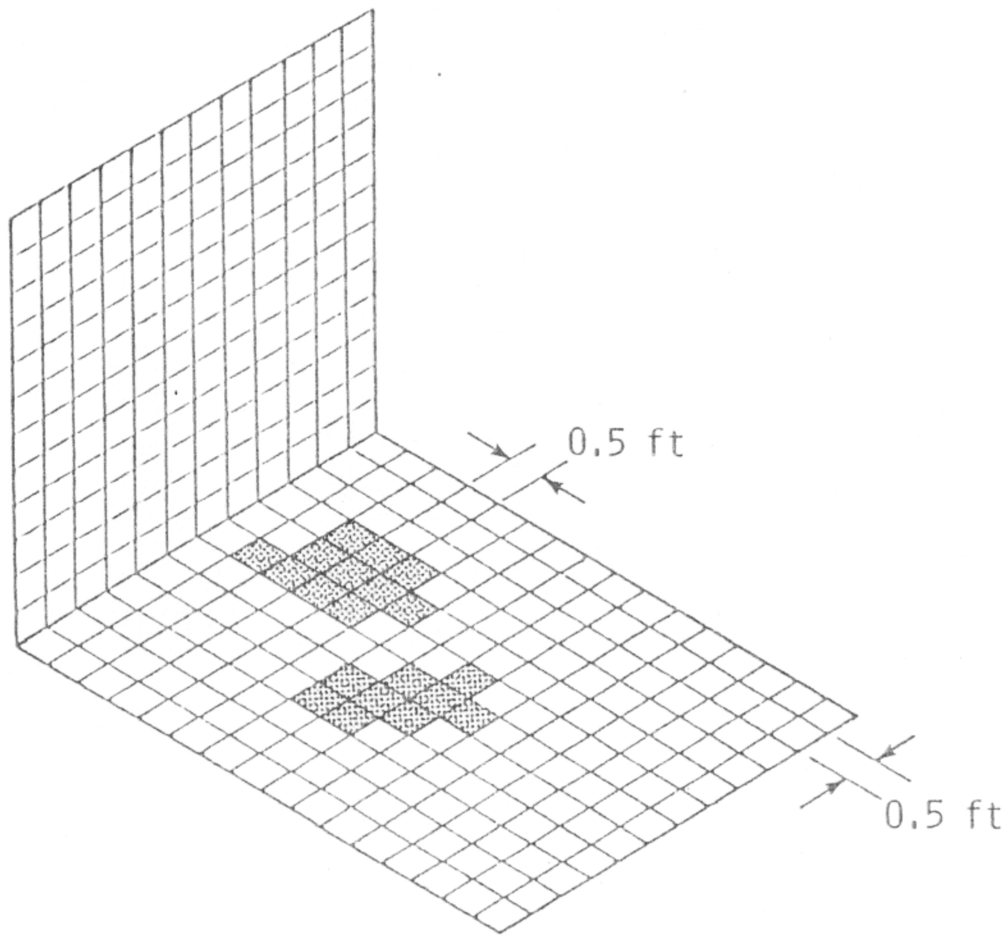


Figure 5

then are the sources of combustion that is fed into a subprogram cabin atmosphere to determine smoke development and gas compositions.

DACFIR Version 3 has a major refinement and improvement over the earlier versions. As shown in Figure 6, the model is designed to simulate fire in a cabin which has one to four compartments. Earlier versions just considered the cabin as one long room. In DACFIR-3, one room can be divided into four rooms attached linearly along the cabin and each of these compartments may have one to six vents or doors or escape hatches or openings to the exterior or through the dividers to one another. DACFIR-3 has retained the capability in DACFIR-2 of handling prescribed flows at doors. This was used to compare the model to test data in which one or more of the doors had a forced flow from the floor. The user is allowed to specify the temperature and composition of this inflow gas (at least one vent). This is a first step in being able to have the model simulate the effect of the exterior fire.

The computer program in DACFIR-3 is considerably different from the earlier versions (Figure 7). The earlier versions used a very primitive method of integrating the equations of the model cabin atmosphere. A very good technique which was used in the Harvard Computer Fire Code-3 is implicit (trapezoidal rule) integration of the atmosphere equation using the Newton-Raphson technique. I am really surprised at the stability and reasonable economy of this technique over the other integration methods. DACFIR-3 adopted a modular construction, at least in the cabin atmosphere part of the program. The model was designed along the lines of the Harvard code and other codes developed in the fire mathematical modeling workshop group. The subroutines that contain the modules can be independently removed and replaced if necessary. DACFIR-3 is a computer program that is easy to maintain, and will be easy to upgrade when future improvements in zone modeling are available.

An overall flow chart of the computer code is shown in Figure 8. Essentially, there are two parts, i.e., the flame spread part and the

DACFIR VERSION 3

- Cabin may be divided into one to four compartments by partitions (class dividers)
- One to six vents (doors, emergency exits) may connect each compartment with others or the exterior
  - Flow rates, directions, and gas properties may be specified at each vent, or they may be computed as part of the cabin atmosphere model
  - As a special case, flow of fire gases in through a vent can be specified

Figure 6

DACFIR VERSION 3 COMPUTER PROGRAM

- Implicit (trapezoidal rule) integration of cabin atmosphere governing equations using the Newton-Raphson method provides stability with reasonable economy

- Modular construction and internal documentation makes the code easy to understand, maintain, and upgrade

Figure 7

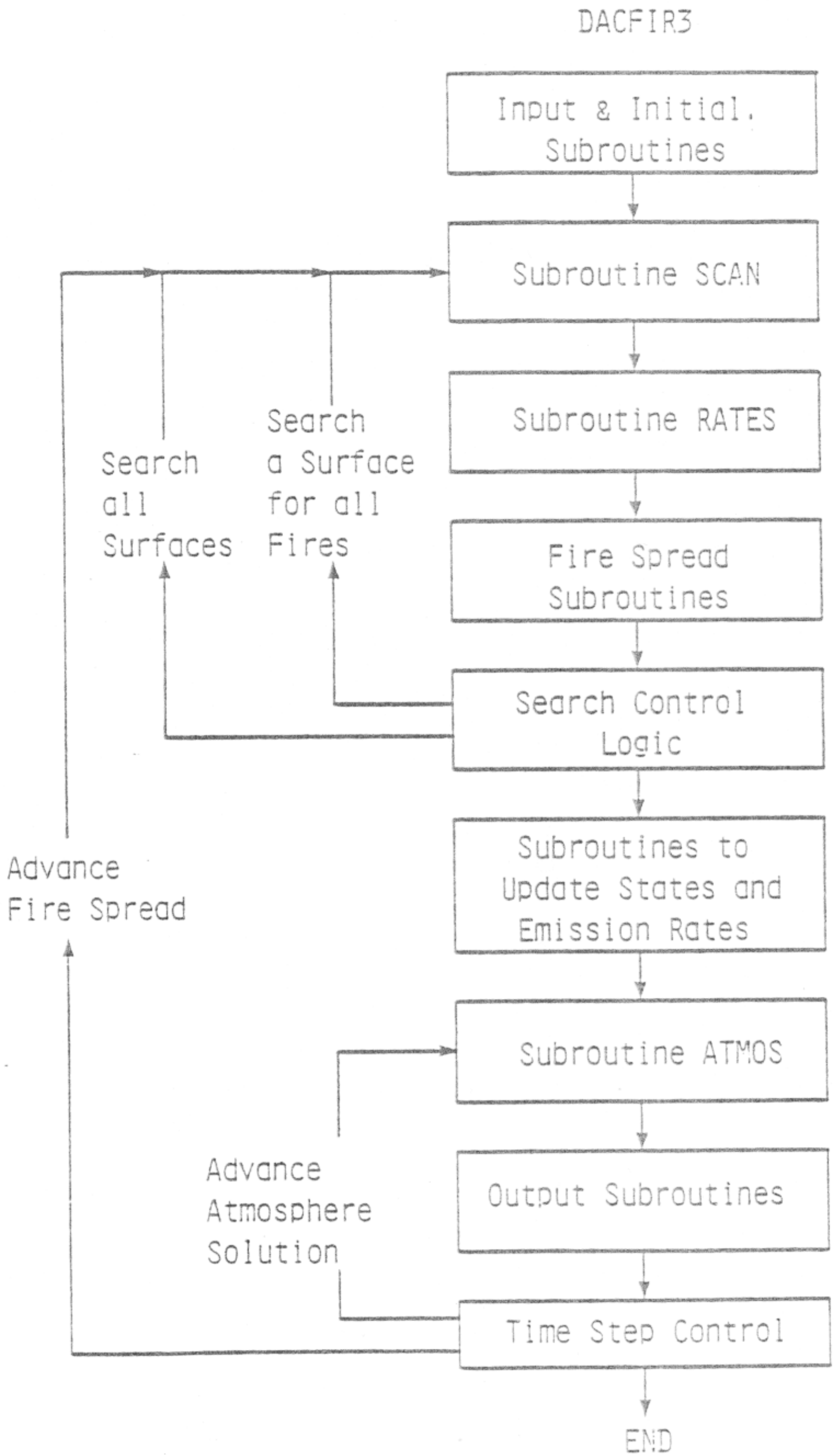

DACFIR3
Input & Initial. Subroutines
Subroutine SCAN
Subroutine RATES
Fire Spread Subroutines
Search Control Logic
Subroutines to Update States and Emission Rates
Subroutine ATMOS
Output Subroutines
Time Step Control
END
Search all Surfaces
Search a Surface for all Fires
Advance Fire Spread
Advance Atmosphere Solution

Figure 8

gas dynamics part. Subroutine "ATMOS" is the controlling part of the computer program for the cabin atmosphere model. The differential equations of fire physics were integrated at a relatively small time step. A cumulative structure for the program was used. The integration of fire physics equations can be advanced independently relative to the flame spread subroutines. The flame spread subroutines scan all elements and determine which elements are ignited and which elements are burned out, etc.

DACFIR-3 uses a zone model approach which is patterned after the model developed by Prof. Emmons and Dr. Mitler of Harvard and Dr. Quintiere's model at NBS. DACFIR-3 uses a two-zone concept to model fire enclosure. It deals with multiple compartments. Figure 9 shows two compartments in a cabin. Each compartment has an upper and a lower zone. The computer program will allow fires to exist within the lower zone or the upper zone. It is convenient that the upper zone was brought down through the plume to the fire base. Dr. Quintiere documented this idea. From a conceptual standpoint, it minimizes the problem about the interface between the plume and the zone. The variables for these gas zones are temperatures, density, and the compositions. Shown in Figure 9 is a particular case where a flow exists, not only between compartments on the right but also on the left through an open door to the exterior. A flow out of the door and return flow into the lower zone are also seen in the picture.

Figure 10 is a list of the variables of the atmospheric model. In particular, a pressure for the entire compartment is calculated and used as a single reference pressure. Conservation equations are shown in Figure 11.

Another new feature of the DACFIR model is the very simple global one-step model of combustion chemistry which is shown in Figure 12. One of the problems in testing is an understanding of what the mass fraction of water vapor might be in the gas. In certain situations, Gas Zone Control Volumes and Mass Flows

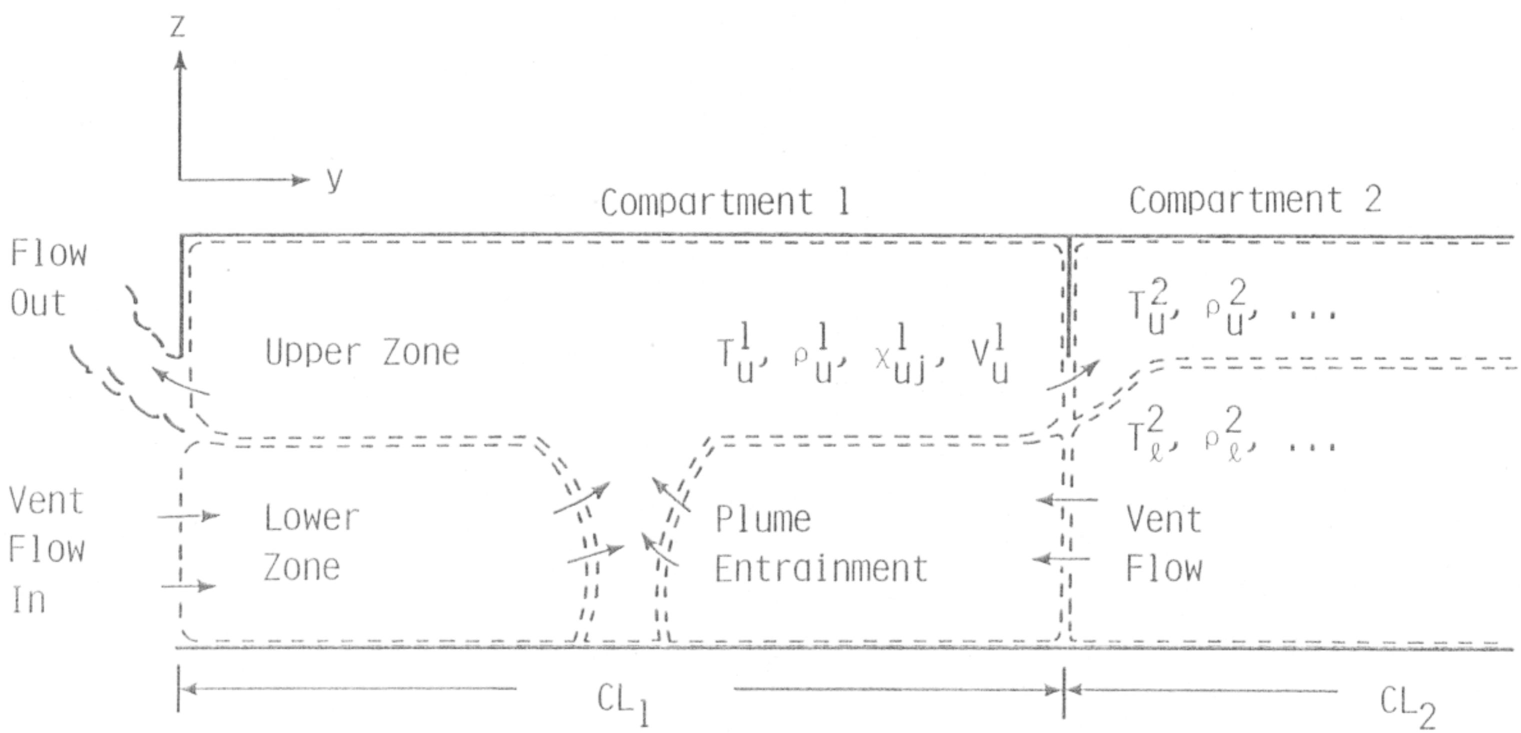


Figure 9

VARIABLES OF THE CABIN ATMOSPHERE MODEL

Variable	Symbol
Lower zone species mass fractions (j values)*	$x_{\ell j}^{i}$
Upper zone species mass fractions (j values)	x_{uj}^{i}
Pressure	p_{f}^{i}
Lower zone density	ρ_{ℓ}^{i}
Upper zone density	ρ_{u}^{i}
Lower zone temperature	T_{ℓ}^{i}
Upper zone temperature	T_{u}^{i}
Lower zone volume	V_{ℓ}^{i}
Upper zone volume	V_{u}^{i}
Thermal discontinuity position	z_{d}^{i}
Materials surface temperature**	T_{sk}^{i}

* Minimum value of j is 5 and the maximum 11

** Minimum value of k is 1 and the maximum 20 per compartment

Figure 10

CONSERVATION EQUATIONS

Conservation of Mass

$$\frac{d}{dt} M_u^i = \sum_{vents} G_{vu}^i + \sum_{plumes} G_p^i + \sum_{fires} G_f^i$$

$$\frac{d}{dt} M_\ell^i = \sum_{vents} G_{v\ell}^i - \sum_{plumes} G_p^i$$

Conservation of Species

$$\frac{d}{dt} (X_{uj}^i M_u^i) = \sum_{vents} X_j G_{vu}^i + \sum_{plumes} X_{j\ell}^i G_p + \sum_{fires} W_{jf}^i + \sum_{smldrs} W_{js}^i$$

$$\frac{d}{dt} (X_{\ell j}^i M_\ell^i) = \sum_{vents} X_{j\ell} G_{v\ell}^i - \sum_{plumes} X_{j\ell}^i G_p{}^i$$

Conservation of Energy

$$\frac{d}{dt} (M_u^i c_p T_u^i) = \sum_{vents} E G_{vu}^i + \sum_{plumes} c_p T_\ell^i G_p^i + \sum_{fires} \dot{Q}_f^i$$

$$+ \sum_{surfaces} \dot{Q}_{cvn}^i + \dot{Q}_{rin}^i - \dot{Q}_{rout}^i$$

$$\frac{d}{dt} (M_\ell^i c_p T_\ell^i) = \sum_{vents} E G_{v\ell}^i - \sum_{plumes} c_p T_\ell^i G_p^i$$

$$+ \sum_{surfaces} \dot{Q}_{cvn}^i + \dot{Q}_{rin}^i - \dot{Q}_{rout}^i$$

Figure 11

OXYGEN CONSUMPTION AND PRODUCT EMISSION

Assumptions

- All combustion is characterized by

$$(CH_2)_n + (3n/2)O_2 \rightarrow nCO_2 + nH_2O$$

- Negligible contribution to the total gas mass by the "trace" species: CO, HCN, HCl, smoke, ...

- Mass consumption rates of burning materials estimated from input rate of heat release and heat of combustion

$$\dot{M}''_k \simeq \dot{Q}_k/\Delta H_{ck} \qquad \text{(kth material)}$$

Source terms in the species equations (major species)

$$W_{O_2} = -\sum_k \gamma_k \dot{M}''_k, \quad W_{CO_2} = \sum_k (44/\omega_k)\dot{m}''_k, \quad W_{H_2O} = \sum_k (18/\omega_k)\dot{m}''_k$$

Figure 12

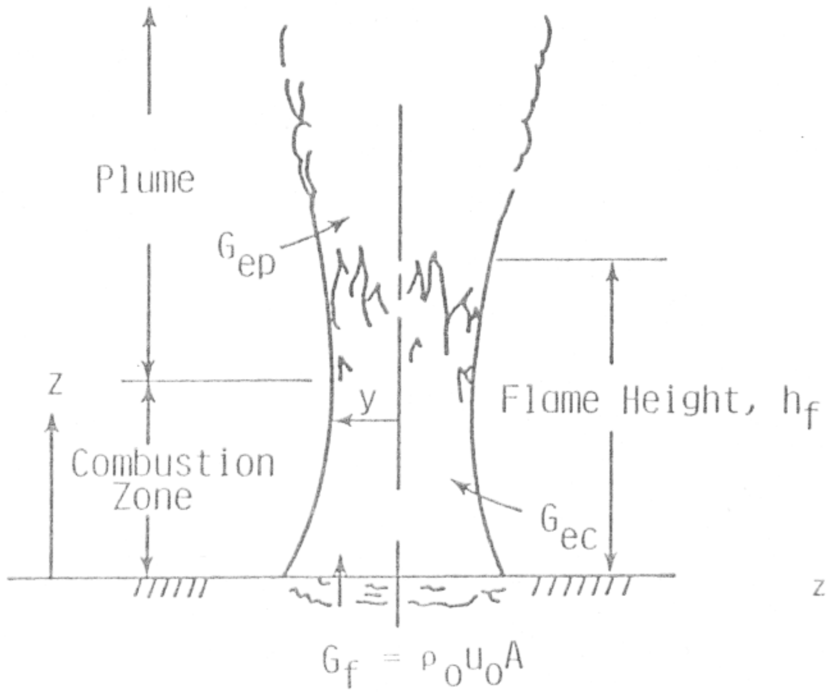
some acid gases might be scrubbed out by condensing water vapor. This inspired the idea of using a very simple combustion model for all fuels, even the polymers that contain constituents other than carbon and hydrogen. This reaction is the source term in the species conservation equations for oxygen, nitrogen, CO_2, and H_2O, and fuel vapor.

DACFIR-3 deals with only four species with the fuel vapor mass fraction set to zero. It is not assumed that there is any unburned fuel vapor existing in the plume or in the upper and lower zones. It is assumed that immediately as the fuel vapor touches the surface of the upper zone control line, it is completely reacted and the products are carried throughout the upper zone. The computer program is structured to have a non-zero fuel vapor mass fraction in the upper zone.

One of the unfortunate things we don't know about is a measure of mass burning rate as a function of anything. The test data that we use is a derivative of that fundamental quantity in terms of heat release rate and product release rate. We can estimate what that mass burning rate is and use that in the species terms by taking the heat release rate and dividing it by heat combustion for materials.

Flame and plume entrainment is a problem that has haunted zone modelers for a long time. At a lower zone, air is entrained into the plume. It travels in the upper zone and dilutes the combustion products. An air entrainment model first introduced by Prof. Steward in Combustion Science and Technology, 1970, and refined by Dr. Fang of NBS is used in DACFIR-3, shown in Figure 13. This model does differentiate between the combusting zone with heat generation and the plume without heat generation above combustion zone. There are two entrainment constraints. The mathematical formulations are also given in Figure 13. This is a classic example of a part of the model which can be removed easily as one subroutine and could be replaced with another.

FLAME AND PLUME ENTRAINMENT



(Steward, Comb. Sci. and Tech., 1970)

(Fang, NBSIR 73-115, 1973)

Parameters $\rho_0,\ u_0,\ \gamma,\ \Delta H_c$

$$y_o = 2A/P$$

$$\omega = [\gamma c_p\, T_\ell^i/(\gamma c_p\, T_\ell^i + x_{\ell O_2}^i\, \Delta H_c)]$$

$$z_s = 1.49\, E_c^{-4/5}\, [\omega/(1-\omega)]^{1/5}$$

$$\cdot\ (\omega\rho_\ell\, \rho_o + \gamma/x_{\ell O_2})^{2/5}\, (\rho_o\, u_o/\rho_a \sqrt{g y_o})^{2/5}$$

$$G_{ec} = A\, u_o\, \rho_\ell\, \omega\, [0.673\, E_c^{4/5}\, \omega^{-3/5}\, (1-\omega)^{1/5}\, (g y_o/u_o^2)^{1/5}\, z/y_o + 1]^{5/2} - 1$$

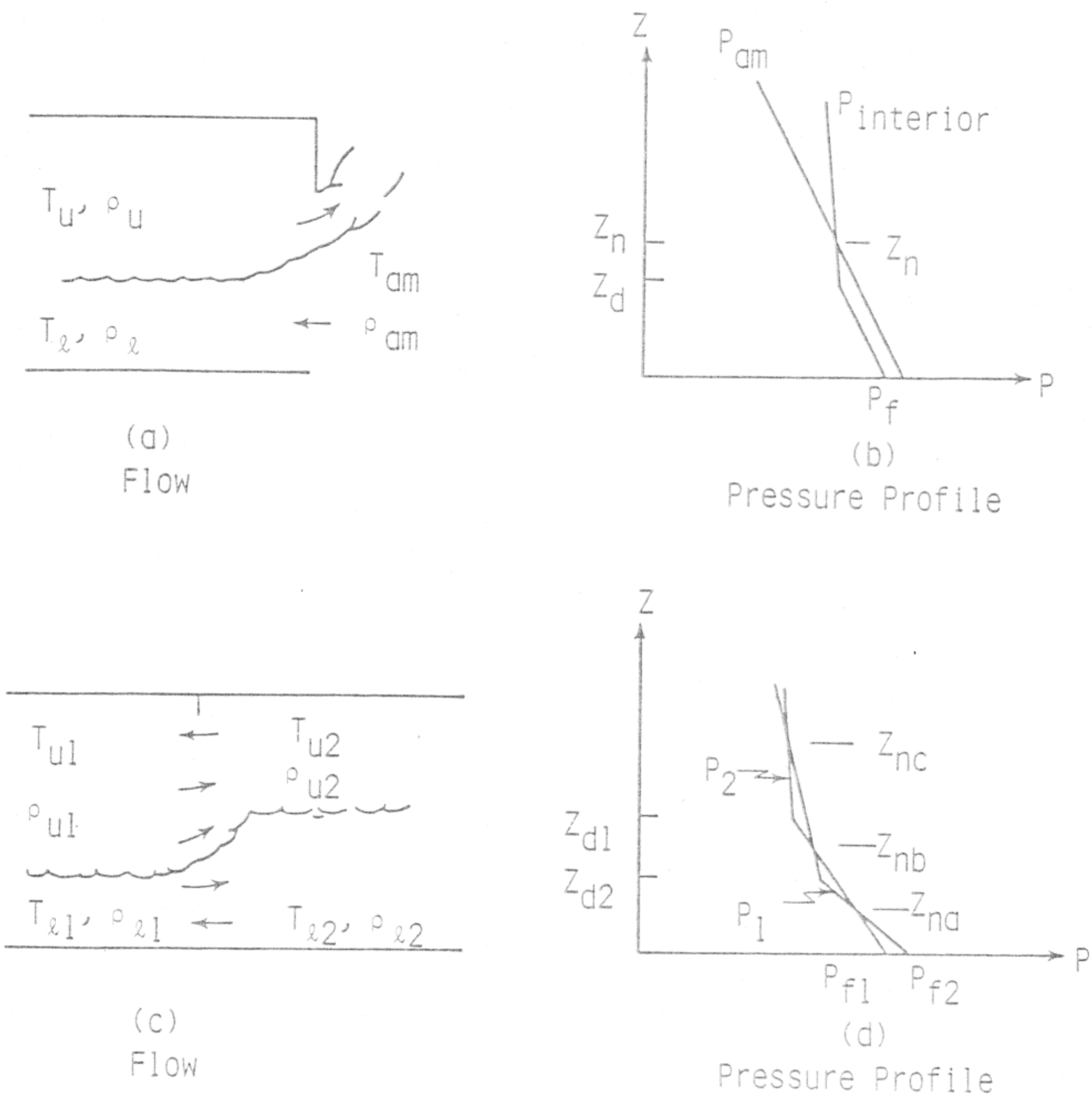
$$G_{ep} = A_s\, u_s\, \rho_\ell \cdot [1.09\, E_p^{4/5}\, (g y_s/u_s^2)^{1/5}\, (1-\rho_s/\rho_\ell)^{1/5}\, (z-z_s)/y_s + 1]^{5/3} - 1$$

Figure 13

The other major new item in DACFIR-3 is a vastly improved method of calculating the pressure and buoyancy driven flows through compartment vents. This is a method that has been used by others, particularly Harvard researchers and Prof. Tanaka. The basic idea is to use the hydrostatic law to compute the pressure variation across from either side of the vent opening and then compute the flow through the opening from the orifice equation knowing the pressure difference. In earlier zone models, one fixed the pressure in the floor to be the ambient pressure and all of the flow or most of the plume was due to the difference of pressures due to buoyancy. In DACFIR-3, the pressure at the floor is a variable also. A pressure difference between two compartments at the floor could generate a pressure-driven flow. When there is a density difference between two zones and the rate of change of pressure with height differs, it leads to a situation where a neutral plane exists in the doors.

Figure 14, (a) and (b), shows flow from a single compartment to the exterior while (c) and (d) show flows between two compartments with the pressure profiles intersecting at several points. It means that there is a flow from compartment one to compartment two above a height and a reverse flow below. It is possible to have two flows between the upper zones. This is possible, but I can't say I have ever seen it in any of our test runs. I am not sure anyone ever will, but the program is set up to handle this very complicated situation.

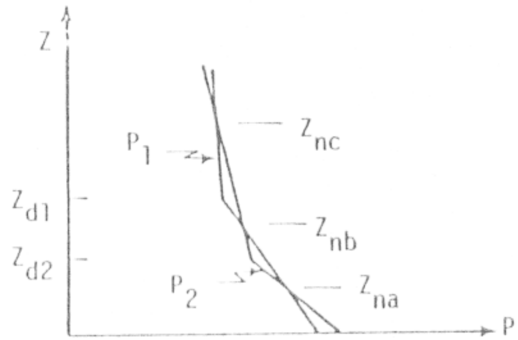
Figure 15 shows vent flow computations. The formulation is no different from that presented by Prof. Emmons in 1978. Our method of solution is a little unique. Rather than a very complicated logic tree to select certain formulas, we have taken the hydrostatic law which is the pressure as a linear function of height, that breaks at the thermal discontinuity position in each compartment. Take P as a function of Z and find the intersections of the pressure profiles in each compartment. We solve those equations and then we decide whether those neutral planes are physically possible. For example, some



(a) & (b) Single Compartment Flow to Exterior
(c) & (d) Flow Between Two Compartments

Figure 14

VENT FLOW COMPUTATIONS



PRESSURE PROFILE

Hydrostatic Law -

$$P_1(z) = P_{f1} - \rho_{\ell 1} g z \qquad z \leq z_{d1}$$

$$P_1(z) = P_{f1} + g(\rho_{u1} - \rho_{\ell 1}) z_{d1} - \rho_{u1} g z \qquad z > z_{d1}$$

$$P_2(z) = P_{f2} - \rho_{\ell 2} g z \qquad z \leq z_{d2}$$

$$P_2(z) = P_{f2} + g(\rho_{u2} - \rho_{\ell 2}) z_{d2} - \rho_{u2} g z \qquad z > z_{d2}$$

Pressure Differences -

$$0 \leq Z < Z_{na} \quad , \Delta P = \Delta P_1(Z)$$

$$Z_{na} \leq Z < Z_{d2} \quad , \Delta P = \Delta P_2(Z)$$

$$\vdots \qquad \vdots$$

Mass Flow Rates

ΔP Constant

$$G_k = \sqrt{2}\, C \Delta x (\rho \Delta P)^{1/2} (z_k - z_{k-1})$$

ΔP = linear function of Z

$$G_k = (2\sqrt{2}/3) C \Delta x\, \rho^{1/2} (1/a) [(\Delta P(z_k))^{3/2} - (\Delta P(z_{k-1}))^{3/2}]$$

$$a \equiv [\Delta P(z_k) - \Delta P(z_{k-1})]/(z_k - z_{k-1})$$

Figure 15

intersections may occur below the floor level or may occur at very high values of Z--higher than the ceiling of the compartment. Once we have decided whether there are any neutral planes in the door then we also check for the position of the thermal discontinuity. The resultant pressure difference is a piecewise linear function of the heights across the vent, either between two compartments or from one compartment to the exterior. P is a function of Z and this function is either constant when the densities are the same on either side or is a linear function of Z. In either case, it can be integrated analytically to obtain two expressions for the mass flow rate which is G_k as a function of the pressure difference. In the tests we have run so far, it ran pretty well. The whole subroutine was programmed into 100 lines of FORTRAN code.

QUESTION:

Dr. Michael A. Delichatsios, Factory Mutual Research Corporation.
How do you know the pressure distribution?

CHARLES MacARTHUR:

I know the pressure at the floor, and I know the density and so all I need is the hydrostatic law to predict the pressure.

QUESTION:

Dr. Michael A. Delichatsios, Factory Mutual Research Corporation.
If such flows exist, there are a lot of eddies. Would this change the flow completely?

CHARLES MacARTHUR:

Yes.

QUESTION:

Dr. Michael A. Delichatsios, Factory Mutual Research Corporation.
Would the hydrostatic flow equations apply?

CHARLES MacARTHUR:

No. The hydrostatic law does not apply in the case where there is any velocity at all in reality. This is an approximation that needs relatively low speed flows. We can approximate the true pressure distribution by the hydrostatic law.

QUESTION:

Dr. Michael A. Delichatsios, Factory Mutual Research Corporation. Can a zone model take into account something that is really the providence of a field model--that is a precise calculation of the pressure and velocity fields at each point.

CHARLES MacARTHUR:

The zone models can't do that, but you brought up an important fact that I might have missed. There is work now being done at NBS on the mixing at the door where two relatively high speed flows in opposite directions with a very high shear rate occur at the thermal end of the neutral plane. There are eddies which promote mixing. That is how some of the upper zone products--temperature and species get mixed down in the lower zone. DACFIR-3 does not have a model of that mixing because, as I understand, there isn't really a model available. One of the reasons we do mass species and energy balances on the lower zone is anticipation of having a mixing at the door parameterized in a formula available so we can predict species concentrations in the lower zone.

QUESTION:

Dr. John de Ris, Factory Mutual Research Corporation. I would just like to comment. Mike brings up a point that I suspect is not an issue, but I think it has to get settled by looking at the Richardson number of those flows. One may be able to estimate at least in some crude way what the Richardson numbers would be here and I wonder if anyone has done that?

CHARLES MacARTHUR:

We knew this was in the wind and that is why we structured the third version this way. This will be discussed at the workshop on Friday and we will give you experimental data.

Our models of the heat transfer from the upper zone are admittedly very simplified, shown in Figure 16, because we can't spend a lot of computing time and effort into developing individual parts. The convective flow of the heat zone is just a simple constant film coefficient multiplying the area of the surface to which the convection is taking place and difference in temperature. I think the assumed sign is incorrect in Figure 16. The gas temperature would be higher than surface temperature in most situations, at least in the upper zone, so Q would be negative. In the computer code, the signs are kept in the right fashion. A major refinement, even though

CONVECTION AND RADIATION

Convective Flow into a Gas Zone

$$\dot{Q}^{i}_{cvn} = hA_s(T_s - T_g)$$

Assumptions -

- $h = 5 \times 10^{-4}$ Btu/ft^2-sec
- Gray gas absorption/emission by each zone
- Mean beam length approximation valid

Radiation Absorbed by a Gas Zone

$$\dot{Q}_{rin} = \varepsilon\sigma\left(\sum_{surfaces} A_{sm}T_s^{\,4} + \varepsilon_n A_{td} T_{nz}^{\,4}\right)$$

Radiation Emitted by the Zone

$$\dot{Q}_{rout} = \varepsilon A_{surf} \sigma T_g^{\,4}$$

$$\varepsilon = 1 - \exp[-(\sigma_s \chi^{i}_{smk}\rho + k_g)L]$$

$$L = 3.6\ (\text{Zone Volume}/A_{surf})$$

Figure 16

convective loss to the surfaces is not one of the major heat loss terms in the energy equation, would be to have some better estimate of what the convection coefficient is. We have adopted a typical value for turbulent flow over a flat surface used particularly by Harvard. It is up in the air as to whether it is any good. Fortunately, the model is not too sensitive to convective heat losses. If we want to do some very careful analysis of the temperatures of materials and use the temperature of surfaces to predict flame spread rate, then we have got to go back and look at this convective loss term a little closer.

Radiation loss is one of our larger terms in most scenarios. The radiation absorbed by the gas zone, $\dot{Q}_{rin}$, takes into account surfaces lining the zone in the first term and radiation from neighboring zones in the second term. Radiation emitted by the zone was calculated by using grey gas approximation with a mean beam length approximation. This is an equation which first appeared in Dr. Quintiere's work in estimating emittance using the smoke density and also an absorption coefficient for gas species and gas band radiation. The $\dot{Q}_{rout}$ term which is the total radiated energy by the upper zone to everything with A_{surf} being the total upper zone surface area.

In Figure 17, the equation of state or the gas law for each specie is given in terms of partial pressure or density. The conservation of volume for each cell and the interface height at the discontinuity are also given. The foregoing physics equations are used to calculate the gas dynamics in the cabin.

The numerical procedures for solving these equations are outlined in Figure 18. Trapezoidal rule integration of ordinary differential equations are coupled with the Newton-Raphson iterative method for a set of algebraic equations. This technique follows the latest developments by the Harvard University Fire Research Group and is very successful in terms of numerical stability and computer time usage.

Gas Law

$$P_f^i = \frac{\rho^i \bar{R} T^i}{\sum_j x_j^i W_m}$$

$$\rho^i = \frac{M^i}{V^i}$$

Conservation of Volume

$$V_t^i = V_u^i + V_\ell^i = \text{constant}$$

Discontinuity Height

$$Z_d^i = f(V_\ell^i)$$

for Rectangular Cross Section

$$Z_d^i = \frac{V_\ell^i}{C_h C_w}$$

Figure 17

NUMERIC SOLUTION OF THE CABIN ATMOSPHERE EQUATIONS

- Equation set is of the form

$$\frac{d}{dt}X_i = f(\{X_i\})$$

- Trapezoidal Rule integration

$$X_i(t+\Delta t) \approx X_i(t) + \frac{1}{2}[f(t) + f(t+\Delta t)]$$

- Solution of the resulting algebraic equation set by the Newton-Raphson iterative method. Estimate k+1 of the value of $\{X_i\}$ at $t+\Delta t$ is obtained from the kth estimate by

$$\{X_i\}^{k+1} = \{X_i\}^k - [J]^{-1}\{F_i\}^k$$

$$F_i^k = X_i^k(t+\Delta t) - X_i^k(t) + \frac{1}{2}[f(t) + f(t+\Delta t)]^k, \quad [J] = \left[\frac{\partial F_i}{\partial X_j}\right]$$

Figure 18

In order to calculate the surface temperatures of materials, three assumptions were made, as shown in Figure 19. The material properties are assumed homogeneous and the surface temperatures are assumed constant during an integration step. A simple Euler integration scheme is used to integrate the energy balance equation at the material surface (Figure 20).

The gas temperature becomes high and gives out heat to materials ahead and in the lower zone. These equations are given in Figure 21. The view factors are given in cabin geometry dimensions which are indicated in Figure 22. A Cartesian coordinate system was used in the model for convenience. Three dimensional indices are used to label the cells.

The seven element states are defined in Figure 23. The allowable transitions from one element state to another element state are shown in Figure 24. The computer code has a subroutine to determine which element state each cell is in. An element's transition from one state to another is governed by the properties of the material associated with the element and by the element's relationship to the fire in the cabin. A fire is defined by a set of continuous elements in state 3.

The rate at which a flame front propagates depends upon several factors. The factors considered in this program are the type of material at the edge of a fire, the size of fire, orientation of the surface, and the background radiation level. The flame spread rates for a given material are input data to the computer program and are in a tabular form as functions of heat flux (Figure 25). The heat flux to elements adjacent to flaming elements is calculated based on the size of an adjacent fire and the overall background radiation level. Three flame spread rates are associated with a vertical surface: vertical up, vertical down, and horizontal. One flame spread rate is associated with horizontal surfaces. The rates and directions are shown in Figure 26.

MATERIALS SURFACE TEMPERATURES

Assumptions

- Interior materials are thin slabs of constant thickness, density, and heat capacity backed by a thick insulation layer or negligible heat capacity and constant thermal conductivity.
- Materials surface temperatures may be considered as constant during a cabin atmosphere integration step.
- Lateral heat conduction is negligible; separate surface temperatures can be used for the parts of a surface in contact with each gas zone.

Figure 19

MATERIALS SURFACE TEMPERATURES

Governing Equation

$$C_m \rho_m S_m \frac{dTs}{dt} = \dot{q}''_{rin} - \dot{q}''_{rout} + h(T_g - T_s) - \frac{k_{in}}{s_{in}}(T_s - T_\infty)$$

Solution by single step Euler integration after the integration of the cabin atmosphere equations

Figure 20

UPPER ZONE RADIATION TO MATERIALS

- To materials in contact with the upper zone

$$q_{zu} = [1 - \exp(-k_u L_u)]\sigma T_u^4$$

- To materials in contact with the lower zone

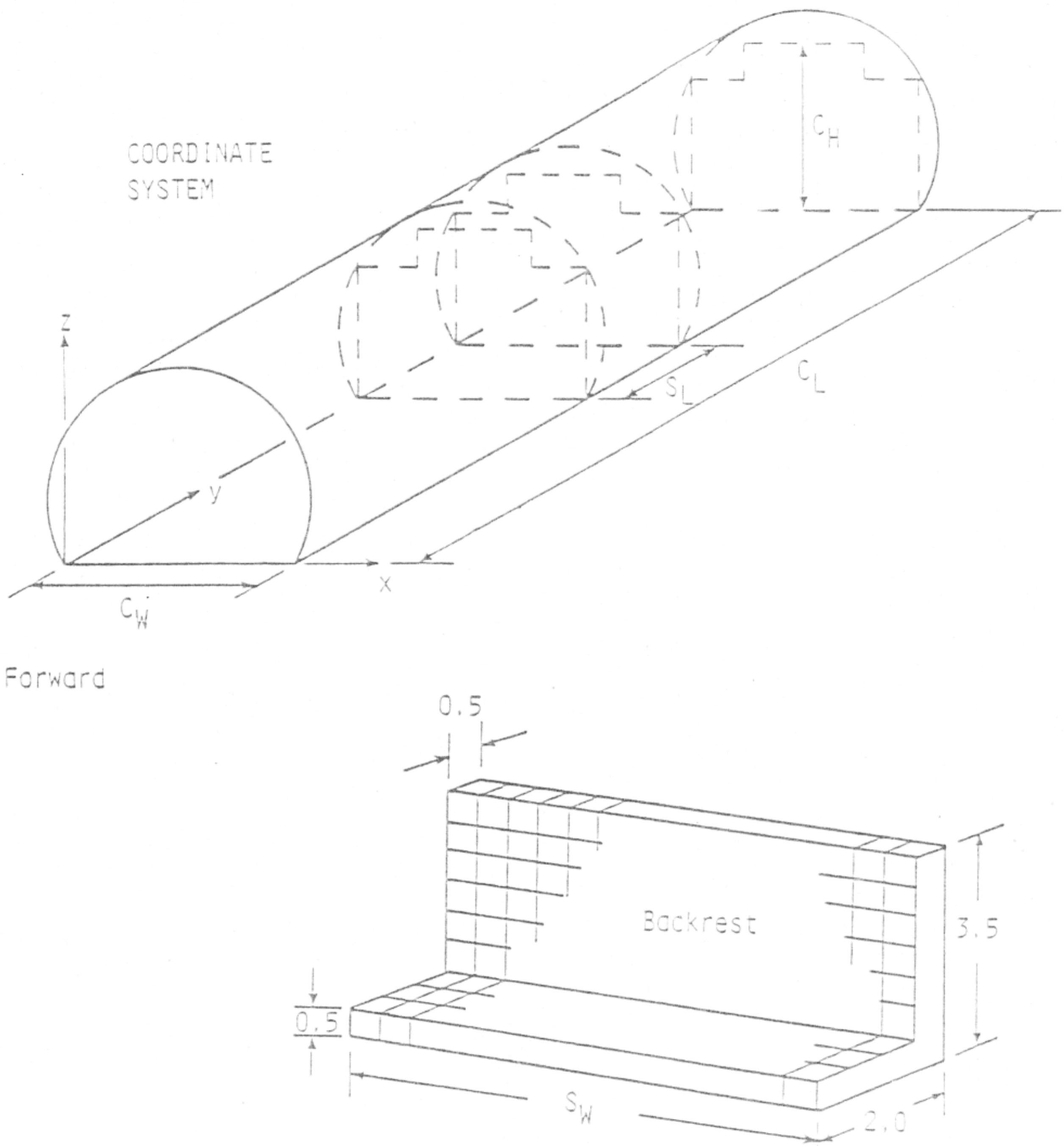
$$q_{z\ell} = \exp(-k_\ell L_\ell)F[1 - \exp(-k_u L_u)]\sigma T_u^4$$

$$F = (2/\pi)[(a/A)\tan^{-1}(b/A) + (b/B)\tan^{-1}(a/B)]$$

$$A = C_W/2Z_d, \quad b = C_L/2Z_d, \quad A = (1+A^2)^{1/2}, \quad B = (1+b^2)^{1/2}$$

Figure 21

CABIN GEOMETRY



Seat Dimensions (ft.)

Figure 22

ELEMENT STATES

State 1 - VIRGIN

The element is in its virgin state; it has not been directly affected by the fire.

State 2 - SMOLDERING

The element is undergoing nonflaming decomposition.

State 3 - FLAMING

The element is undergoing self-sustaining combustion.

State 4 - CHARRED

The element has burned out and will no longer smolder or burn.

State 5 - HEATING, NO FLAME CONTACT

The element is receiving heat flux sufficient to cause it to smolder but smoldering has not yet begun.

State 6 - HEATING, WITH FLAME CONTACT

The element is being touched by the flames of a fire but has not yet ignited.

State 7 - SMOLDERING AND COOLING

The element began smoldering when the heat flux reached a specified level; the flux has now dropped below that level but the material is still smoldering.

Figure 23

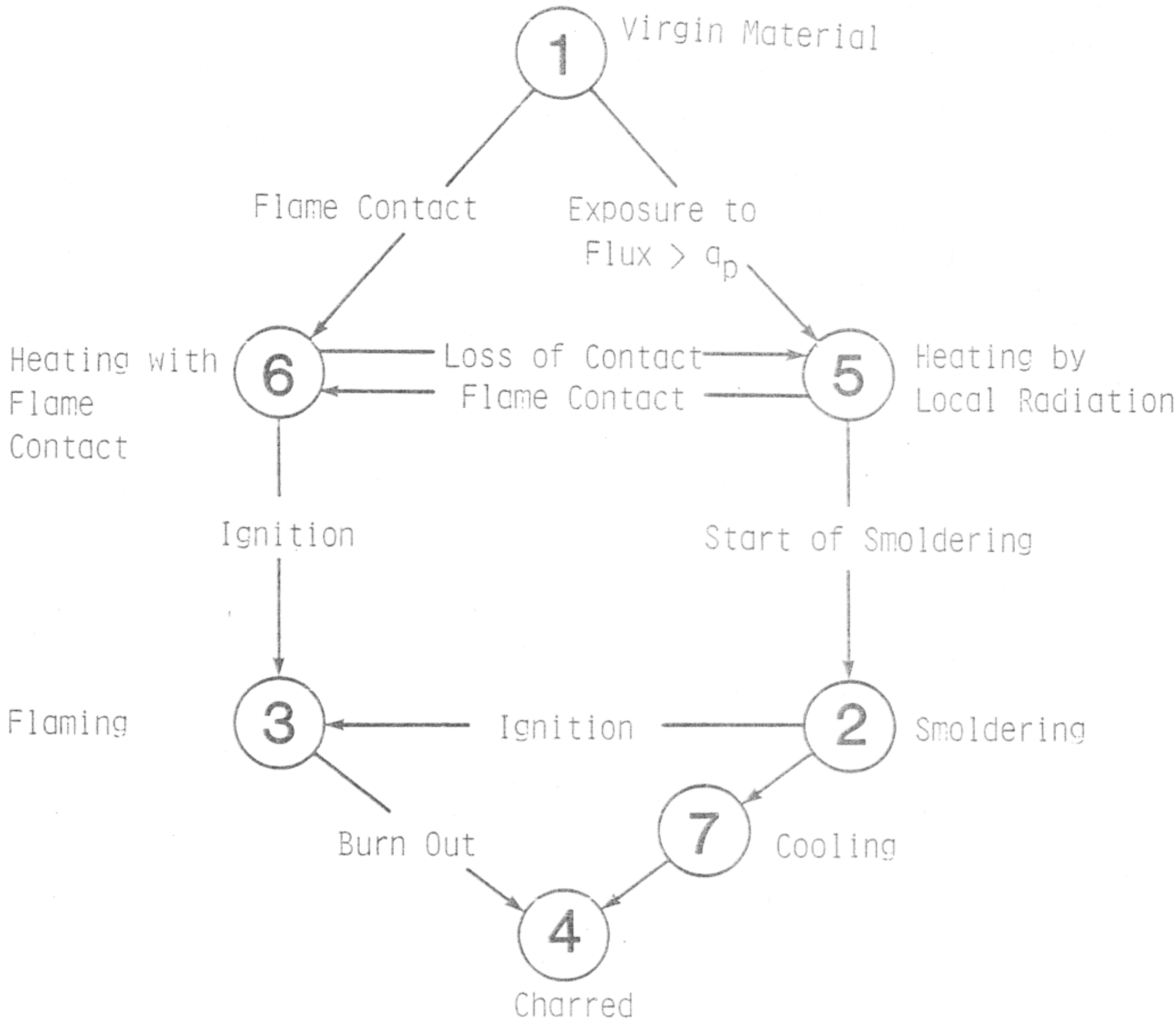

1
Virgin Material
Flame Contact
Exposure to
Flux > q_p
6
Heating with
Flame
Contact
Loss of Contact
Flame Contact
5
Heating by
Local Radiation
Ignition
Start of Smoldering
3
Flaming
Ignition
2
Smoldering
Burn Out
7
Cooling
4
Charred

Figure 24

INPUT DATA ON MATERIALS FIRE BEHAVIOR

FLAMING PROPERTIES

All data given as tabular functions of applied heat flux for each material

f_h, f_u, f_d - Horizontal, Vertical Upward and Vertical Downward Flame Spread Rate (ft/sec)

r_h - Rate of heat release (Btu/ft^2-sec)

r_{sf} - Rate of smoke release (Part/ft^2-sec)

r_{fi} - Rate of release of the ith gas specie (lbm/ft^2-sec)

t_f - Ignition delay with flame contact (sec)

t_{fc} - Time to burn out from flaming state (sec)

SMOLDERING PROPERTIES

Single values for each material

q_p - Flux level to induce smoldering (Btu/ft^2-sec)

r_{ss} - Rate of smoke release (Part/ft^2-sec)

r_{si} - Rate of release of the ith gas specie (lbm/ft^2-sec)

t_p - Smoldering initiation delay (sec)

t_{pc} - Time to smolder out (sec)

t_{pe} - Smoldering lag time (sec)

Figure 25

The flame radiation calculation is based on an equation derived by Dayan and Tien, Combustion Science and Technology, Vol. 9, 1974, pp. 41-47, for a cylindrically shaped fire on a horizontal surface facing upward. It is used in the present model to compute the radiation level at the edge of any fire base. These equations and the equations used for calculating flux levels are shown in Figure 27. The flame height is calculated with the equation derived by Steward and Fang and refined by Fang (NBSIR 73-115). The smoldering range is obtained from the model by Dayan and Tien, shown in Figure 28.

The statistics of computer program for DACFIR-3 are given in Figure 29. There are 4050 source statements with a required memory core of 326,000 bytes. The execution time on a DEC VAX-11/780 is 1500 seconds CPU time for a simulated time of 400 seconds. The sample outputs are given in Figures 30-32. The test cases to be simulated are three test runs performed in a 737 fuselage at Johnson Space Center/NASA. The test conditions are described in Figure 33.

The height of the thermal discontinuity is given in Figure 34. As time goes by, the thermal discontinuity descends down to a lower level as the upper layer becomes thicker. It becomes stabilized after 60 seconds. The calculated gas temperatures are compared with the measurements in Figure 35. The reasons for discrepancy in temperature measurements at the beginning of the test are not clear to us, We are going to look into this problem. Otherwise, the calculations agree reasonably well with the measurements. Gas temperature calculations for test runs 5A and 14A are compared with actual averaged temperature measurements in Figure 36 and 37. The model needs fine tuning to get a better agreement.

The gas concentrations of CO, HF and HCN are compared with actual measurements in Figures 38 and 39. The calculations show reasonable agreement with the test results at the early stage of testing. The disagreements become obvious after 180 seconds. This

FLAME SPREAD RATES AND DIRECTIONS

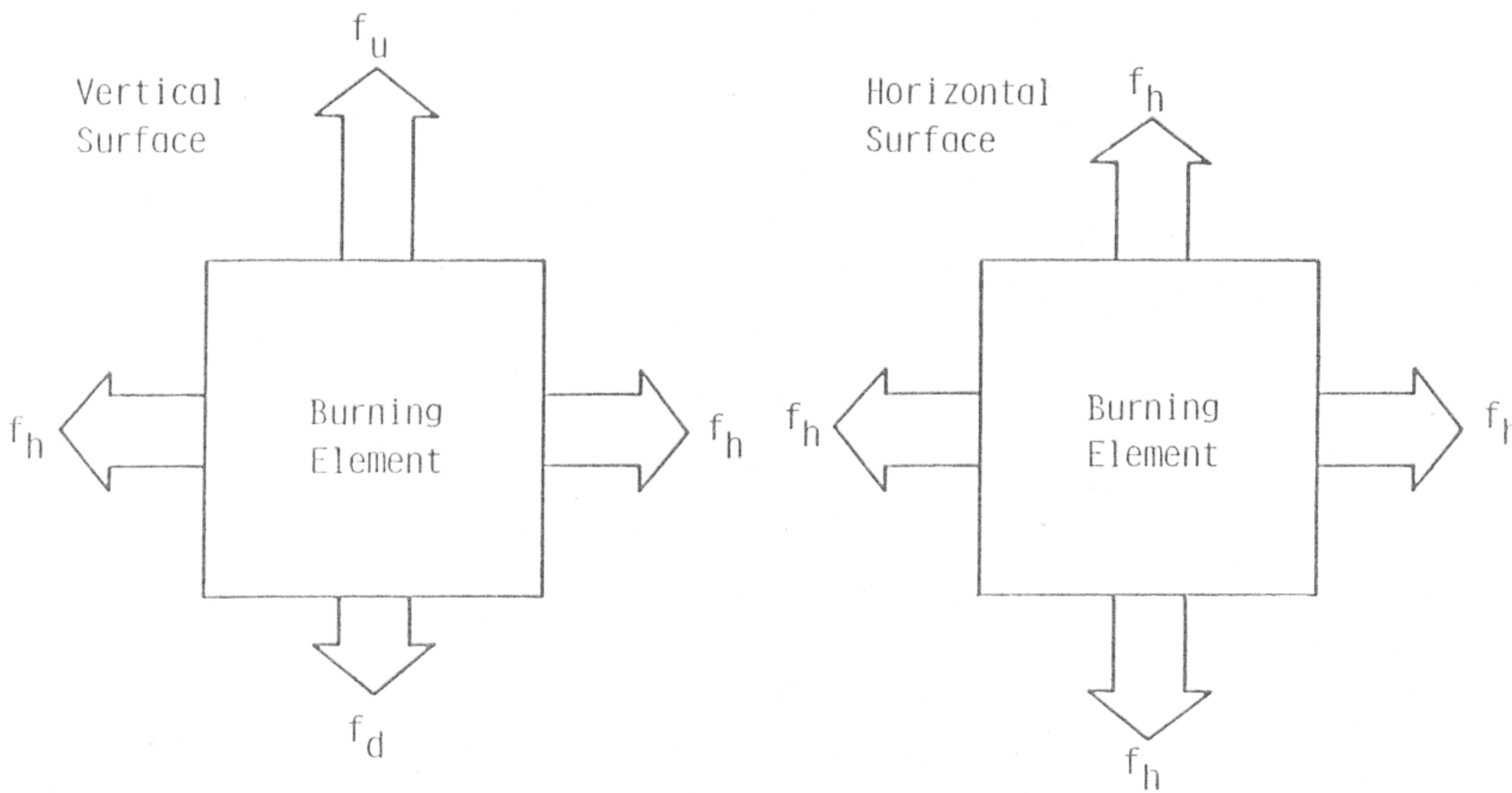
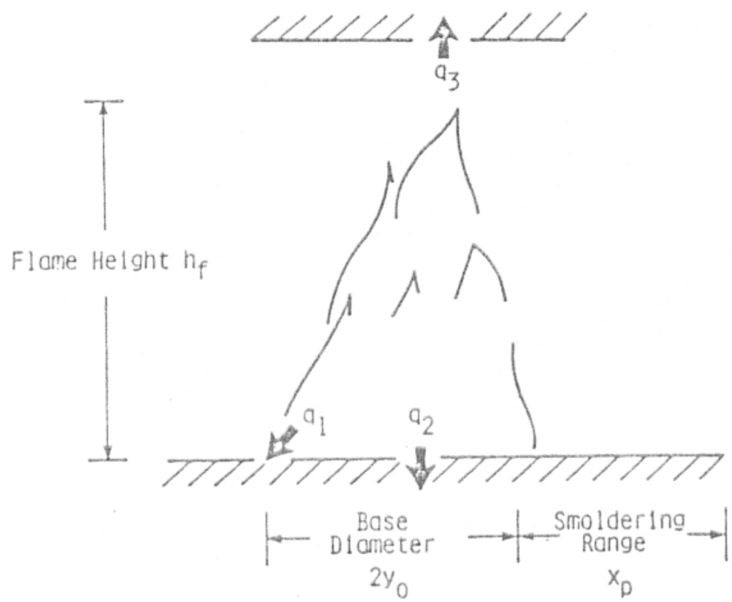


Figure 26

FLAME RADIATION



Assumptions -

- Cylindrical Flame volume; radius y_0, height, h_f.
- Uniform gray gas with absorption coefficient k_f and emissive power e_b

(Dayan and Tien, Comb. Sci. and Tech. 1974)

$k_f = 0.21\ \dot{P}_S''(h_f g)^{-1/2}$, $\quad \alpha_c = \alpha_c(k_f, h_f, y_0)$, $\quad e_b = 16.3$ (Btu/ft^2-sec)

Flux Levels (Btu/ft^2-sec)

Flame foot: $q_1 = 0.5\alpha_c e_b$ $\quad$ Avg. over base: $q_2 = 0.84\alpha_c e_b$

Overhead: $q_3 = \frac{1}{2}\left[1 - (4\zeta^2-3) / \sqrt{(4\zeta^2+9)(4\zeta^2+1)}\right]$ $\quad \zeta = Z/y_0$

Figure 27

FLAME HEIGHT

(Fang, NBSIR 73-115)

- Empirical correlation with plume temperature ($2.25T_\infty$)

$$h_f = (1.49 + 0.916\ K_a^{1/5})P_a^{1/5} N_b^{2/5} y_o$$

$$K_a = (E_c/E_p)^4(1 - \omega)[2.25f_1 + \omega(\rho_o' T_o' - 1)/\rho_o']^3/[1.95\omega^3 f_2^3(1 - \rho_s')],$$

$$P_a = \omega f_2^2/[E_p^4(1 - \omega)], \qquad f_1 = \omega(1 - \rho_o')/\rho_o' + \gamma/x^i_{o_2},$$

$$N_b = \rho_o u_o/(\rho\ g y_o), \qquad f_2 = \omega/\rho_o' + \gamma/x^i_{o_2},$$

$$\rho_o' = \rho_o/\rho, \quad T_o' = T_o/T^i, \quad \text{and } \rho_s' = \rho_s/\rho .$$

SMOLDERING RANGE

- Obtained from model of Dayan and Tien

$$x_p = x - y_o \qquad \pi y_o x^3 + (0.5h_f^2 - \pi y_o^2)x^2 = y_o^2 h_f^2(e_b/q_p - 0.5)$$

Figure 28

PROGRAM STATISTICS

DACFIR Version 3 (1 April 1981)

Language:	FORTRAN IV (1966 ANSI Standard)
Source Statements:	4050, (2250 additional comment lines)
*Memory Required:	326,000 bytes peak virtual size
*Typical Execution Time:	1500 seconds CPU time
	(Data case: single compartment, 5 trace gases, 2 vents, 8 surfaces, 1 seat row, 4 materials, step size 2.0 sec, tolerance 0.0005, simulated time 400 seconds.)

*Statistics from implementation on a DEC VAX-11/780 which runs at ≈ 100,000 floating point operations per second. Data case shown consists of approximately 150 million f.p. operations.

Figure 29

TIME- 48.000 SECONDS   DACFIR3 TEST 14B 21-MAR-1981 03:00:00

COMPARTMENT	ZONE	DEPTH (FT)	VOLUME (CU FT)	GAS TEMP (F)	GAS DENSITY (LBM/CU FT)	SMOKE CONC (OD/FT)	MASS FRACTIONS OF MAJOR GASES O2	CO2	H2O	PRESSURE (LBF/SQ FT)
1	UPPER	2.424	1158.1	219.32	0.05640	0.253	0.20889	0.00150	0.00061	2120.26
	LOWER	4.576	2817.9	85.10	0.07285	0.000	0.23000	0.00000	0.00000	

ZONE	GAS CONCENTRATIONS (PPM) N2	O2	FUEL	CO2	H2O	CO	HCL	HCN	HF	NO2
UPPER	803133.	194423.	0.	1016.	1016.	379.	10.	11.	11.	1.
LOWER	792793.	207207.	0.	0.	0.	0.	0.	0.	0.	0.

INTERIOR FIRES

FIRE	BASE AREA (SQ FT)	VAPOR GEN RATE (CU FT/SEC)	HEAT GEN RATE (BTU/SEC)	PLUME ENTRMNT (CU FT/SEC)	FLAME LENGTH (FT)	ABSN COEFF (1/FT)	SMOKE GEN RATE (PART/SEC)	OXY CNSPTN RATE (LBM/SEC)
1	4.00	0.400000E+00	0.207200E+03	0.176585E+02	5.19	0.698700E+00	0.172000E+03	0.384160E-01
2	1.50	0.150000E+00	0.475750E+01	0.177093E+02	3.77	0.331662E+00	0.478500E+02	0.203893E-02
3	0.75	0.750000E-01	0.360933E+01	0.292482E+02	2.59	0.146279E+01	0.476926E+02	0.154686E-02
4	2.25	0.219375E+00	0.163256E+02	0.396667E+02	3.98	0.280375E+00	0.680073E+02	0.358570E-02
5	0.75	0.731250E-01	0.166663E+01	0.455738E+02	2.29	0.213923E+00	0.655406E+01	0.366053E-03

TRACE GAS GENERATION RATES (LBM/SEC)

FIRE	CO	HCL	HCN	HF	NO2
1	0.136400E-03	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
2	0.294250E-03	0.412500E-04	0.610500E-06	0.338250E-04	0.000000E+00
3	0.471634E-04	0.657794E-05	0.000000E+00	0.000000E+00	0.000000E+00
4	0.922028E-03	0.155121E-04	0.399064E-04	0.000000E+00	0.313219E-05
5	0.105297E-03	0.000000E+00	0.332876E-05	0.000000E+00	0.000000E+00

SURFACE CONDITIONS

SURFACE	CONTACT AREA (SQ FT) UPPER ZONE	LOWER ZONE	CONVECTIVE FLOW (BTU/SEC) UPPER ZONE	LOWER ZONE	RADIATIVE FLOW (BTU/SEC) UPPER ZONE	LOWER ZONE	TEMPERATURE (F) UPPER PART	LOWER PART
1	0.000	616.000	0.000	-6.892	0.000	56.444	106.085	106.085
2	79.746	256.254	3.366	-2.867	7.954	23.480	144.162	106.085
3	168.000	0.000	11.280	0.000	16.756	0.000	97.835	97.835
4	56.000	0.000	2.217	0.000	5.585	0.000	148.750	148.750
5	280.000	0.000	11.086	0.000	27.927	0.000	148.750	148.750
6	56.000	0.000	2.217	0.000	5.585	0.000	148.750	148.750
7	168.000	0.000	11.280	0.000	16.756	0.000	97.835	97.835
8	79.746	256.254	3.366	-2.867	7.954	23.480	144.162	106.085
PARTN								
1	20.664	50.336	0.818	-0.435	2.061	4.612	148.750	101.130
2	20.664	50.336	0.818	-0.435	2.061	4.612	148.750	101.130
TOTAL	928.821	1229.179	46.447	-13.496	92.639	112.629		

VOLUME AND ENERGY FLOW RATES THRU VENTS (CU FT/SEC), (BTU/SEC)

VENT	1	2
CONNECTS	1 TO 5	1 TO 5
NET UPR-UPR		
VOLUME	0.000000E+00	0.551926E+02
ENERGY	0.000000E+00	0.507242E+03
NET LWR-LWR		
VOLUME	0.500000E+03	0.461298E+03
ENERGY	0.475364E+04	0.439392E+04

SOLUTION DATA - TIME STEPS IN MILLISECONDS
STEP 2000. ITR 3. STEP 2000. ITR 6. STEP

SAMPLE OUTPUT -

CABIN ATMOSPHERE DATA

Figure 30

```
ELEMENT STATE SUMMARY - CONDITIONS ON ALL SURFACES AT END OF FLAME SPREAD CALCULATIONS
                 1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27

SMOLDERING       0   0   0   0   0   0   0   0   0
FLAMING         16  11   3   0   0   0   0   0  21
CHARRED          0   0   0   0   0   0   0   0   0

 FLAMING,SMOLDERING,AND CHARRED AREAS BY MATERIAL TYPE (SQ FT)

MATERIAL NO          1          2          3          4
AREA AFLAME        4.00       2.75       0.75       5.25
AREA SMLDRG        0.00       0.00       0.00       0.00
AREA CHRRD         0.00       0.00       0.00       0.00

TIME-    48.000 SECONDS             DACFIR3 TEST 14B  21-MAR-1981 03:00:00

DISTRIBUTION OF ELEMENTAL STATES AT END OF FLAME SPREAD CALCULATIONS
```

SAMPLE OUTPUT -
FIRE SPREAD DATA

```
INTEGERS CORRESPOND TO STATES OF INDIVIDUAL ELEM-

               1-AMBIENT STATE
               2-SMOLDERING STATE
               3-AFLAME
               4-CHARRED
               5-HEATING,NOT IN CONTACT WITH FLAME
               6-HEATING,IN CONTACT WITH FLAME
               7-SMOLDERING,COOLING

       AFT
       111111111111111111111111111111111111111111111111111111111111111111111111
       111111111111111111111111111111111111111111111111111111111111111111111111
       111111111111111111111111111111111111111111111111111111111111111111111111
       111111111111111111111111111111111111111111111111111111111111111111111111
       111111111111111111111111111111111111111111111111111111111111111111111111
       111111111111111111555511311111111151111111111111111111111111111111111111
       111111111111111115333313331111111163111111111111111111111111111111111111
       111111111111111115333313331111111163111111111111111111111111111111111111
       111111111111111115333313331111111163111111111111111111111111111111111111
       111111111111111115333311311111111155555111111111111111111111111111111111
       111111111111111111555511111111111155551111111111111111111111111111111111
       111111111111111111111111111111111111111111111111111111111111111111111111
       111111111111111111111111111111111111111111111111111111111111111111111111
       111111111111111111111111111111111111111111111111111111111111111111111111
       111111111111111111111111111111111111111111111111111111111111111111111111
LINING
 SURF  000000000000000000000000000000000000000000000000000000000000000000000000
NUMBER 111111111111111111111122222222222233333445555555555556677777888888888888
```

Figure 31

```
TIME=     48.000 SECONDS                DACFIR3 TEST 14B  21-MAR-1981 03:00:00

     FOR SEAT GROUPS---J= 1- 4   CUSHION,BOTTOM
                       J= 5- 7   BACKREST,LWR REAR
                       J= 8-11   BACKREST,UPR REAR
                       J=12      BACKREST,TOP
                       J=13-18   BACKREST,FRONT
                       J=19-21   CUSHION,TOP
                       J=22      CUSHION,FRONT

     SEAT GROUP NO 1

-------------------
                   22  111111333
-------------------
 CUSHION,FRONT
                   21  111111113
                   20  111111113
 CUSHION,TOP
                   19  111111113
-------------------
                   18  111111111
                   17  111111111
                   16  111111111
 BACKREST,FRONT
                   15  111111111
                   14  111111111
                   13  111111111
-------------------
                   12  111111111
-------------------
 BACKREST,TOP
                   11  111111111
                   10  111111111
 BACKREST,UPR REAR
                    9  111111111
                    8  111111111
-------------------
                    7  111111111
                    6  111111111
 BACKREST,LWR REAR
                    5  111111111
-------------------
                    4  111111333
                    3  111113333
 CUSHION,BOTTOM
                    2  111113333
                    1  111113333
-------------------
```

SAMPLE OUTPUT -

FIRE SPREAD DATA

Figure 32

TEST CASES*

(Preliminary Results)

- Test 3B - 56 ft long, 11 ft wide, 7 ft high 737 fuselage section; 2 5×2.5 ft doors open to exterior; 2×2 ft pan of Jet A at floor level and cabin center; no materials.

- Test 5A - As in 3B except cabin is 20 ft long, and one door has a forced 500 cfm flow into the cabin.

- Test 14A - 56×11×7 cabin; 2 5×2.5 doors, one with forced 500 cfm flow; 1×1 ft pan of Jet A beneath the outboard seat of a 3 seat row (surplus A/C seat); 4 ft wide simulated wall panel of Tedlar/epoxy-fiberglass/Nomex homeycomb; 4 ft simulated polycarbonate PSU; 20 ft of simulated ceiling panel of same construction as wall panel.

* Test report in preparation by NASA-JSC

Figure 33

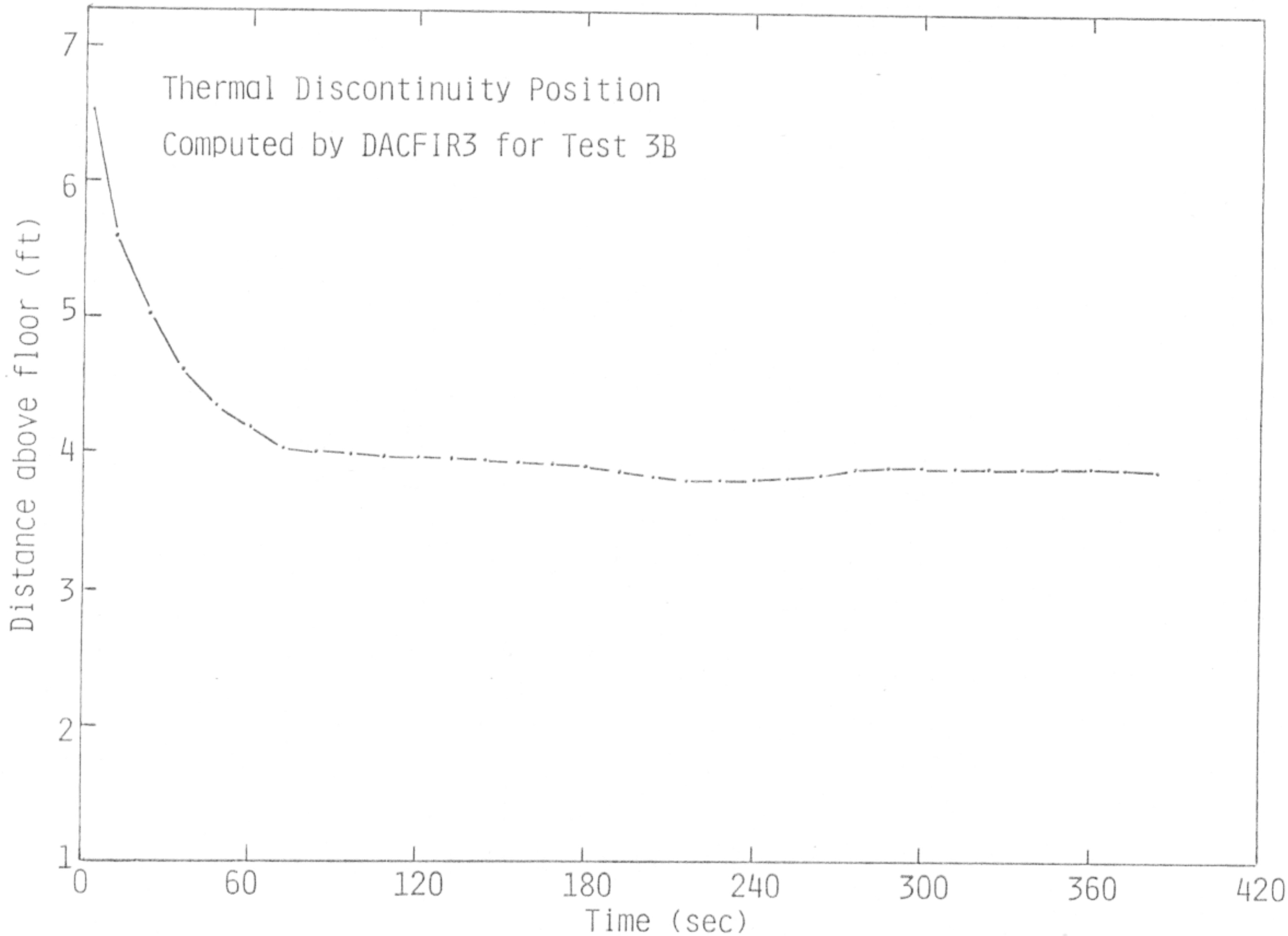

Thermal Discontinuity Position
Computed by DACFIR3 for Test 3B
Distance above floor (ft)
7
6
5
4
3
2
1
0
60
120
180
240
300
360
420
Time (sec)

Figure 34

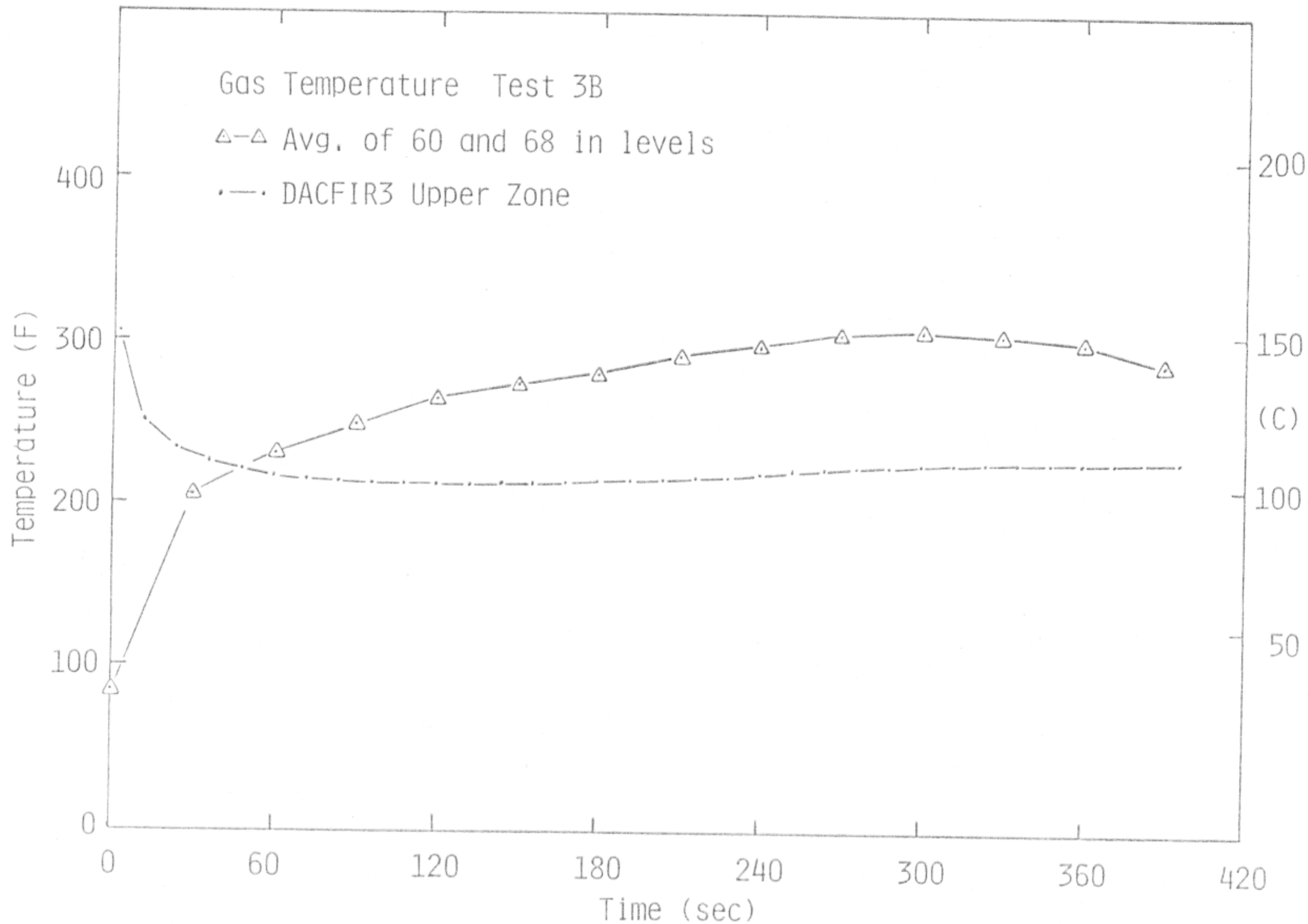

Gas Temperature Test 3B
Avg. of 60 and 68 in levels
DACFIR3 Upper Zone
Temperature (F)
0
100
200
300
400
(C)
50
100
150
200
0
60
120
180
240
300
360
420
Time (sec)

Figure 35

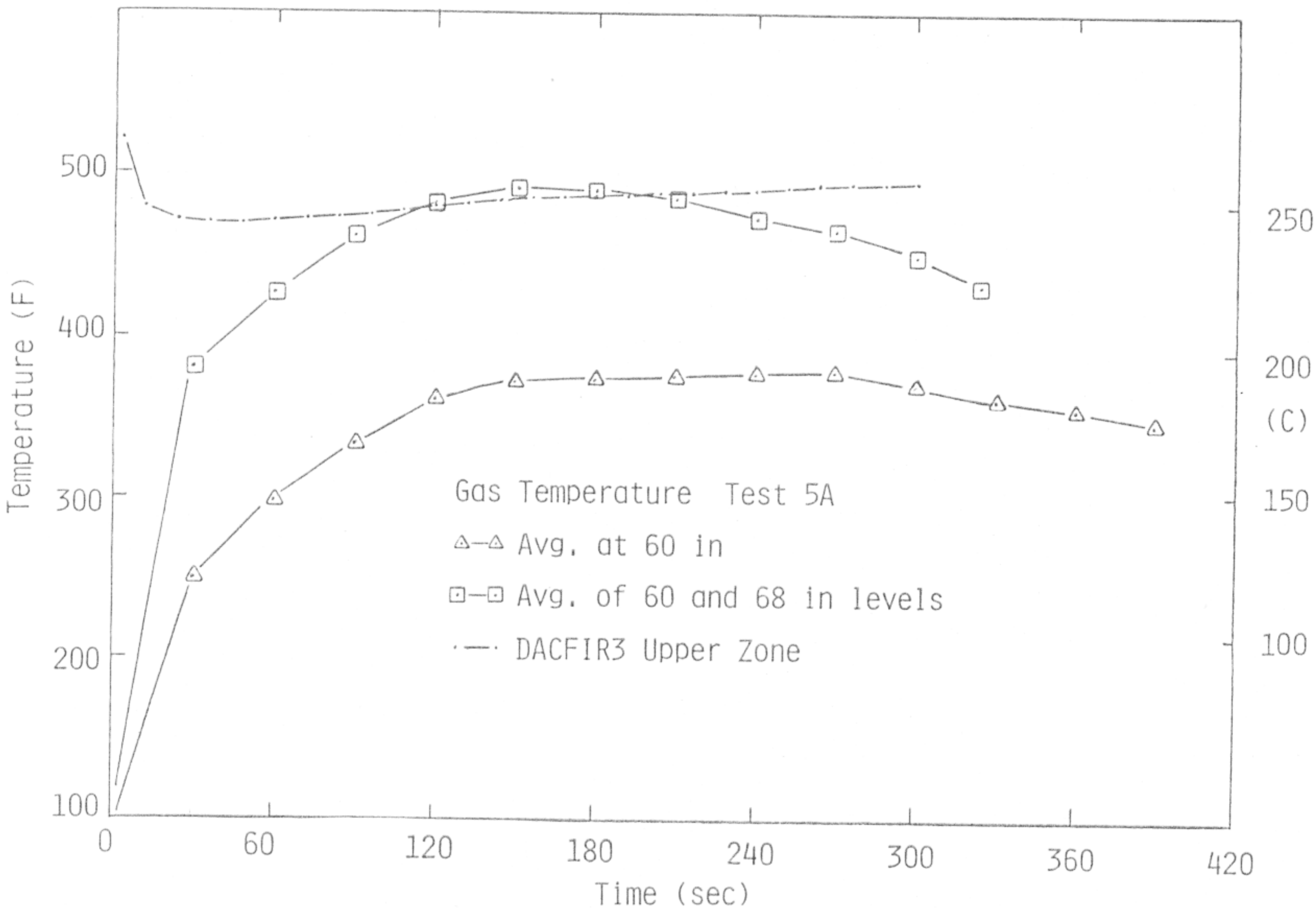

Gas Temperature Test 5A
Avg. at 60 in
Avg. of 60 and 68 in levels
DACFIR3 Upper Zone
Temperature (F)
100
200
300
400
500
(C)
100
150
200
250
Time (sec)
0
60
120
180
240
300
360
420

Figure 36

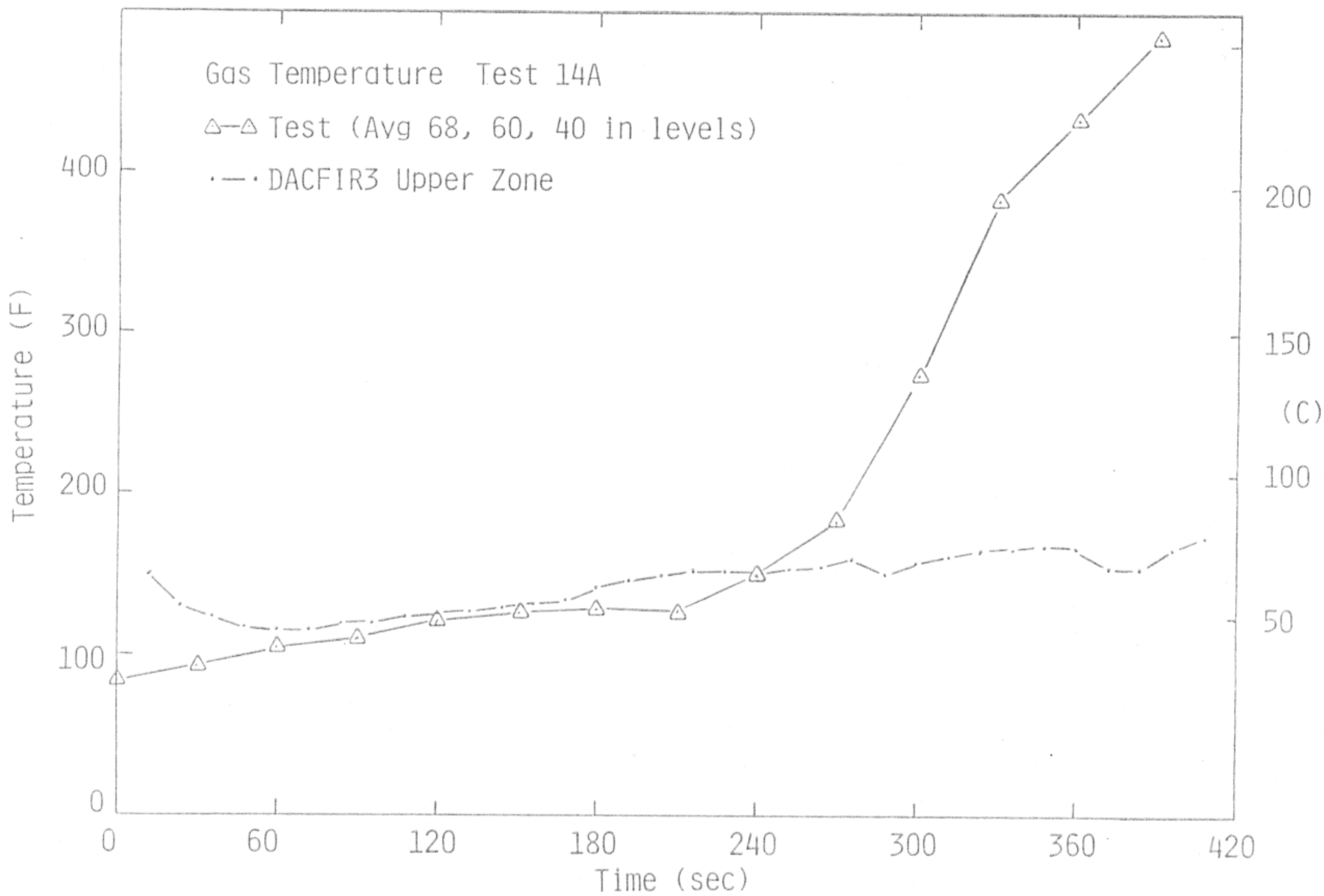

Gas Temperature Test 14A
Test (Avg 68, 60, 40 in levels)
DACFIR3 Upper Zone
Temperature (F)
0
100
200
300
400
(C)
50
100
150
200
Time (sec)
0
60
120
180
240
300
360
420

Figure 37

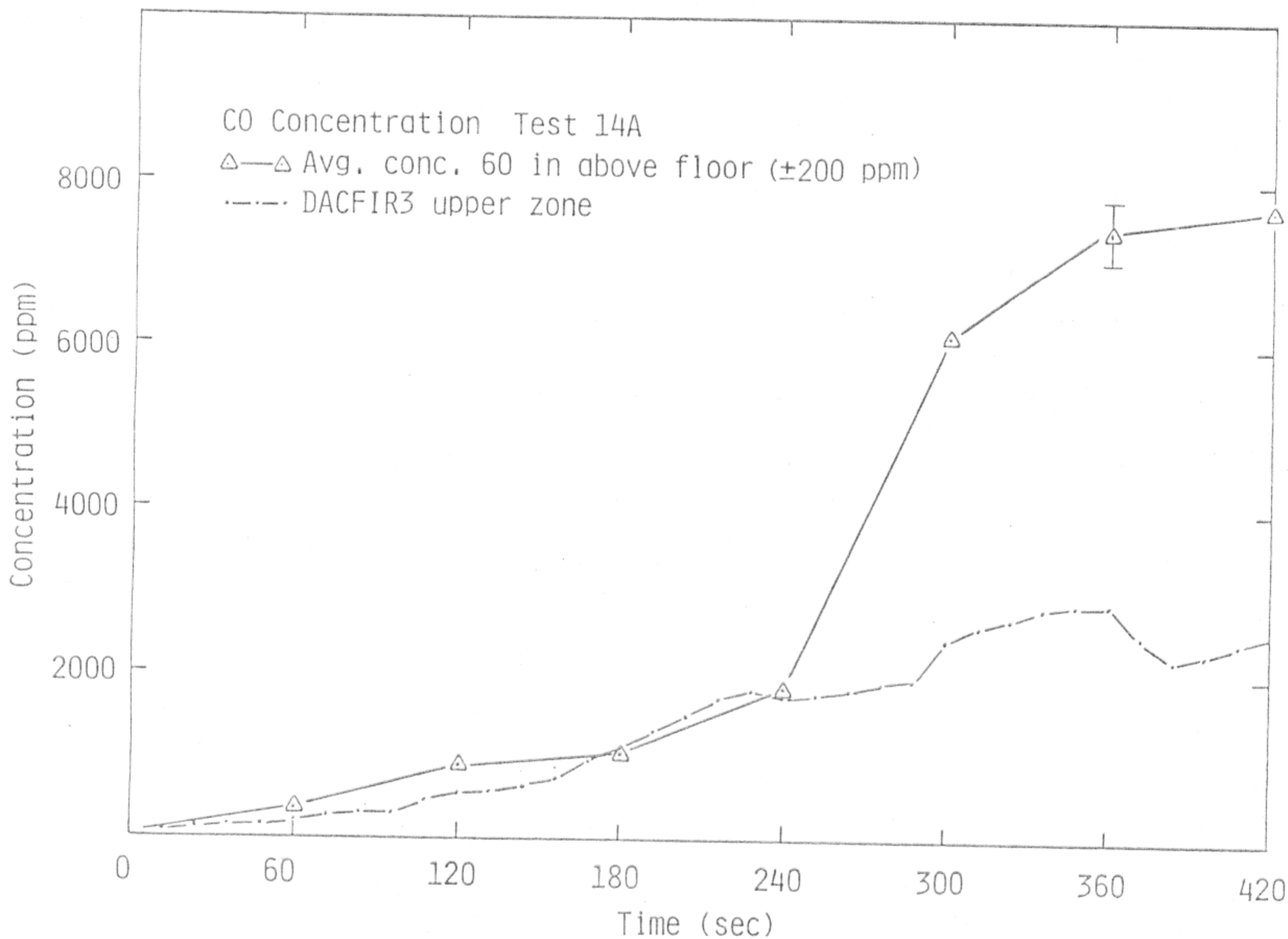

CO Concentration Test 14A
Avg. conc. 60 in above floor (±200 ppm)
DACFIR3 upper zone
8000
6000
4000
2000
Concentration (ppm)
0
60
120
180
240
300
360
420
Time (sec)

Figure 38

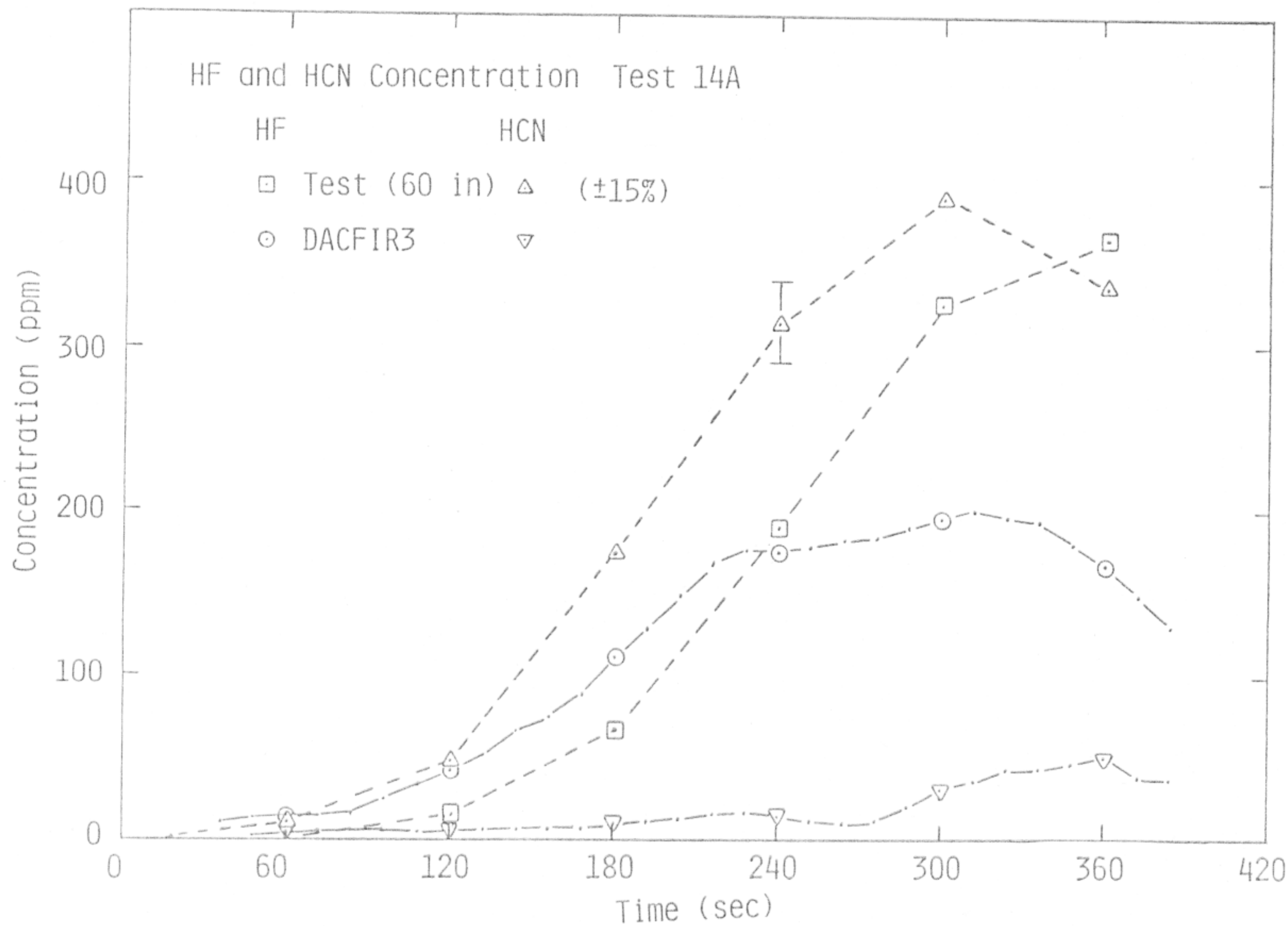

HF and HCN Concentration Test 14A
HF
HCN
Test (60 in)
(±15%)
DACFIR3
Concentration (ppm)
400
300
200
100
0
60
120
180
240
300
360
420
Time (sec)

Figure 39

is possibly due to the input material data which gives constant species release rate during the test period.

The current version of DACFIR-3 needs further refinements and fine tuning. The model is physically sound and the numerical procedures are proven workable and economical. The major shortcomings of the model validation are the reliability and availability of material properties as input data. In particular, the autoignition data and the flame spread rate data were obtained in a laboratory scale apparatus and may not be directly applicable to a real full-scale fire. There is a need to correlate the laboratory data to a full-scale test. The species release rates, which were obtained from a laboratory-scale apparatus, require further examination. The effects of reduced oxygen concentration on spread and emission rates need to be incorporated into the model once the data becomes available (Figure 40).

The additional refinements are shown in Figure 41. The computer code needs improvements and rearrangement to streamline its computations. In order to account for the radiation on vertical and ceiling surfaces, the circular cylindrical flame model may not be adequate.

A final draft report will be completed and forwarded to the FAA for review in two months. The computer code and the listing are available through the FAA.

POTENTIAL REFINEMENTS AND PROBLEM AREAS

- Auto-ignition of materials by radiation.
  - Auto-ignition data is not available.
  - Practical method of computing "non-local" radiation flux to individual elements is needed.
- Flame spread rate data is questionable.
  - OSU Apparatus is not appropriate for flame spread measurements.
- Known variation of rate of release with cumulative release not now incorporated.
  - Increases quantity of input data substantially.
- Effects of reduced oxygen concentration on spread and emission rates not incorporated.
  - Data not available.

Figure 40

ADDITIONAL REFINEMENTS

- Improvements to the computer code

  - Better detailed cabin geometry; improved seat modeling, larger coverage by the element grid, inclined or curved surfaces, ...

  - Remove word packing for state data to increase speed; remove State 7 (cooling).

  - Generalize spread algorithms to handle arbitrary shapes.

- Flame radiation models for fires on vertical and ceiling surfaces.

  - Circular cylinder model is probably not adequate.

** Simple, practical models of the combustion of cabin materials and composite structures are needed to interpret and supplement lab test results (input data). Validation of the lab tests has not received sufficient attention.

Figure 41

CORRELATION WORK AND FLAME SPREAD

JAMES QUINTIERE

Head of the Math Modeling Group, Center for Fire Research, National Bureau of Standards (NBS). Ph.D. Mechanical Engineering, New York University.

CORRELATION WORK AND FLAME SPREAD

James Quintiere
Center for Fire Research
National Bureau of Standards

We have two projects for which we are responsible to the FAA, as shown in Figure 1. One is entitled, "Correlation between Laboratory-scale/subscale/full-scale Fire Tests." We are a half year into that project. The second is a project on the development of some new concepts in flame spread methods. I will try to outline what we are up to in these two projects in the following slides.

The output of the correlation work will be presented to the FAA at the end of the year. We are in the midst of it right now, and both myself and Bill Parker are involved in this. We are focusing on three elements in looking at the relationship between test methods, scale modeling and full-scale fire results. Those elements might be composed of flammability, burning rate, flame spread, smoke, and toxicity (Figures 2 and 3). The correlation work consists of literature reviews in two major areas, shown in Figure 4. We want to find out what has been done; specifically, how do test methods correlate with full-scale results, what analyses has there been of fire test methods in the past, and the same goes with regard to scale modeling. We are excluding pressure modeling in the scale modeling review. We are just looking at atmospheric modeling techniques and how well they have performed. We are approaching this beyond detail and routine features of a literature review. We want to see if we can understand the underlying features of some of these test methods.

The analyses (Figure 5) may call for some generic mathematical modeling in simple terms of what the test method is trying to do. We need to get at what the significant outputs of these test methods are. In this process, we might be able to identify what are the more important things that are being measured and have relevance as compared

PROJECTS

1. CORRELATION BETWEEN LABORATORY SCALE, SUB-SCALE, AND FULL-SCALE FIRE TESTS

   Fy 81: Oct. 1980 - Sept. 1981

2. FLAME SPREAD TEST METHODS DEVELOPMENT

   April 1981 - March 1983

CFR
NBS

Figure 1

"CORRELATION"

Figure 2

ELEMENTS

- "FLAMMABILITY" IE. BURN RATE, SPREAD RATE, . . .
- SMOKE
- TOXICITY

Figure 3

LITERATURE REVIEWS

- TEST METHOD DATA WITH FULL-SCALE FIRES
- PHYSICAL SCALING METHODS WITH FULL-SCALE FIRES

Figure 4

ANALYSES

- MODELS OF GENERIC TEST METHODS
- SIGNIFICANCE OF TEST DATA
- RELATIONSHIP TO POST CRASH FIRE SCENARIO

Figure 5

to maybe what is just empirical to provide a ranking order of materials in this testing apparatus.

The objective (Figure 6) is to relate this to the FAA's fire scenario that they are studying; i.e., the postcrash fire. This is the focus of the output of this review and basically that is the objective. Through this literature review, through some analyses of test methods and an understanding of what the FAA is up to in their full-scale postcrash fire tests, we hope to develop a strategy for making recommendations on what kinds of test methods, what kinds of data, what kind of approach should go into unravelling this and come up with a risk assessment for this particular scenario. This is the objective. We are in the midst of this work which will be reported at the end of the project in September or October of this year.

The second project, the flame spread test method development, is about to commence. We have already done developmental work for materials in a room fire which will be used as guidelines to the approach to this project. We are preparing to start testing some concepts. Now, we are putting together an apparatus to get this project underway.

What is this project all about? We are attempting to develop two concepts that will allow us to predict mathematical relationships for rate of flame spread in terms of measured quantities from small-scale test apparatuses. We view flame spread in a very simple two-element mode. One is so-called creeping spread, which is spread against the flow of gases, against the wind if you prefer, shown in Figure 7. This is like spreading downward on a wall or spreading laterally on a wall. The other mode of flame spread is wind-aided flame spread, also shown in Figure 7. This could be flame spreading up a wall or spreading under a ceiling and the wind can be generated by the fire itself. In this sense, we are trying to separate the two extreme modes of flame spread and develop some test method strategy for this.

OBJECTIVES

- APPLICATION AND INTERPRETATION OF TEST METHODS AND SCALING TO MEASURE THE HAZARD DUE TO AIRCRAFT MATERIALS IN POST CRASH FIRES.

Figure 6

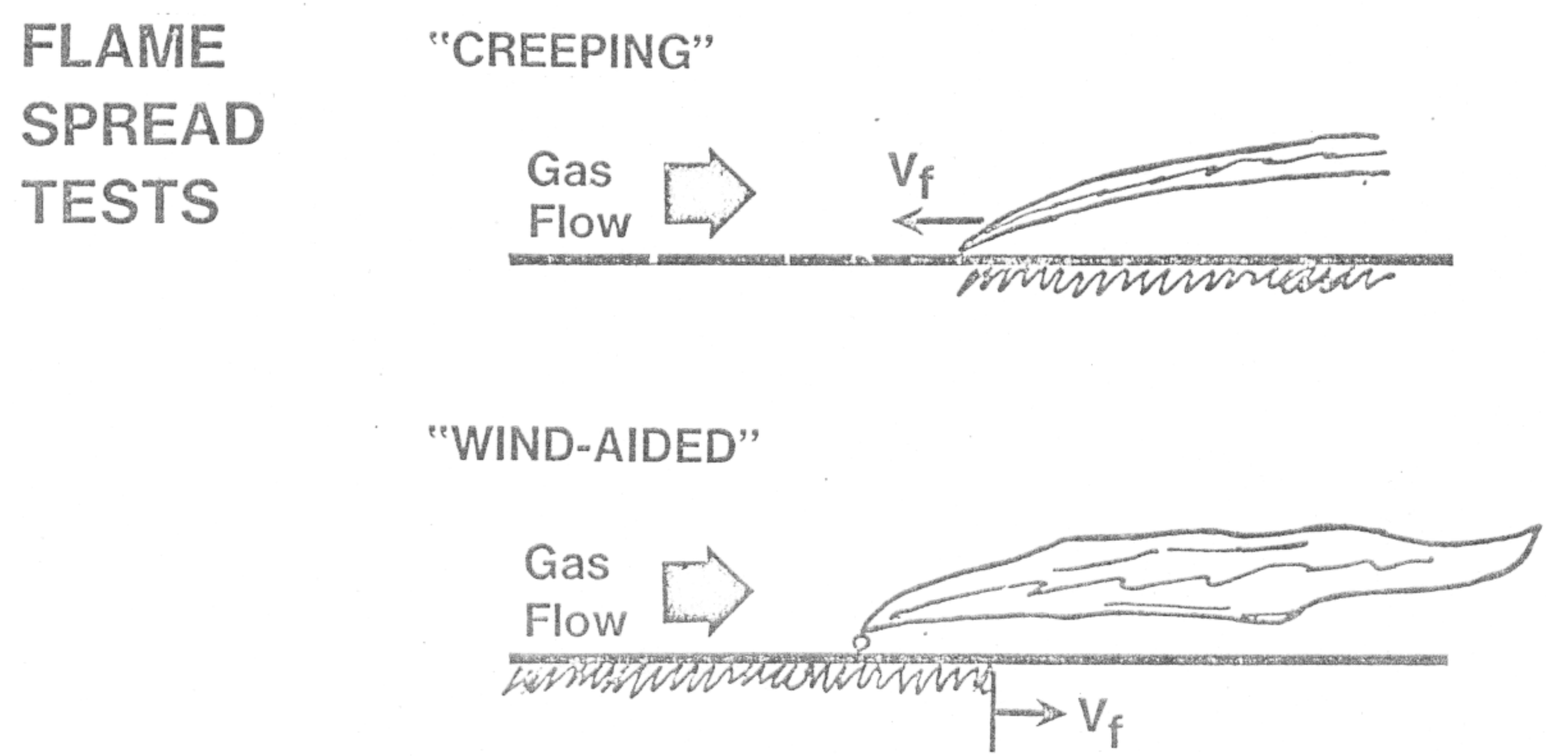

FLAME
SPREAD
TESTS
"CREEPING"
Gas
Flow
V_f
"WIND-AIDED"
Gas
Flow
V_f

Figure 7

In order to do this, we would like to explore materials that are distinctly different to cover all aspects of fire properties and flame spread. The list of materials is shown in Figure 8. We would choose at NBS three materials that tend to represent what people look at in the building side of fire spread. The FAA would select three materials that are more relevant to the aircraft fire problem. In this way, we would come up with a wide range of materials. Tentatively, we have selected wood, which may be a particle board or a fiberboard, and PMMA which is a favorite specimen for a lot of people. We would like to produce some data consistent with those from former studies. Low density polyurethane foam has the unique property of being very low density and has interesting flame spread characteristics. Panel material from an aircraft is a very complex multilayered material. Seat cushion and perhaps a carpet will also be the candidate materials. This is a tentative set of materials for flame spread studies.

The approach to the creeping spread problem will be outlined here (Figure 9). We have two test apparatuses. One would be operated to study flame spread downward. The other will be operated to study flame spread laterally. Both are radiant panel type apparatuses. A distributed amount of radiation shines on the sample such that the high radiation flux is at the end of the sample ignited; the low radiation end of it is the direction toward which the flame is spreading. By appropriate operation and analyses of the data, we hope to derive a relationship that would yield flame spread as a function of some material properties. The apparatus that we have been operating at the present time is in the lateral mode. The radiant panel is inclined. In that orientation, it shines radiation of about 5 watts per square centimeter at the igniting end to about a couple of tenths of a watt down at the far end. The sample is about 8" tall and about 2-1/2' in length in this lateral direction. The flame spread can be seen moving on this sample. This apparatus was designed by Alex Robertson of NBS. It has been tested up to now for possible use by the International

MATERIALS	WOOD
	PMMA
	PU FOAM
	PANEL
	SEAT CUSHION
	?

Figure 8

APPROACH: "CREEPING"

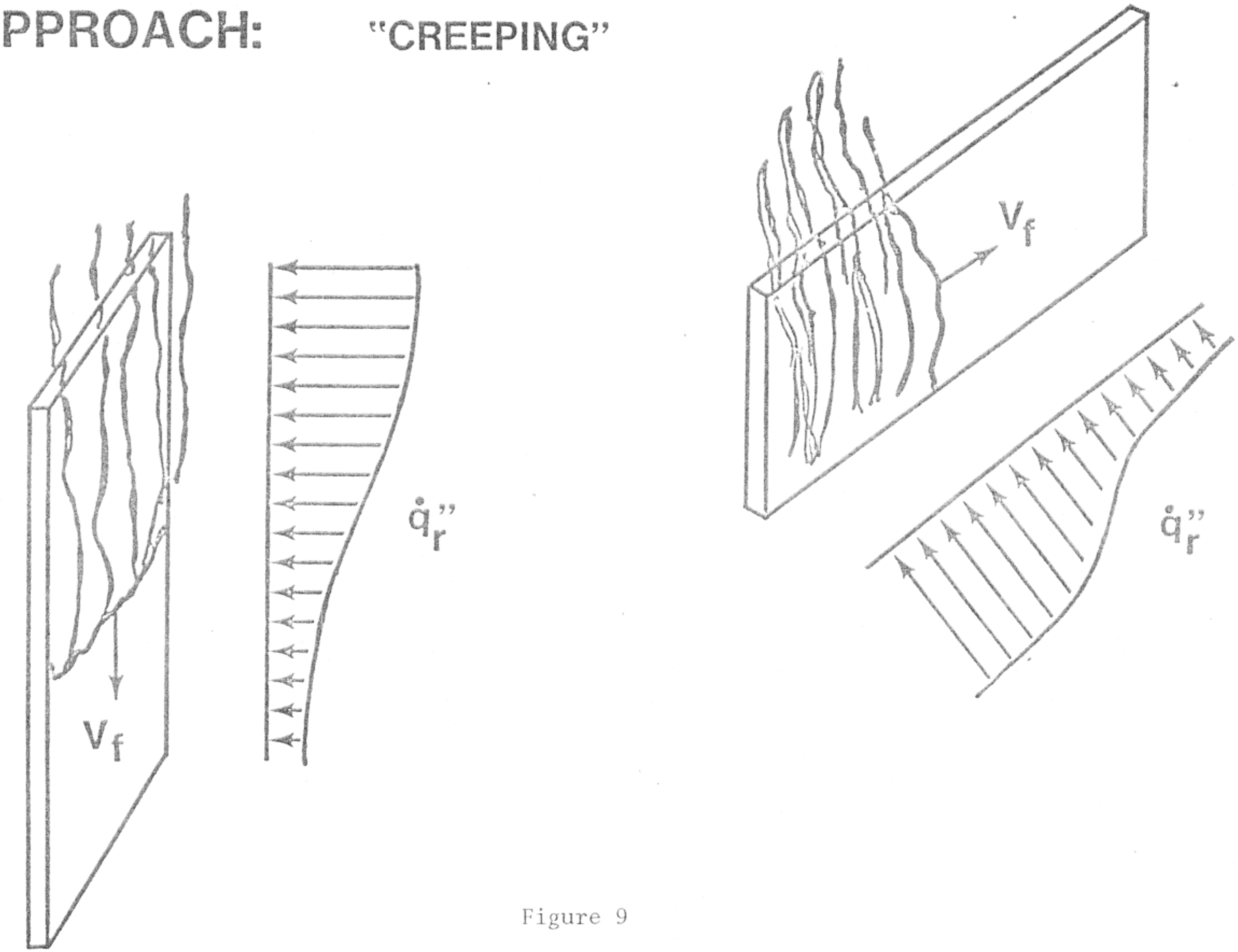


Figure 9

Standards Organization. They are considering such an apparatus, but they are not using it in the same way that we are planning for this work. Work with this apparatus has also been supported under Coast Guard sponsorship. We are preparing to initiate work here.

Questions of whether we need to extrapolate in some fashion to a turbulent flame are unclear to us right now. I think you will agree that if we are considering flame spread down at the leading edge, the flame is going to look the same whether it is 6' tall or 6" tall. Flame spread in the lateral direction may be another question. We can do such things as treat the boundary layer and make it turbulent and look for differences in the apparatus. Testing a larger sample with this apparatus is not too practical at the present time. This is a convenient way of getting a relationship by testing one material at one time. It will yield flame velocity as a function of flux or more important as a function of surface temperatures. This is what we are trying to achieve.

What we are seeking is, by using this apparatus and by using some specific way of operating it and interpreting the data, a relationship shown in Figure 10. The results of testing the material will be this parameter C_f and T_{ig}, so-called ignition temperature for this mode of flame spread. We have studied this and a paper on this subject that will be coming out in Fire and Materials. Some flame spread data are shown in Figures 11 and 12.

The approach for deriving wind-aided flame spread rate is outlined as follows. Flame spread upward or under a ceiling is very rapid. Current techniques that are used to judge the flammability of materials in that mode are not scientifically based. The challenge then is how can we make some measurements for materials to obtain an expression for this rapid spread upward or under ceiling. We don't believe that we can achieve that by making a measurement where we watch the flame moving. We can achieve that by making measurements

RESULT

$$V_f = C_f (T_{ig} - T_s)^{-2}$$

DETERMINE C_f, T_{ig}

Figure 10

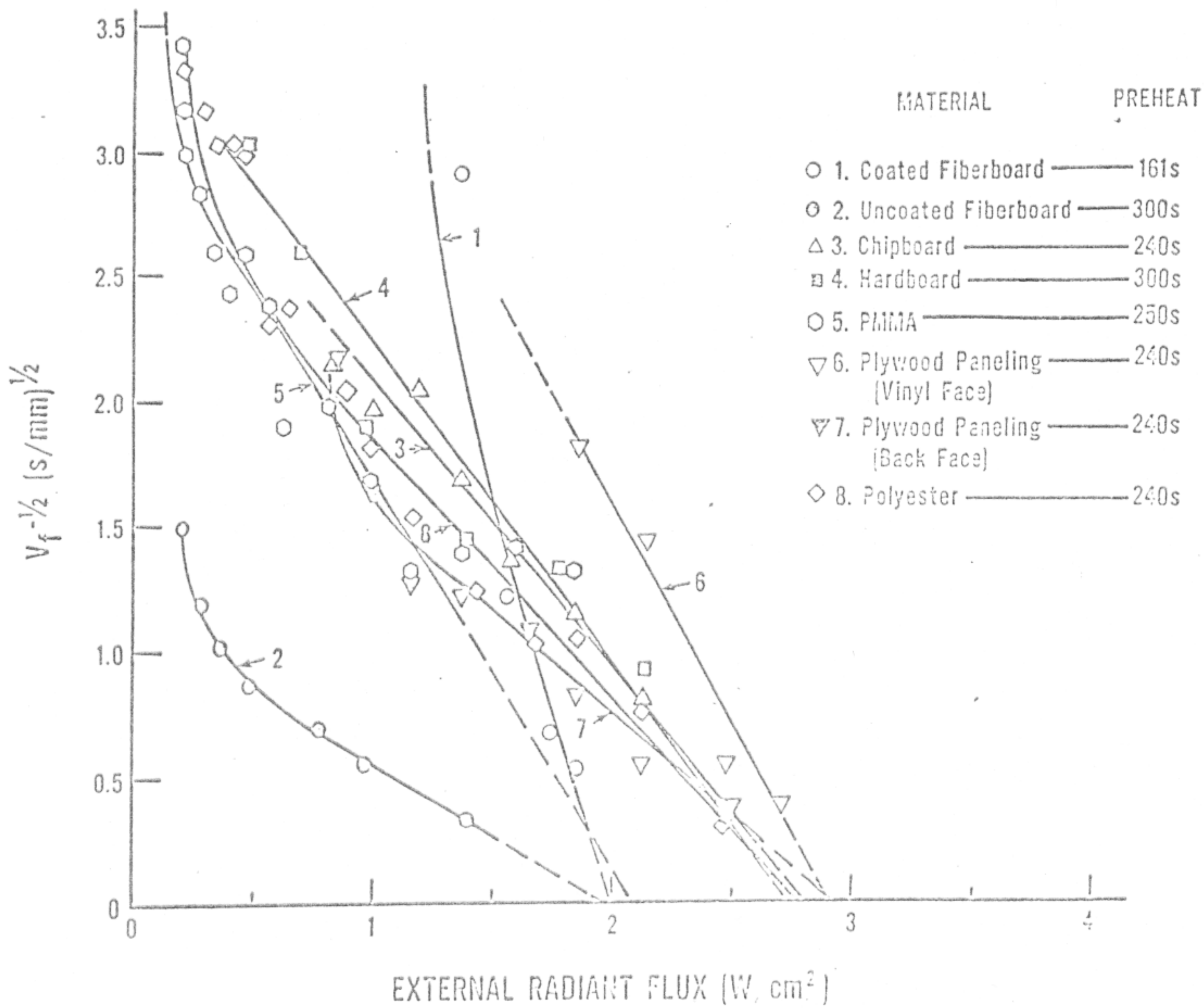

MATERIAL
PREHEAT
1. Coated Fiberboard 161s
2. Uncoated Fiberboard 300s
3. Chipboard 240s
4. Hardboard 300s
5. PMMA 250s
6. Plywood Paneling (Vinyl Face) 240s
7. Plywood Paneling (Back Face) 240s
8. Polyester 240s
$V_f^{-1/2}$ (s/mm)$^{1/2}$
EXTERNAL RADIANT FLUX (W/cm^2)

Figure 11

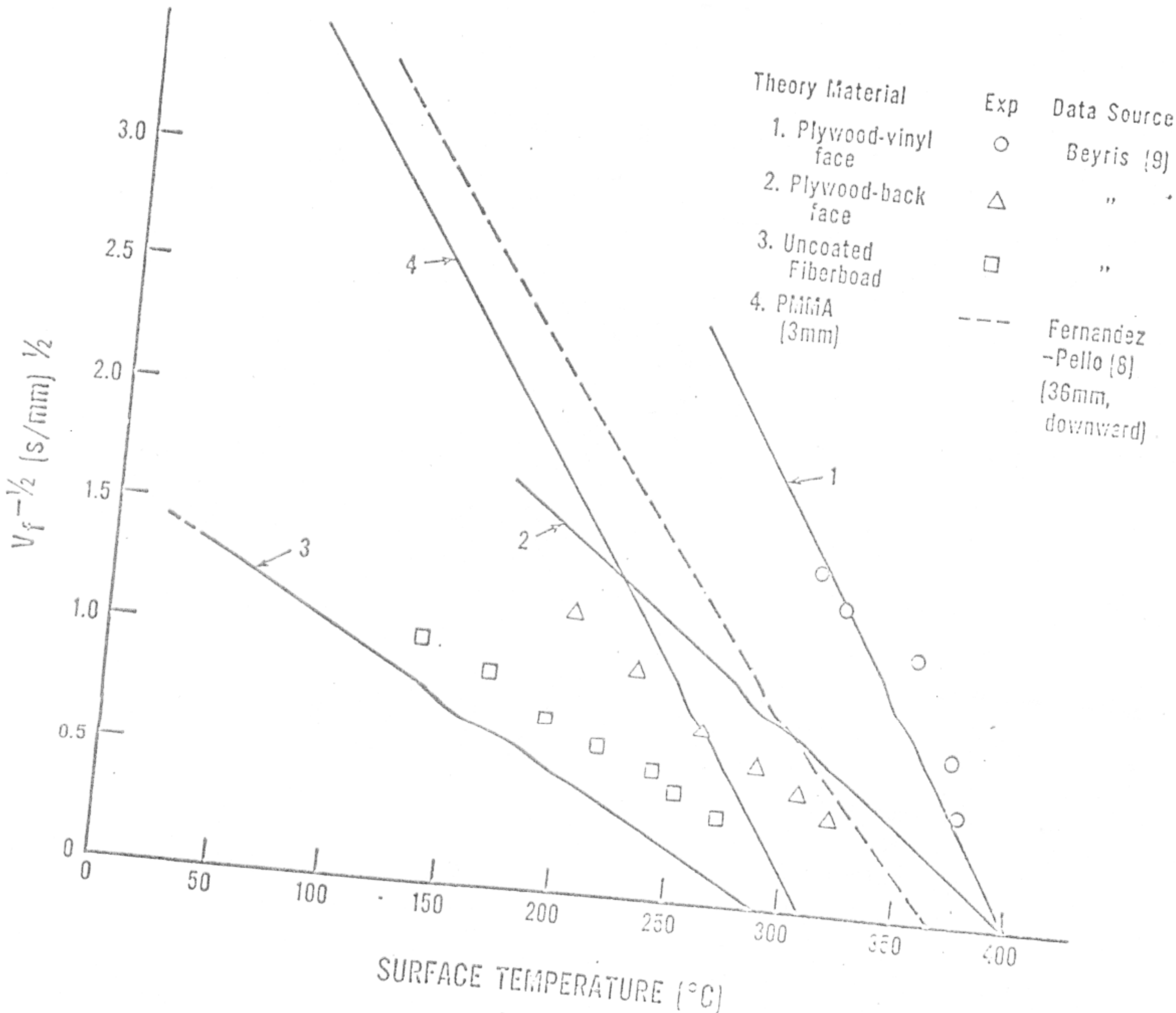

Theory Material
1. Plywood-vinyl face
2. Plywood-back face
3. Uncoated Fiberboad
4. PMMA (3mm)
Exp
Data Source
Beyris (9)
"
"
Fernandez -Pello (8) (36mm, downward)
1
2
3
4
$V_f^{-1/2}$ (s/mm) $^{1/2}$
0
0.5
1.0
1.5
2.0
2.5
3.0
0
50
100
150
200
250
300
350
400
SURFACE TEMPERATURE (°C)

Figure 12

for a fixed amount of material burning in a so-called steady fashion. The flame is not spreading, but it is burning and its burning rate may be changing with time. We need to expose it to radiation. The heat transfer characteristics of that flame above the burning part of the sample is important, shown in Figure 13. Eventually in the course of this work, we expect to develop an apparatus in which we have radiation shining on the material. At an inert place above the material, we will measure flame height and flame heat flux. We are not quite sure how to put all this together in a convenient test method package yet. This is the goal of this work.

In the meantime, before we build a test apparatus, we would look at measurement parameters (Figure 14) which are effective parameters for real materials--heat of vaporization, heat of reaction, effective air--fuel ratio, and maybe flame length and heat transfer. Bill Parker is working on some techniques to measure at least the first three quantities. We will measure them in an apparatus which is known as the NBS Rate of Heat Release Colormeter. It has a number of radiant panels and can be operated with a sample vertically or horizontally. We will look at the sample vertically. We will operate it in a mode in which we are using the oxygen consumption technique to measure energy release rate. The sample will be on a load cell so we will measure the weight loss continuously. We will measure the energy release rate by oxygen consumption. From that, we hope to be able to deduce these properties.

The analyses on the test data are shown in Figure 15. What we seek is to look at the effect of heat flux. We need to couple into any flame spread results the effect of time, Obviously, a thick material will burn a longer time than a thin material and these differences have to be accounted for ultimately. Hopefully, we can develop a flame spread relationship that will functionally be written down as opposed to just symbolically written down. We don't feel that we at NBS have the ability to generate all of this work and we

APPROACH: "WIND-AIDED"

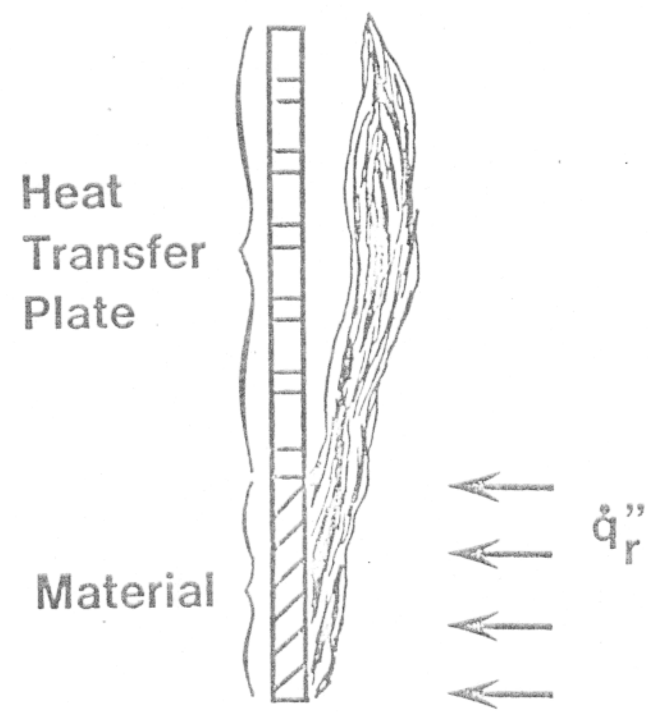


Figure 13

RESULT

- EFFECTIVE HEAT OF VAPORIZATION, L
- EFFECTIVE HEAT OF REACTION, ΔH
- EFFECTIVE AIR-FUEL RATIO, r
- FLAME LENGTH (l_f) AND HEAT TRANSFER, ($\dot{q}_f''$)

Figure 14

ANALYSIS

- EFFECT OF HEAT FLUX
- EFFECT OF TIME
- DEVELOP PREDICTIVE MODEL

  V_f = FUNCTION (L, $\triangle$H, r, $\mathring{q}''_f$, ...)

Figure 15

are getting some special analytical support that will assist us to develop a relationship. It may not be a unique situation, but it will be a step in the direction that the modelers need. On the other side of this, it will still be a way in which people can rank materials--even if they don't want to use the results of this equation. Hopefully, we will have done it with a better scientific basis than people had the resources to do 20 to 30 years ago when some of the current flame spread test methods, that are currently in existence, were developed.

QUESTION:

What is the C_f factor?

JAMES QUINTIERE:

The C_f factor has things like thermal conductivity, and heat transfer from the flame in it. What would be interesting is, if we develop some techniques for the upward flame spread and have some techniques for the downward flame spread, to see if some of these parameters are consistent between the two techniques. For example, will ignition temperature, if derived from downward flame spread by data analysis, be the same as ignition temperature for upward flame spread that we fit in the model like this? The same goes for these other things, the constants like thermal conductivity.

QUESTION:

When oxygen consumption technique is used, do you consider reactions as stoichiometric?

JAMES QUINTIERE:

The only thing you can say about oxygen consumption is that you could find a lot of examples where it looks like it was a sound technique. There may be some that chemists can turn up that don't work so well. It seems that from what is in the literature that you can't say the technique is going to work, but works for enough of the cases that it looks like it is OK.

QUESTION:

Is preheat level included in the test matrix?

JAMES QUINTIERE:

Yes, the work on the radiant panel test for the lateral spread--preheating is an important consideration in assuring that we made the proper analyses from the results. The reason is that the rate of flame spread is not a unique function of heat flux. It is only a unique function of the heat flux if the sample that you are heating has equilibrated as a result of that external radiant heat flux. That time for equilibration is the preheat time that we need. It is different for each material. It is something that we have to fix; otherwise to use such a technique as a test method, the operator of the test would always have to know what that preheat time is for the material.

QUESTION:

How do you measure heat of vaporization?

JAMES QUINTIERE:

To measure the heat of vaporization, it probably would be best to do it in some inert atmosphere. It is not practical though with the apparatus that we are considering to use right now. We don't know if we measure heat of vaporization with char oxidation whether that is the same one you would measure in an inert atmosphere or what the differences are.

UNDSAFE CODE APPLIED TO AIRCRAFT CABIN FIRE MODELING

K.T. YANG

Professor, Aerospace and Mechanical Engineering Department, University of Notre Dame. Ph.D. in Heat Transfer, Illinois Institute of Technology. Senior Technical Editor of The Journal of Heat Transfer.

UNDSAFE CODE APPLIED TO AIRCRAFT CABIN FIRE MODELING

K.T. Yang
University of Notre Dame

We have heard quite a bit about the relationship between room fire and aircraft cabin fire. It should be quite clear that despite the differences in the scenarios and also material characterizations, there may still be basic fire modeling techniques applicable to both situations. Our project at Notre Dame is also part of the FAA math modeling effort through the Interagency Agreement between FAA and NBS. The principal investigators and their associates are listed in Figure 1.

The objective of our project, shown in Figure 2, is to use a two-dimensional field model (UNDSAFE) that we have developed in the last several years and apply it to an aircraft cabin fire problem. The specific things we would like to look at are effects of fire source strength and location. There are several different places in a fuselage where a fire could be initiated. We would also like to take a look at the effect of doorway configuration. UNDSAFE is a two-dimensional model, The only change we can make is the height of a doorway opening. We would also like to take a look at the effects of seating, if seats would actually burn. Finally, we would like to take a look at the effect of vertical venting. We have done some preliminary work in this particular area. It is a very effective way of venting the combustion products out of a room. We would like to take a look at that for aircraft cabin fire venting problems.

UNDSAFE code was developed for room fires and we have since made some modifications on the basic code to simulate aircraft cabin fire. Major modifications and current progress are shown in Figure 3. The heat losses along the ceiling to the outside vent become important factors. On the basis of some very crude modeling, we can also take into account the additional heat release given off by

COMPUTER MODELING OF AIRCRAFT CABIN FIRE PHENOMENA

GRANT NB81NADA 2000
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS

TO

DEPARTMENT OF AEROSPACE AND MECHANICAL ENGINEERING
UNIVERSITY OF NOTRE DAME

INVESTIGATORS:	RESEARCH ASSOCIATE	GRADUATE ASSISTANTS
DR. JOHN R. LLOYD	K. SATOH	X. Y. ZHONG
DR. A. MURTY KANURY		H. S. KOU
DR. K. T. YANG		

Figure 1

OBJECTIVES: TWO-DIMENSIONAL FIELD MODEL (UNDSAFE) SIMULATION OF LONGITUDINAL SPREAD OF HOT GASES IN A FUSELAGE

EFFECTS OF FIRE SOURCE STRENGTH AND LOCATION

EFFECTS OF DOORWAY CONFIGURATION

EFFECTS OF SEATING AND BURNING SEATS

EFFECT OF VERTICAL VENTING

Figure 2

UNDSAFE MODIFICATION:

CEILING HEAT LOSS

SEATING

SEAT HEAT SOURCE

PASSIVE SMOKE CONCENTRATION

CURRENT PROGRESS

SIMULATION OF FULL-SCALE EXPERIMENT

SIMULATION OF CABINS WITH SEATS

Figure 3

the seat when seat surface temperature reaches a pre-set level. Finally, we include an additional equation for smoke concentration, assuming the heat source is also a smoke source. Smoke will be propagated throughout the cabin. Currently we are working on two separate problems. One is a simulation of a full-scale cabin fire experiment. The second one is a simulation of fire in a cabin with seats.

A decision was made last September in Dayton to use both a zone model by C. MacArthur and a field model by Notre Dame to simulate a full-scale fire experiment at NASA/Johnson Space Center. Test 3B, which was a fire inside a 737 fuselage with seats and two openings was chosen to be modeled (Figure 4). We are going to make a comparison at the 60-second point into the fire. During the test, data indicated that fuel weight loss rate was almost constant, as shown in Figure 5. This simplifies the situation, even though the actual code can actually incorporate that into the computation.

The second one takes into consideration the heat losses through the ceiling. There is a heat transfer coefficient for the fuselage. Obviously, it takes some time before the heat loss effect becomes important. At the 60-second point, we did not feel that the problem was so serious that you had to include heat loss through a ceiling. The dimensions of a 737 test article and instrument locations are shown in Figures 6, 7, 8, and 9.

Figure 6 shows the fuselage configurations of a 737. It is almost symmetrical and looks like a two-dimensional configuration, other than the fact that two doors are in the aft. In order to use a two-dimensional code, we have to make some modification to accomodate that.

When you talk about a simulation of this type, you really have to stop and think about what you are doing. Because of the many parameters in this model and also because we use a two-dimensional

SIMULATION OF FULL-SCALE EXPERIMENT

SOURCE OF EXPERIMENT

NASA/FAA/UDRI CABIN MOCK-UP FIRE TEST (B-737)

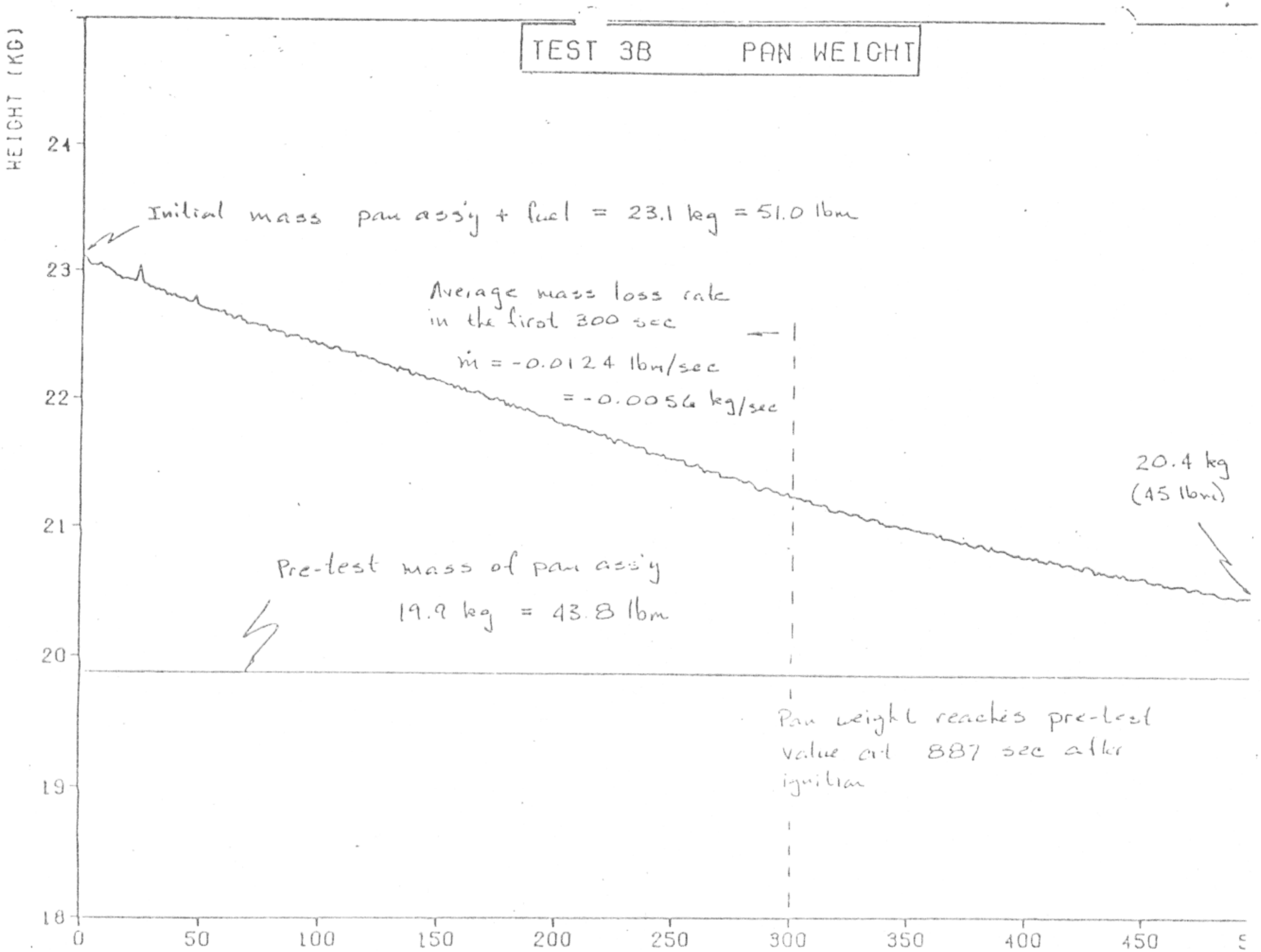
TEST 3B

COMPARISON AT 60 SECONDS

CONSTANT FUEL WEIGHT LOSS

NEGLIGIBLE CEILING HEAT LOSS

Figure 4



TEST 3B PAN WEIGHT
WEIGHT (KG)
24
23
22
21
20
19
18
0
50
100
150
200
250
300
350
400
450
Initial mass pan ass'y + fuel = 23.1 kg = 51.0 lbm
Average mass loss rate in the first 300 sec
$\dot{m}$ = -0.0124 lbm/sec
= -0.0056 kg/sec
20.4 kg (45 lbm)
Pre-test mass of pan ass'y
19.9 kg = 43.8 lbm
Pan weight reaches pre-test value at 887 sec after ignition

Figure 5

737 CABIN MOCK-UP DIMENSIONS — TEST 3B

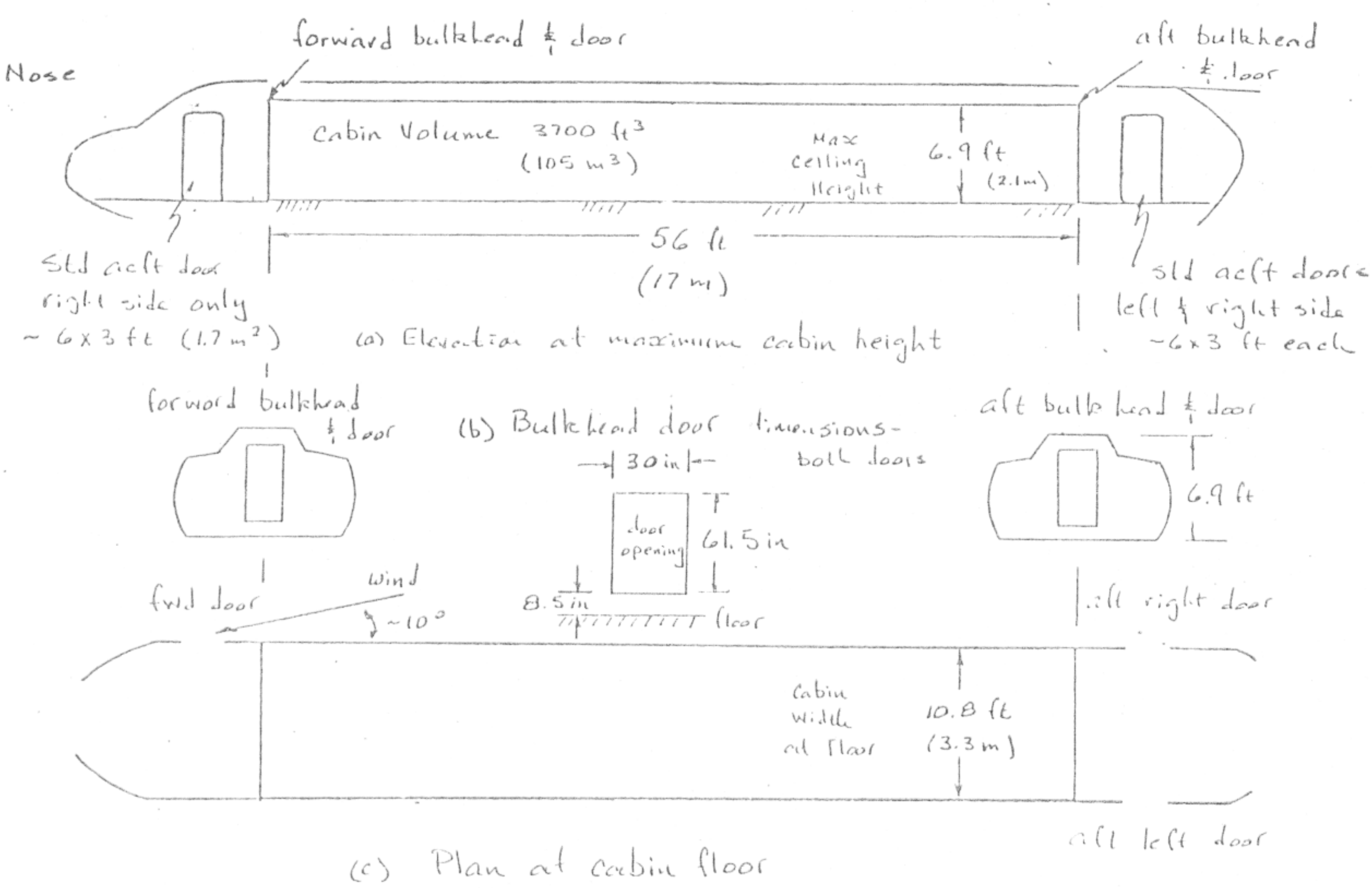
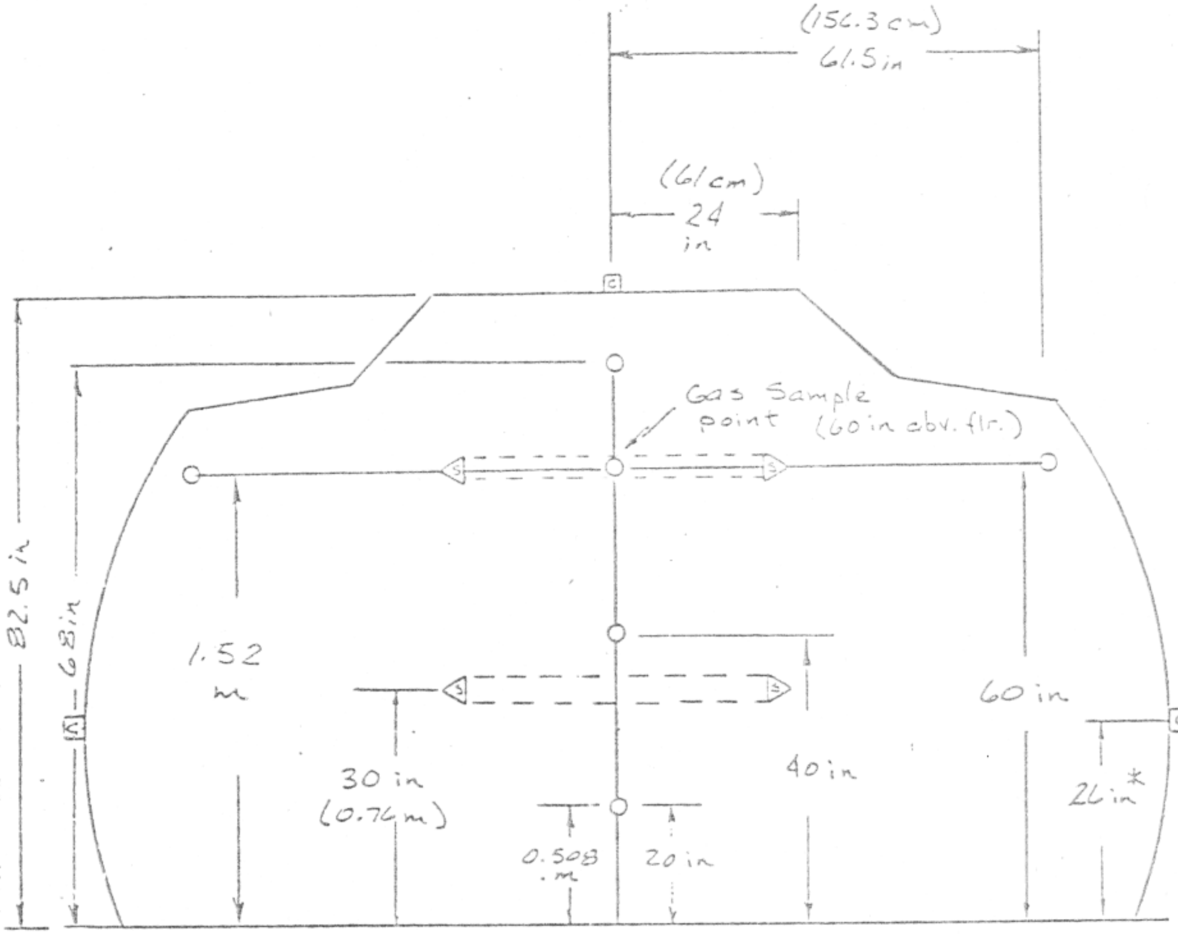


Figure 6



○ - Thermocouples (.26 AWG chromel/Alumel bare welded junction, unshielded)

- Smoke Meters: 1 meter light path centered on cabin ℄ and ⊥ to left-right symmetry plane

- Calorimeters: Medtherm Corp 64 Series, water cooled total flux transducers

(* Elevation of sidewall calorimeters uncertain at this time, 26 in is best guess)

Figure 7

FUEL PAN LOCATION AND DETAILS — TEST 3B

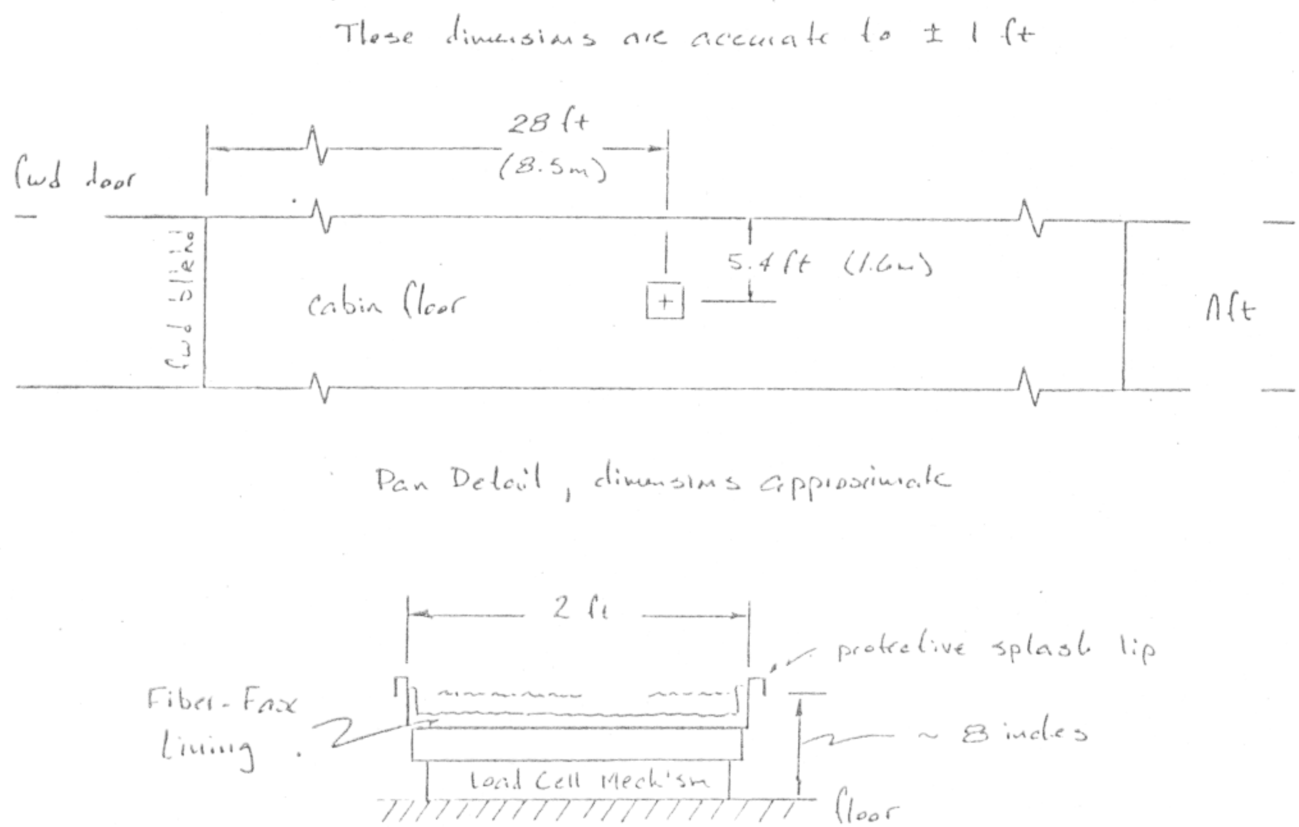


Figure 8

FAA/NASA/UDRI 737 CABIN FIRE TEST

INSTRUMENT POSITIONS 56 FT FUSELAGE SECTION

T/C tree's not to scale - see next page.

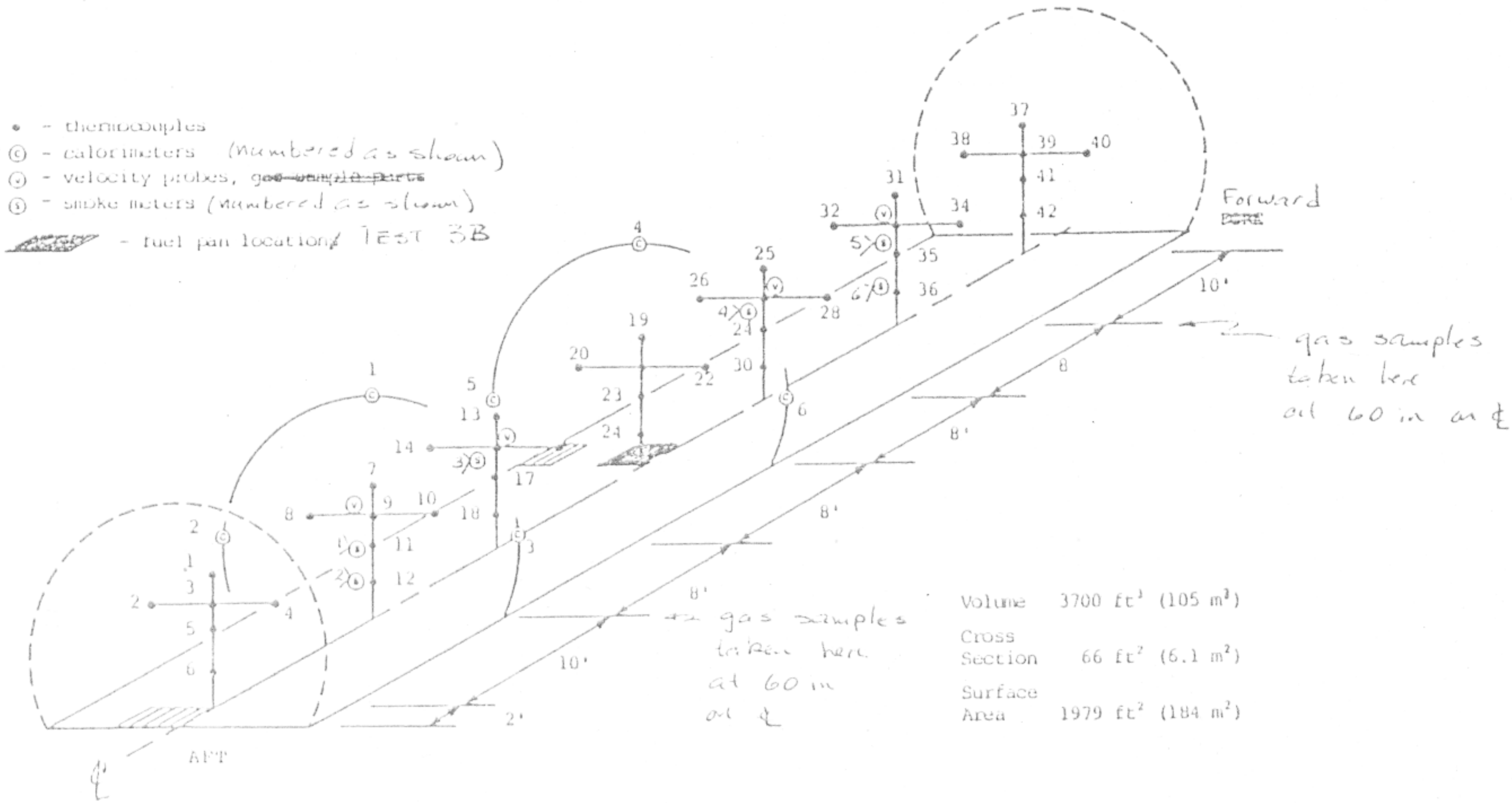


Figure 9

code, only the two-dimensional equivalents of three-dimensional phenomena are simulated. We hope that we will be able to do this because the basic configuration is very close to two-dimensional, but there are places in the geometry where three-dimensional effects become quite important. We vary these parameters to get a reasonable agreement with the experimental data. The basic equivalents are heat load, fire shape, and doorway heights, shown in Figure 10. We do have a loose constant in a turbulence model which would enable us to employ different mixing levels to see how that would affect the result.

We do not anticipate that a perfect agreement between simulation and experimental data will be obtained. Besides, there were also uncertainties in experimental measurements, as indicated in Figure 11. The numerical values of two-dimensional equivalent quantities for heat loss, door height and fire shape are listed in Figure 12. The two-dimensional equivalent heat load feels hotter (349 KW) than the actual experimental value (235 KW). The door height is 1.05 meters compared to 1.56 meters. This is understandable because in a three-dimensional case, an additional chocking effect occurring at the doorway cannot be modeled by a two-dimensional code. We have a 4 x 4 cell of a fire source at the bottom and 2 x 8 cells on the top to generate heat. This arrangement will give a ratio of height and base of a fire to obtain a desirable fire shape.

Figure 13 shows a comparison of calculations with experimental data. The top portion of the simulation is quite good throughout the length of the fuselage.

Figure 14 gives the appearance that width is very large compared to fuselage length. This is actually not the case. We plotted it this way simply because this is the way that data were obtained. The width is small compared to the length of a fuselage. Figure 15 shows calculated temperatures at four different heights for a heat source

RATIONALE FOR THE SIMULATION STUDY

TWO-DIMENSIONAL SIMULATION MODEL

2D vs. 3D

DOORWAY HEIGHT

DETERMINATION OF 2-D EQUIVALENT OF

HEAT LOAD

FIRE SHAPE

DOORWAY HEIGHT

CONSTANT IN TURBULENCE MODEL

Figure 10

FULL-SCALE EXPERIMENT SIMULATION EXPECTATIONS

UNCERTAINTIES IN EXPERIMENTAL MEASUREMENTS

TEMPERATURE MEASUREMENTS CLOSE TO FIRE

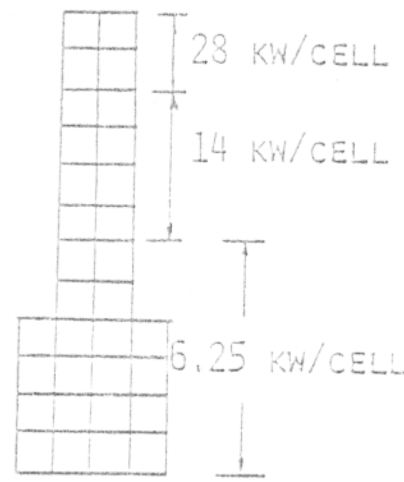
EXTENT OF FIRE PLUME

NO ATTEMPT TO OBTAIN PERFECT AGREEMENT

Figure 11

DETERMINATION OF 2-D EQUIVALENCE

	EXPERIMENTS	2-D EQUIVALENT
HEAT LOAD	235 KW	349 KW
DOOR HEIGHT	1.56 M	1.05 M
FIRE SHAPE	-	



CONSTANT IN TURBULENCE MODEL		0.2

Figure 12

2. COMPARISON OF 6XPT WITH UNDSAFE PREDICTION
(EXPERIMENT 235 KW ; PREDICTION 349 KW)

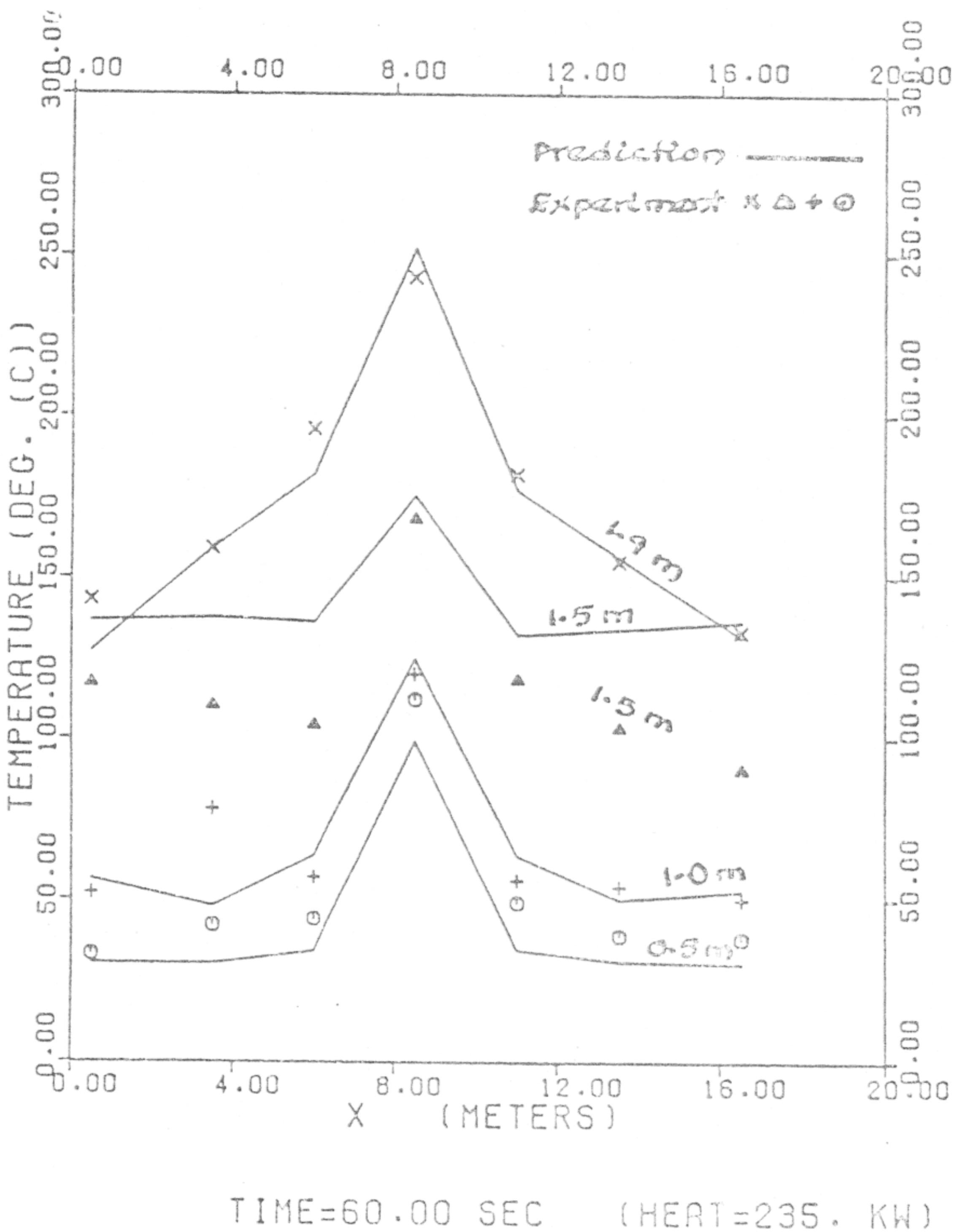
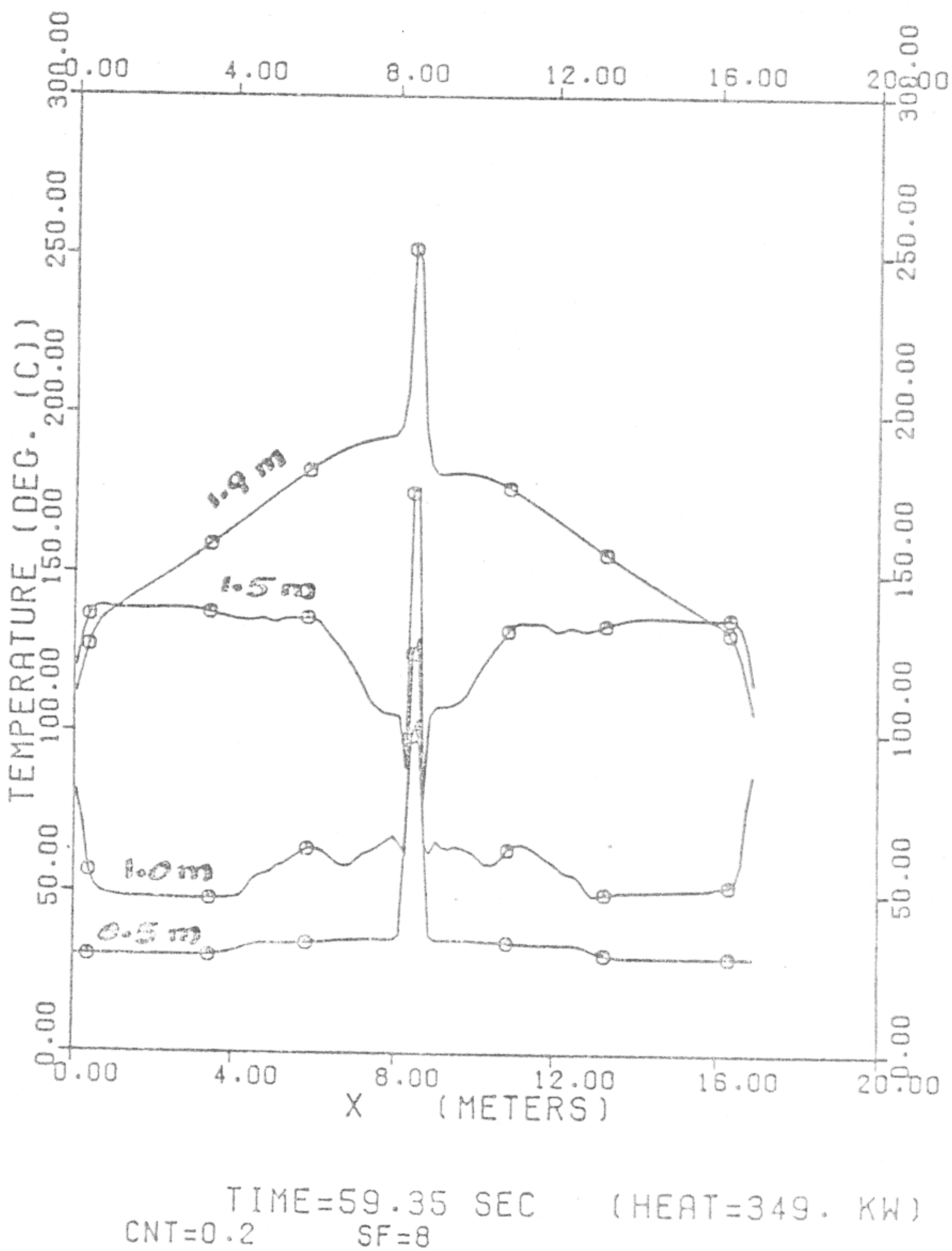
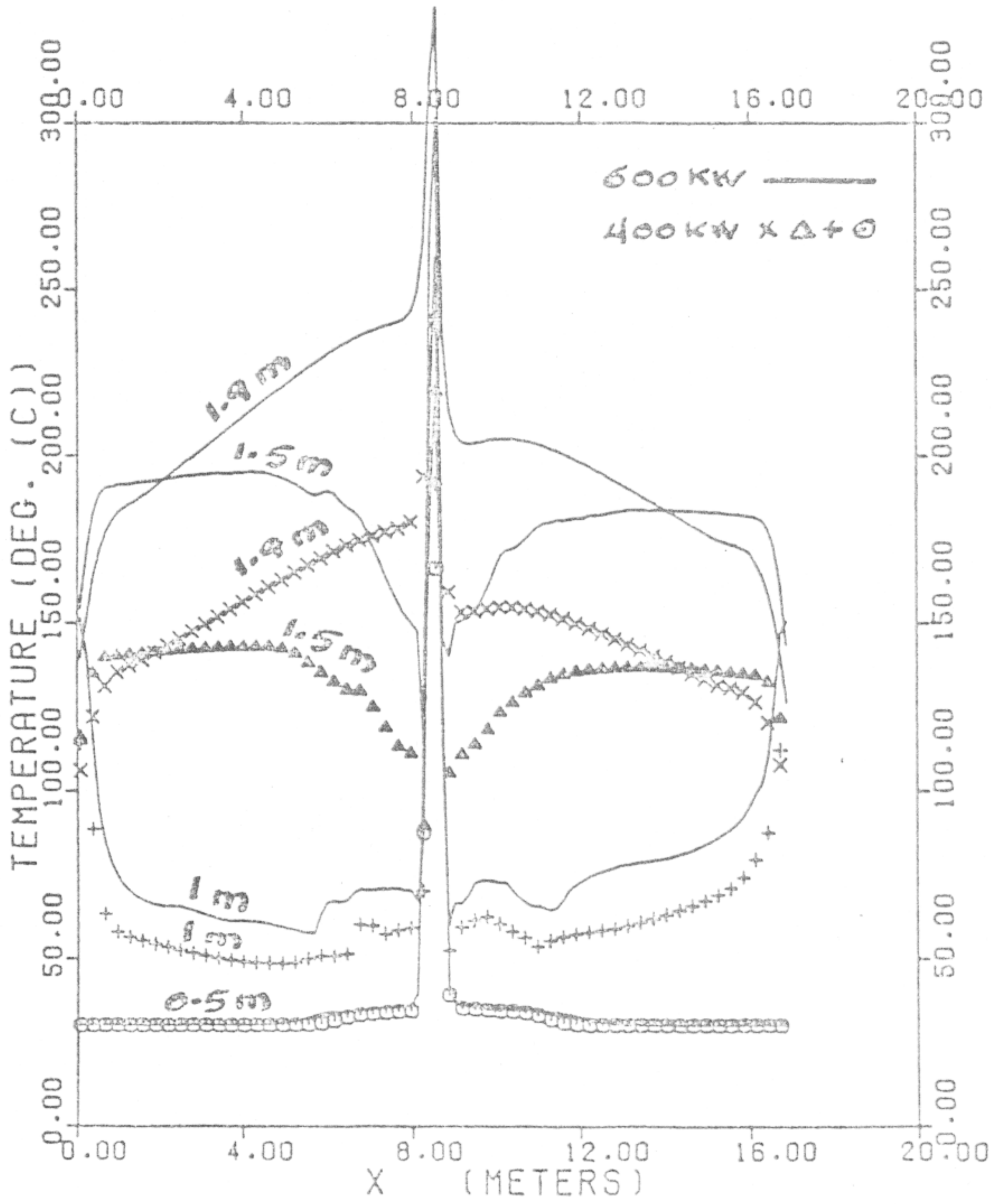


Figure 13



0.00
4.00
8.00
12.00
16.00
20.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
TEMPERATURE (DEG. (C))
1.9 m
1.5 m
1.0 m
0.5 m
X (METERS)
TIME=59.35 SEC (HEAT=349. KW)
CNT=0.2 SF=8

Figure 14



TIME=59.8 SEC (HEAT=400 & 600 KW)
CNT=0.2 SF=0

Figure 15

of 349 KW. The effects of heat input rates (400 KW and 600 KW) on temperature profiles are shown in Figure 16. The effect of energy distribution is shown in Figure 17.

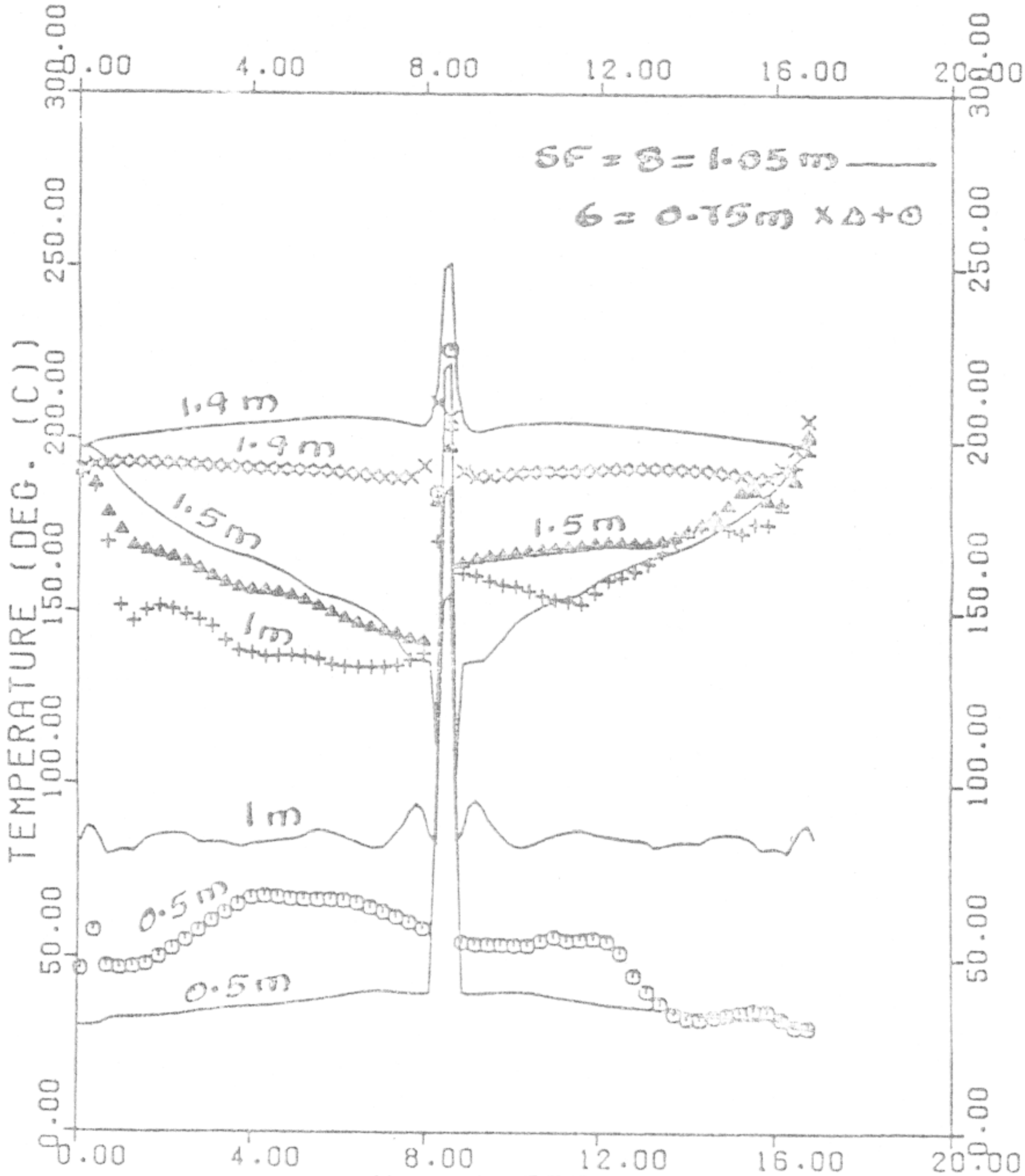
The next ten figures have to do with the second exercise that we have gone through. We are going to simulate fires in a wide-body cabin with seats. The geometrical arrangement of seating is modeled by a two-dimensional equivalent. In this model, six seats are set along the same line with a heat source taking place between the third and fourth seats from the left. Figure 18 shows the temperature profiles in a cabin without seats. The two-zone effect is clearly demonstrated.

Two distinct seat configurations were used in the model. The first seat configuration has a solid seat bottom, and the second seat configuration has an opening under a seat cushion.

The total input for this particular computation was 700 KW and also when temperatures exceed about 1000°F, each cell will generate an additional 5 KW. A sequence of fire spread from an early fire at 0.96 second to a fully developed fire at 32.15 seconds is shown in Figures 19 to 27.

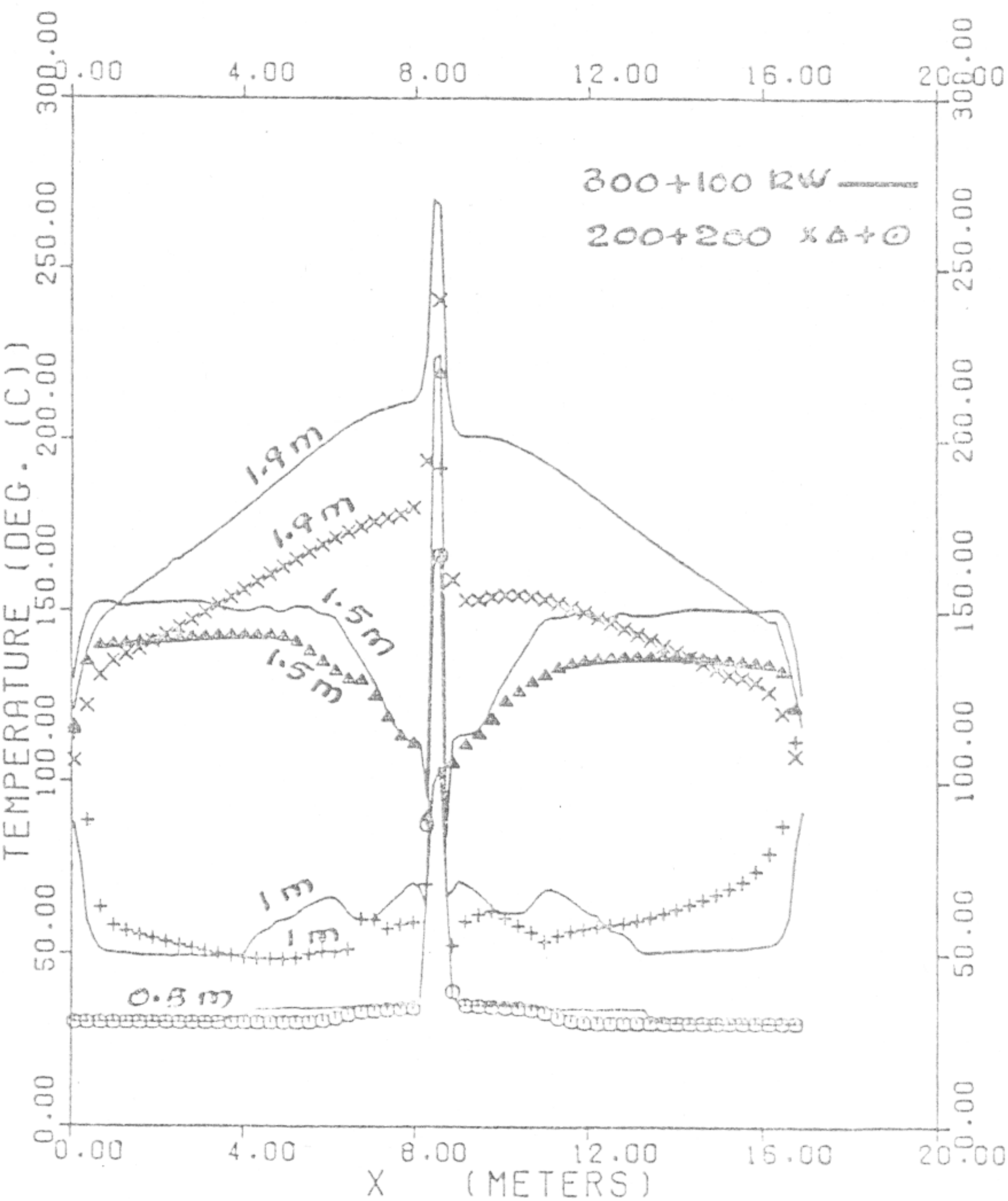
A fire was first confined in between the seats (Figures 19 and 20). Hot gases rising from the fire reach the ceiling and start to move along the ceiling (Figures 21 to 25). At 5.76 seconds into the fire, the hot gases reach the two openings at both ends. Due to different soffit heights, the flow patterns are different (Figure 26). A two layer effect is clearly indicated. At 32.15 seconds, the fire becomes fully developed. The neighboring seats are heated and the hot gases at the top become thicker and descend down to the lower layer (Figure 27). UNDSAFE code also calculated velocity vectors and species concentrations inside an aircraft cabin. The gas recirculations near the openings are clearly demonstrated by the changing of vector directions at the corners. This effect has not been simulated by a zone model calculation.

5. EFFECT OF SOFFIT HEIGHT SF



TIME=59.7 SEC (HEAT=400 KW)
CNT=0.08 SF= 6 & 8

Figure 16



TIME=59.8 SEC (HEAT=400 KW)
CNT=0.2 SF=8

Figure 17

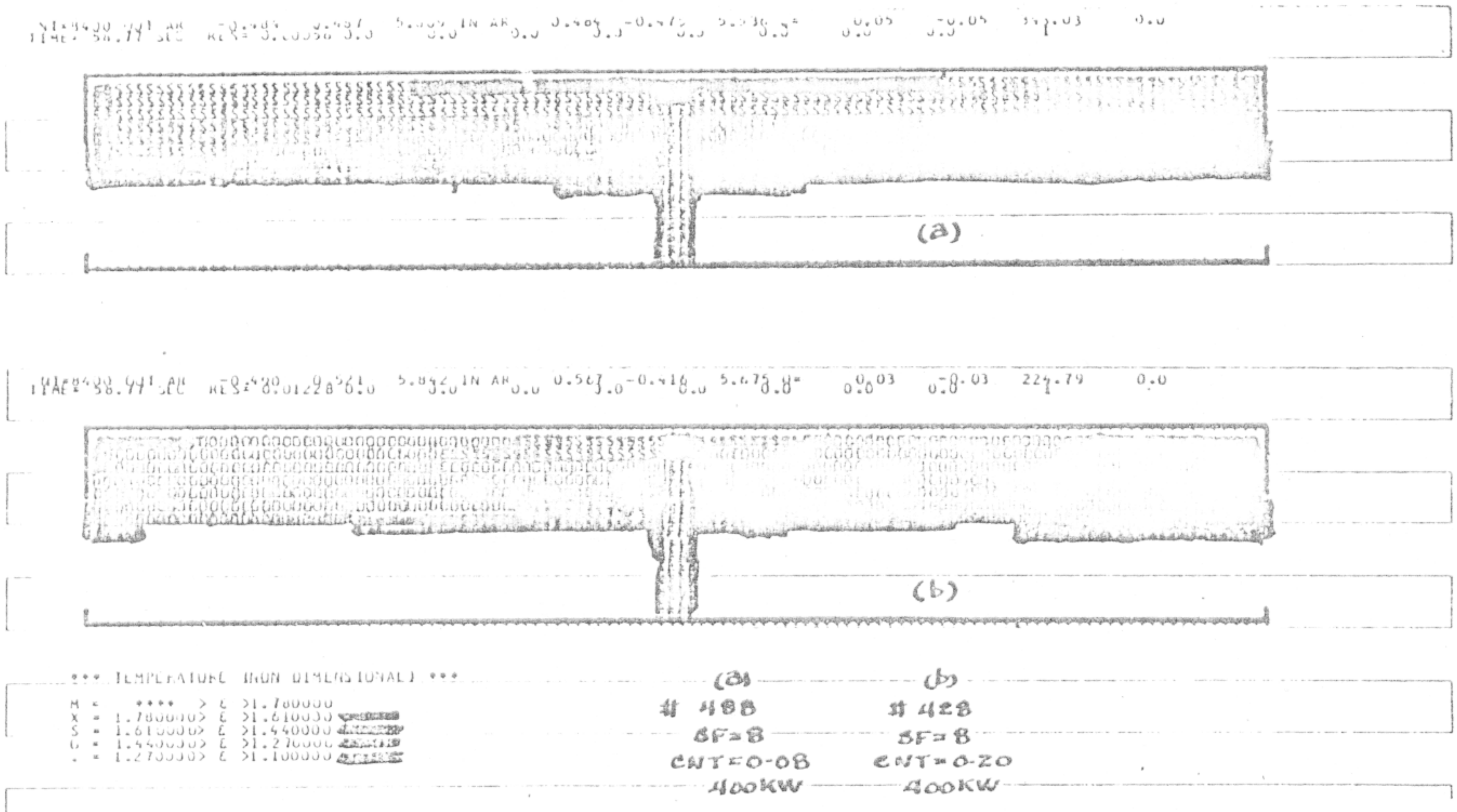

(a)
(b)
*** TEMPERATURE (NON DIMENSIONAL) ***
M = **** > E >1.780000
X = 1.780000> E >1.610000
S = 1.610000> E >1.440000
O = 1.440000> E >1.270000
. = 1.270000> E >1.100000
(a)
# 488
SF=8
CNT=0-08
400KW
(b)
# 428
SF=8
CNT=0-20
400KW

Figure 18

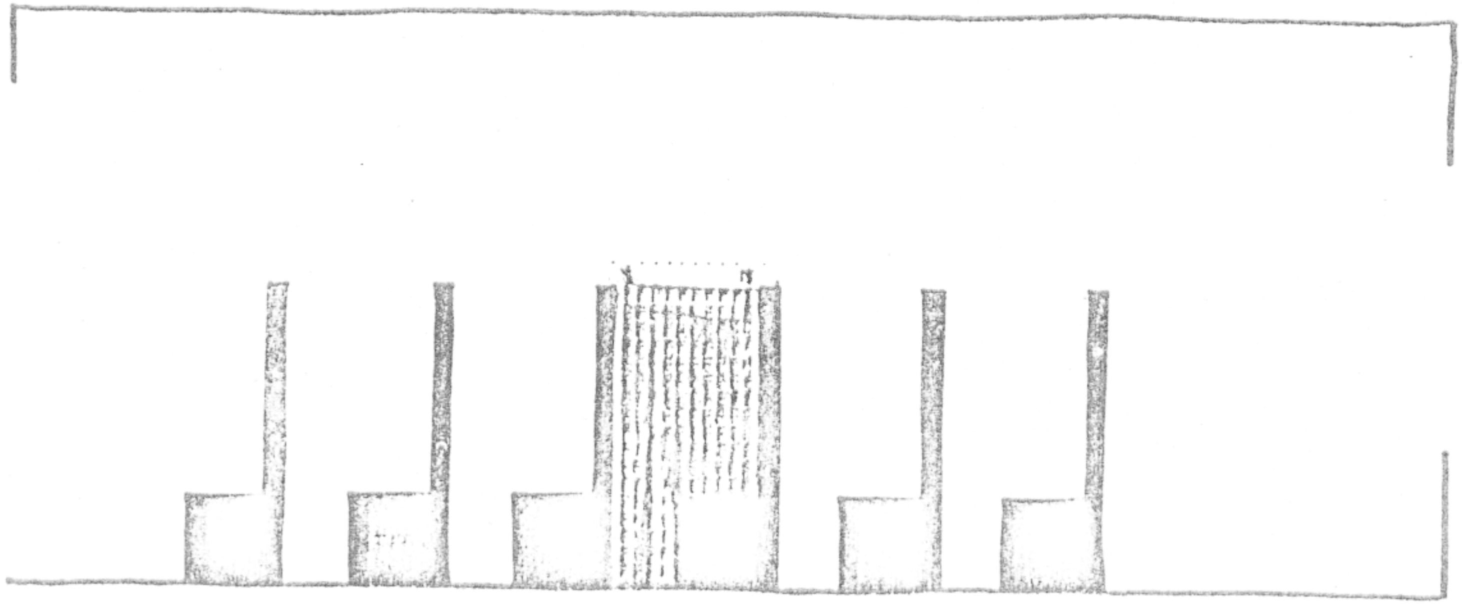
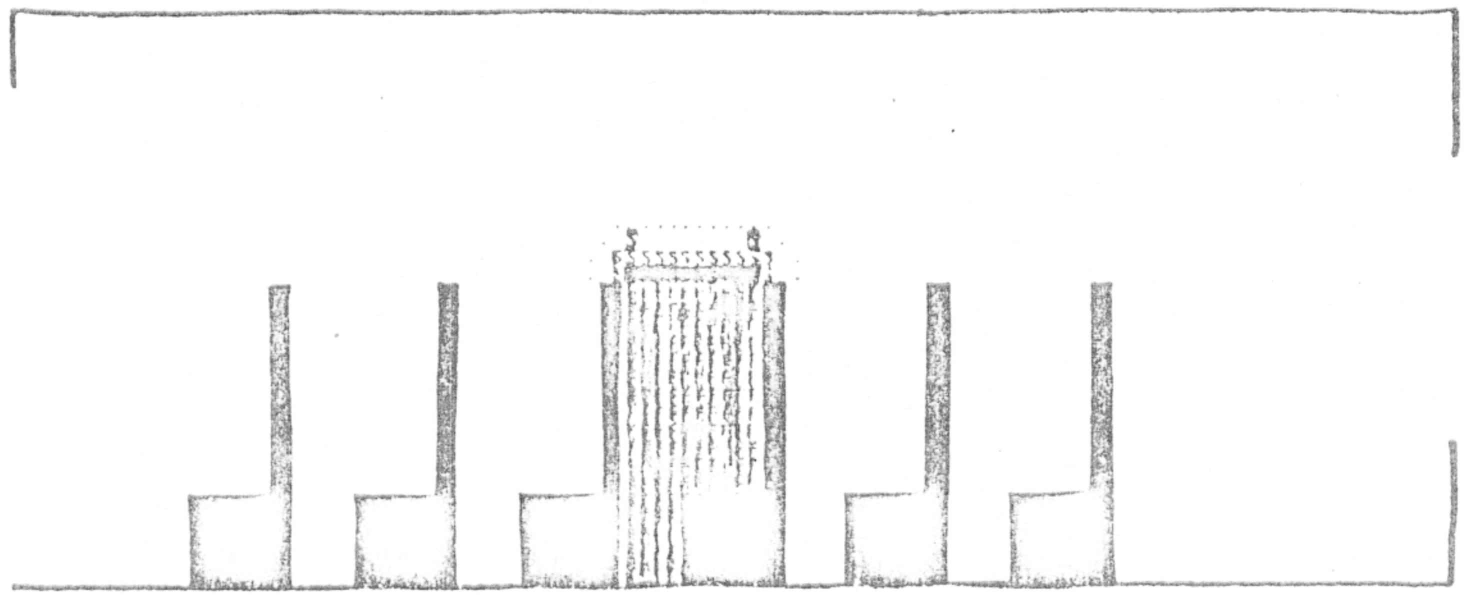
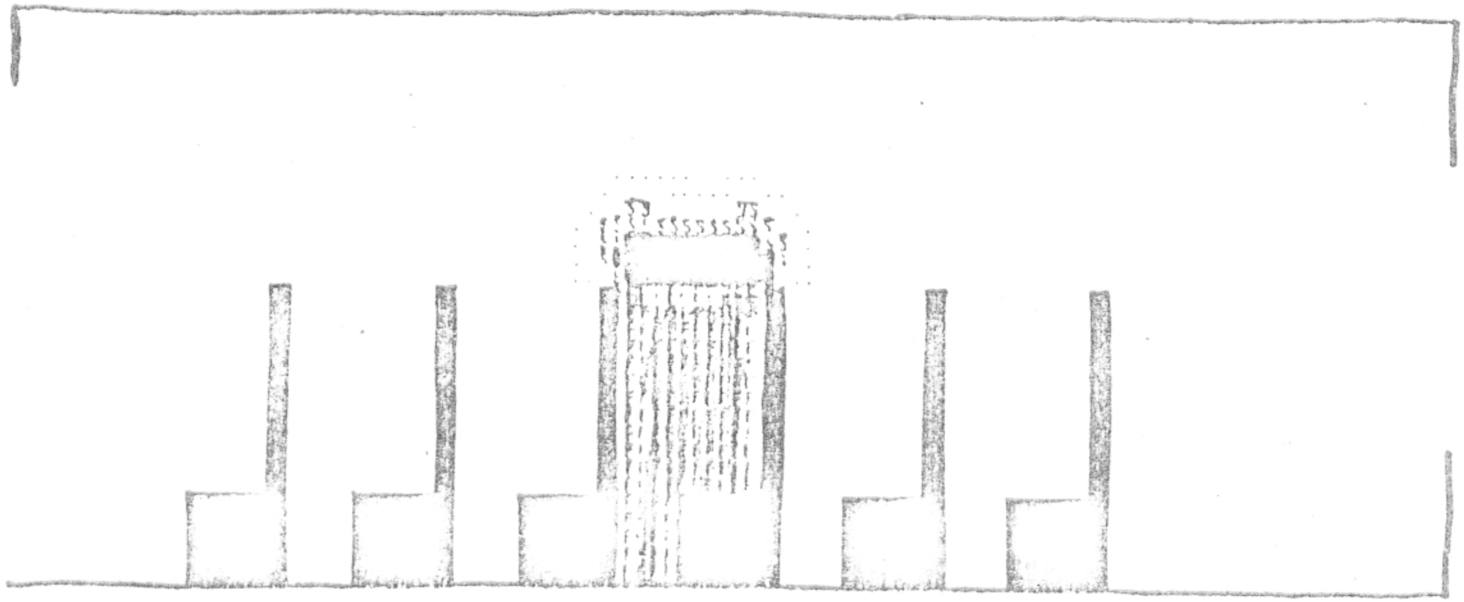


Figure 19



TIME = 1.44 SEC

Figure 20



TIME = 1.92 SEC

Figure 21

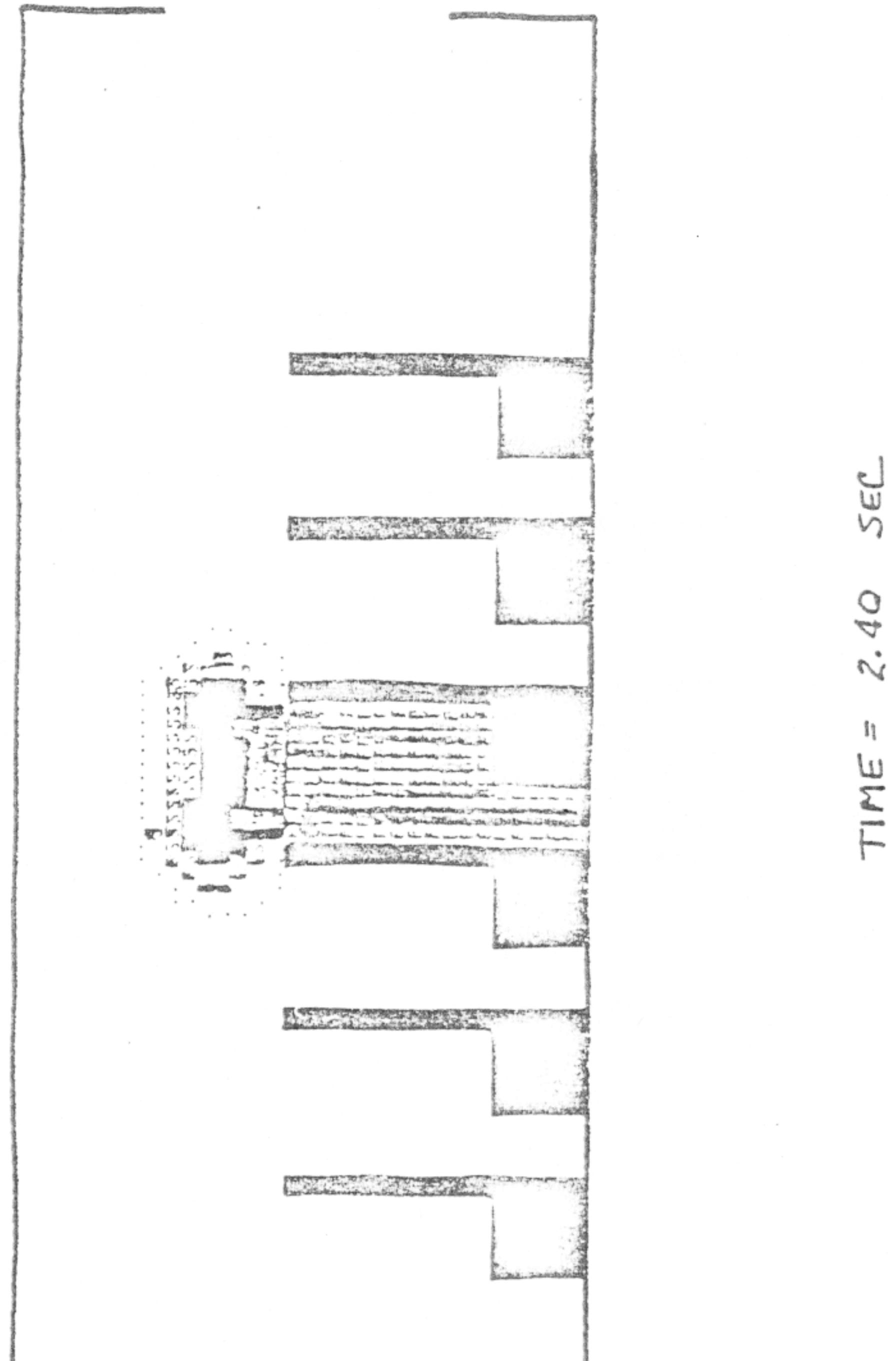
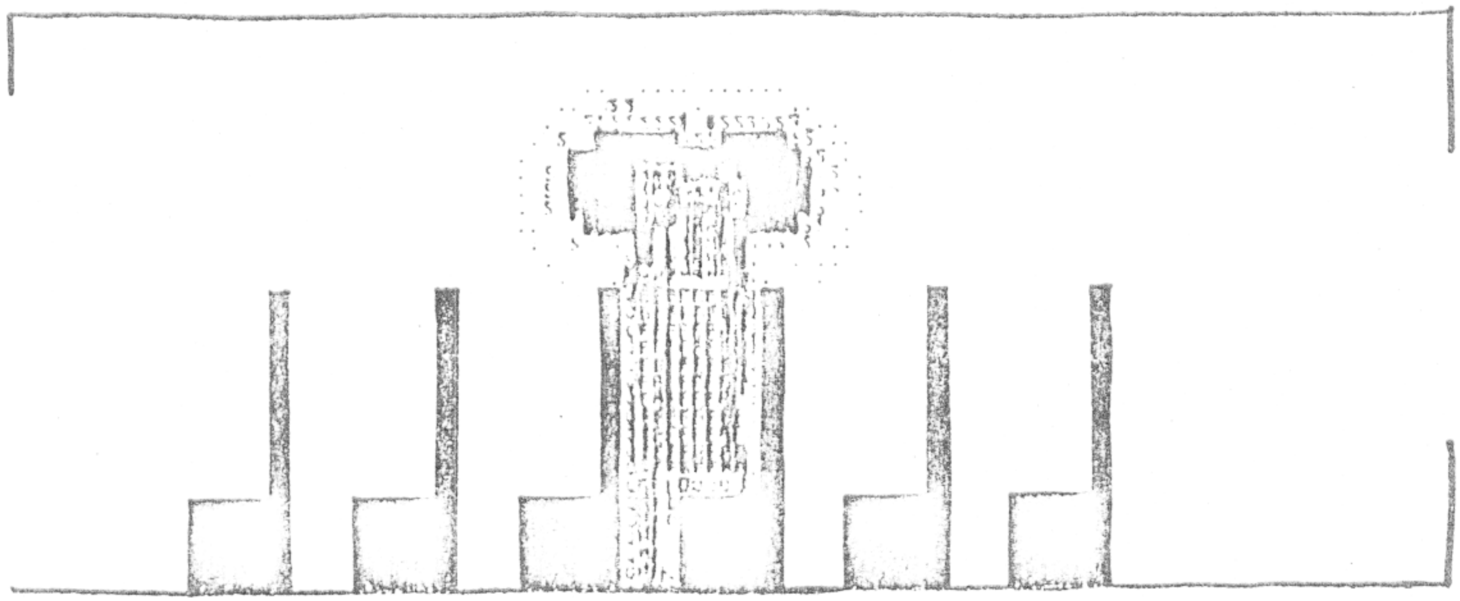
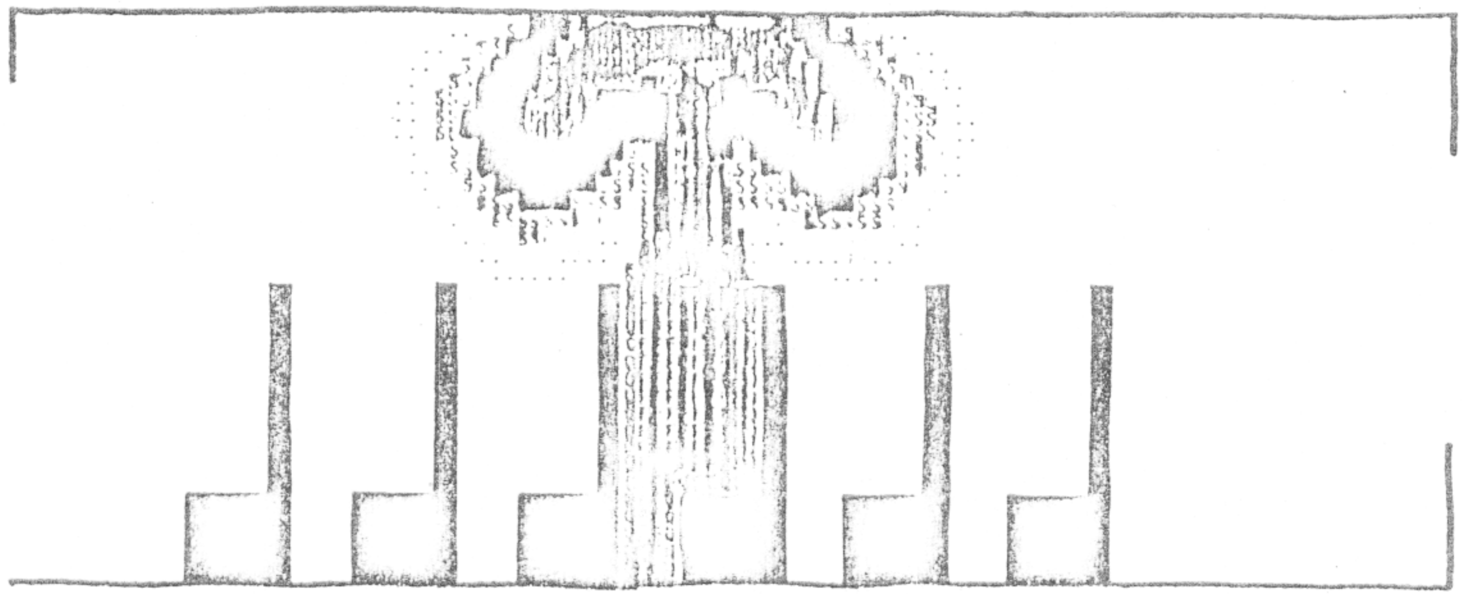


Figure 22



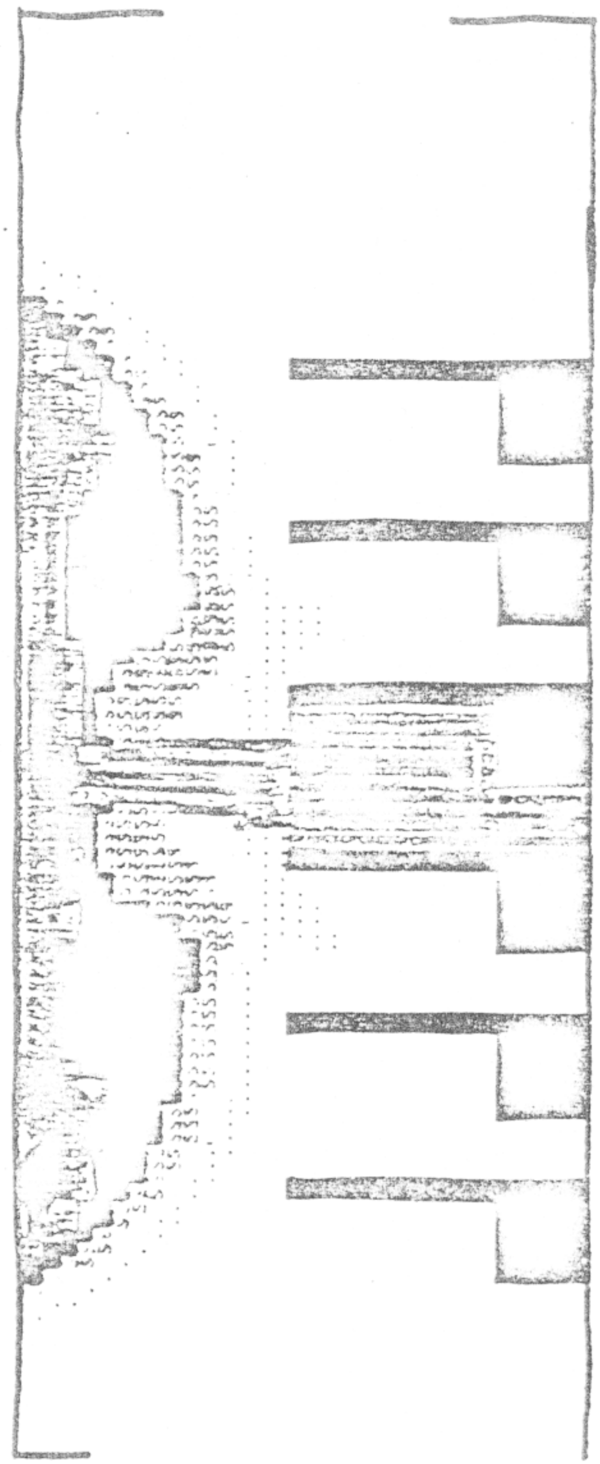
TIME = 2.88 SEC

Figure 23



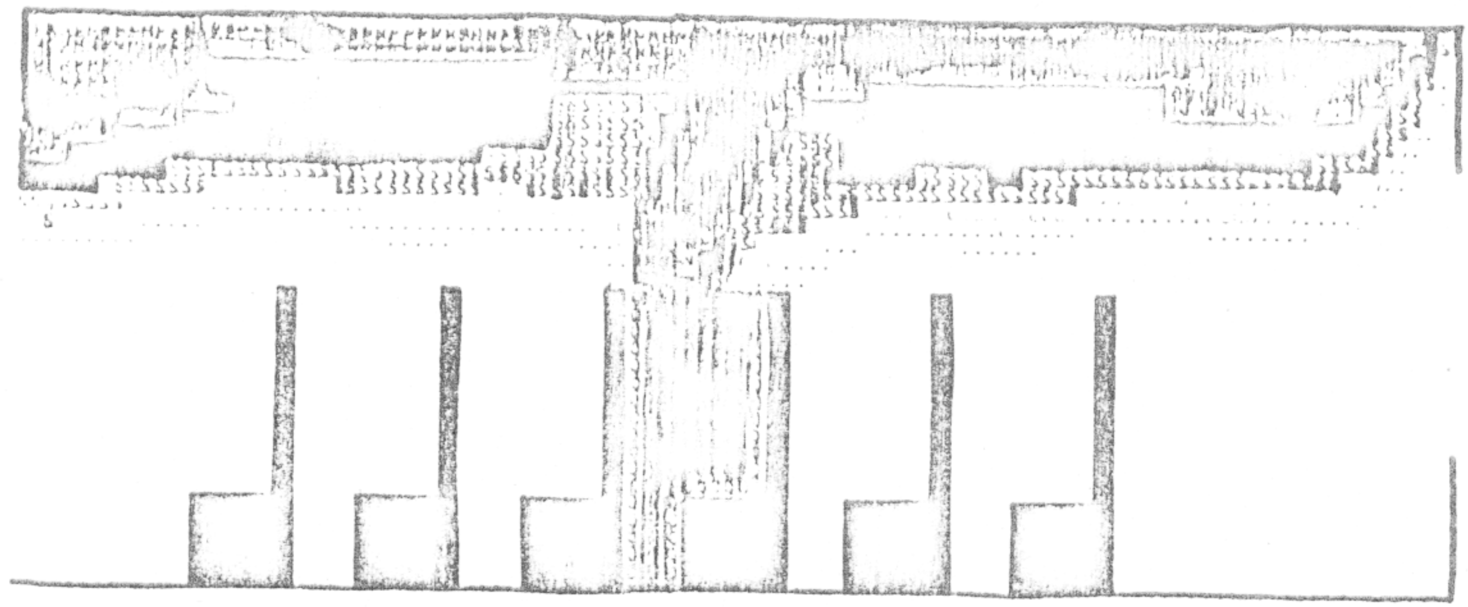
TIME = 3.84 SEC

Figure 24



TIME = 4.80 SEC

Figure 25



TIME = 5.76 SEC

Figure 26

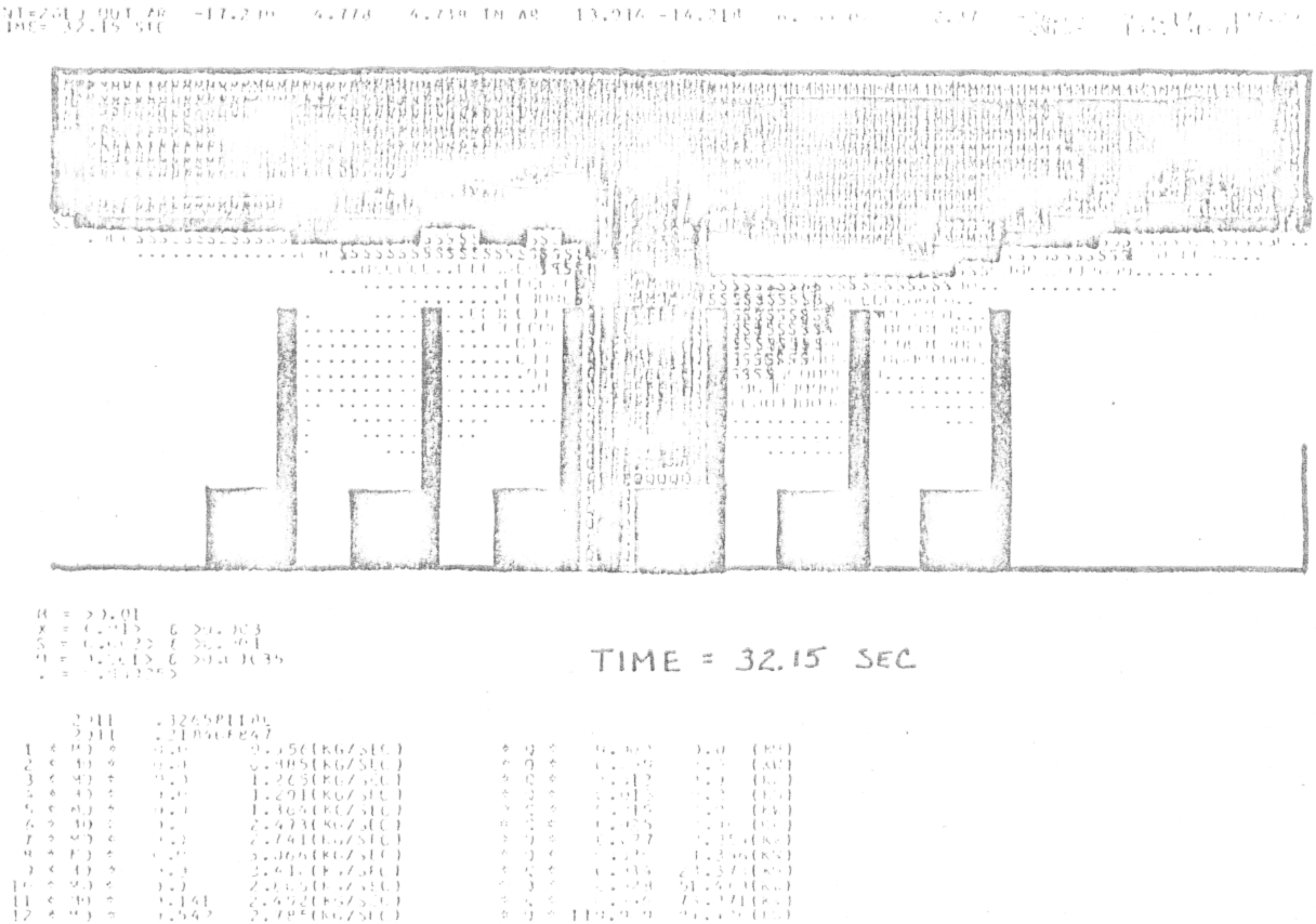


Figure 27

We have made a different set of calculations with seats having openings underneath. The calculations show that some hot gases rising from a fire are redirected to other seats because the cool air circulates through openings under the seats. We have additional burning of seats and additional heat is generated in that particular area. This is an interesting comparison between two sets of calculations. It implies that fire spread can be limited if air circulation is limited. This favors a blocking or partition concept in an aircraft design. From a safety viewpoint this is not very conclusive. It implies that a higher seat back would have a beneficial effect as far as fire safety is concerned. Another interesting point is that with an open bottom, temperatures are much lower than at surrounding areas away from the heat source because circulating air cools the flame temperature. There is a trade-off. Further studies are required to clear this interesting problem.

QUESTION:

Where is the fire located?

K.T. YANG:

The fire is located at the center of the fuselage.

QUESTION:

The temperatures are low compared to that in a fire, less than 200°C?

K.T. YANG:

Yes, the temperatures are low. We were concerned about this. That is the reason why a flame is shaping up like this in the model.

QUESTION:

Everything shown in Figure 14 is calculated?

K.T. YANG:

Yes, everything is calculation. If you connect all the points with a straight line you will get a curve. If you connect the experimental points by straight lines, you get a different curve, which indicates what actually is going in the main fuselage.

QUESTION:

Those calculations say that the plume is about 20 or 30 centimeters wide?

K.T. YANG:

Yes.

QUESTION:

Is this because you are forcing it into two dimensions?

K.T. YANG:

No, I don't think this is the case. Don't forget, this scale is misleading. The fuselage is something like 56 feet.

QUESTION:

All right, maybe it is 40 centimeters in width. For a two-dimensional model maybe that is some justification. But for a radial model, it is clearly going to be maybe a foot wide or more.

K.T. YANG:

Additional data will be needed to determine that.

QUESTION:

The maximum temperature is only 250°C over the plume where combustion is located. There is no combustion?

K.T. YANG:

No, the combustion occurs in the plane.

QUESTION:

How do you define the plane? The lowest level of the temperature should be much higher.

K.T. YANG:

I think what you are getting at is some skepticism on the part of people who have run fire tests and made measurements inside planes, and the skeptical position is with regard to the possibility that you might measure the temperatures which are not higher than 250°C in a place where there is burning going on.

We have often thought about how really accurate measurements are and we can get the temperatures much lower than they are if you take into account the radiation factors. You have to be very careful about exactly the measurement conditions.

The problem might be that there was a very coarse thermocouple grid in the experiment. Instead of having the thermocouples on the axis of a fire, it may be one foot off. If you are trying to match the numerical values of two temperatures, then you are way off.

This is the best data we have. We have to have some way to make some comparison just to see what kind of equipment and data we are talking about.

MODELING HEAT FLUXES FOR AIRCRAFT

RONALD ALPERT

Assistant Manager, Basic Research Department, Factory Mutual Research and Engineering Corporation. Ph.D. in Mechanical Engineering, Massachusetts Institute of Technology, 1970. Joined Factory Mutual in 1969.

MODELING HEAT FLUXES FOR AIRCRAFT

Ronald Alpert
Factory Mutual Research
and Engineering Corporation

The title of this project is computer modeling of aircraft cabin fire phenomena.

We are going to formulate a few efficient computer subroutines that could be used in a comprehensive zone model. I am going to describe the plans for this project.

The first task, shown in Figure 1, is to develop integral models of fire spread under corridor ceilings. The integral models can be very efficient on computer time and yet reasonably accurate. The geometry in Figure 1 is this one where a flow exists along the wall and the ceiling. The wall will be combustible, but the ceiling may or may not be combustible. The side walls are to confine the flow at the wall and the ceiling. The plane view on top shows what might happen if the ceiling is combustible.

A flame occurs and the flame front progresses down the ceiling. That is the general view of what we are looking at.

Factory Mutual is under an FAA contract to conduct an experimental study on physical modeling. We have run intermediate-scale and small-scale experiments on ceiling burning. A good deal of data exists from these experiments which could be used as a comparison with theoretical prediction calculated from integral models.

Figure 2 delineates the specific objectives of Task 1 work. During the first year, we will be looking at the first two topics. First, we will want to validate existing integral models of combustion in fire plumes. Second, we will also develop and validate integral models for wall fires.

There are several different types of integral models that we have developed at Factory Mutual for fire plume combustion. The

TASK 1: INTEGRAL MODELS OF FIRE SPREAD UNDER CORRIDOR CEILINGS

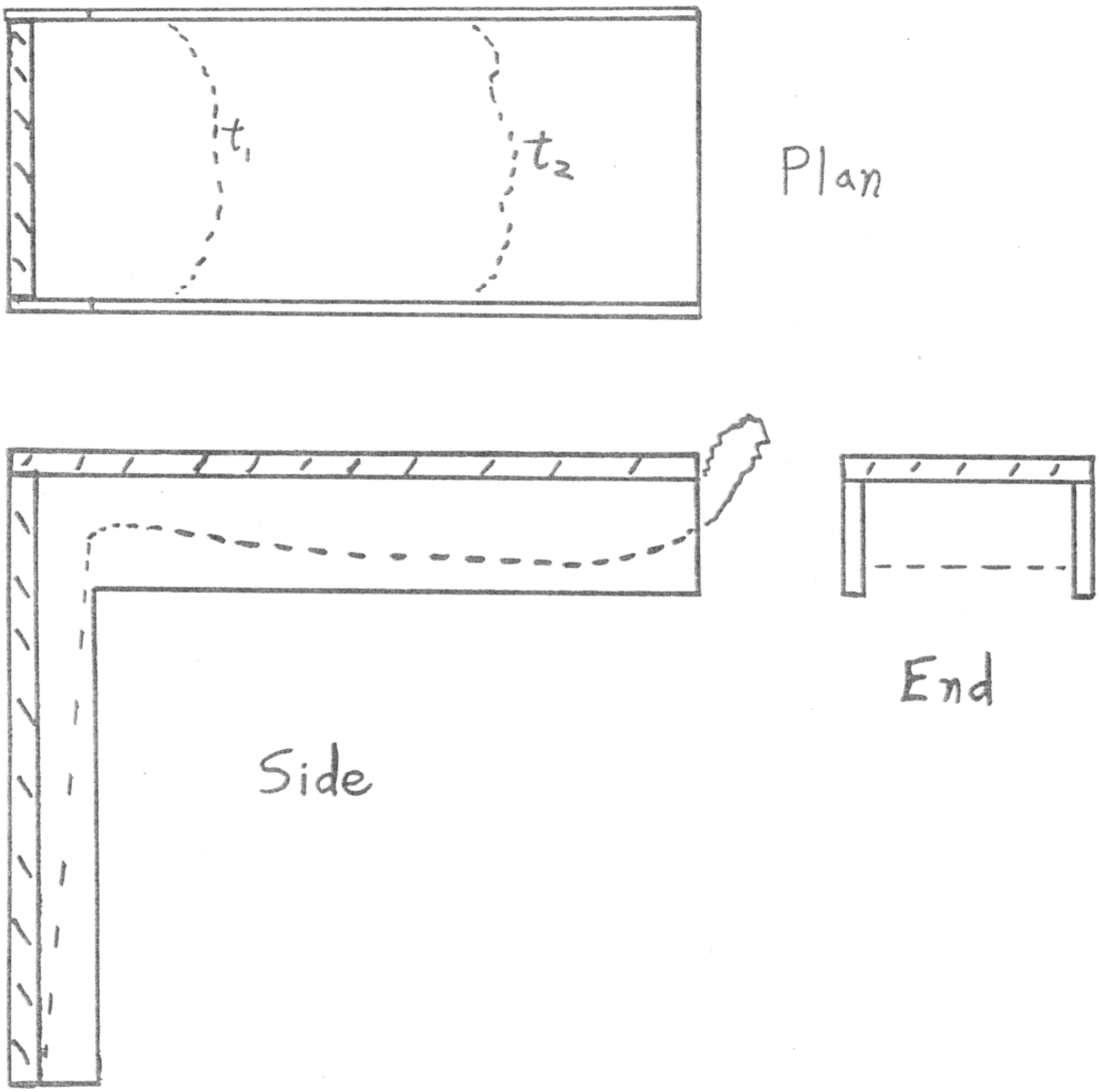


Figure 1

TASK 1: INTEGRAL MODELS OF FIRE SPREAD UNDER CORRIDOR CEILINGS

Validation of Integral Combustion Models for Turbulent Fire Plumes and Wall Fires

Formulation of an Integral Model for Reacting, Turbulent Wall-Ceiling Flows

Solution of the Ceiling Flow Combustion Model with Comparison to FMRC-FAA Experiments

Formulation of Transient, Under-Ceiling Fire Spread for Incorporation into Zone Models

Figure 2

first model was developed by Dr. Francesco Tamanini. His integral model is a modification of the numerical techniques for reaction in a buoyant turbulent plume. He makes assumptions in order to simplify his model and develop a rather efficient integral model for buoyant turbulent combustion in a fire plume. This is one model that is quite promising for use with fire plumes. This integral model will allow low cost predictions on the rate of burning in fire plumes. We need experimental data for verification of this model.

Another model of buoyant combustion in the plume is Dr. John de Ris' stochastic mixing model, involving the evolution of probability density function in the plume. Again, we have a simplified model which requires comparison. Optimization from experiments in this process is actively being pursued right now.

An experimental apparatus developed by Dr. F. Tamanini was used to verify the integral models of plume combustion. It has a water-cooled chamber with gas burners. By raising the burner up, various levels of a plume can be experimentally studied. The flame enters a duct with gas analyses instruments downstream. We can determine the chemical composition of the products and degree of reaction at that level in the plume. In addition, a radiometer is mounted in the side of the chamber so we can look at a thin slice of flame. The radiant output from the slice of flame can be compared with the heat release at that same level. A typical result is that the energy release rate integrated in the plume is a function of height above the burner. It can determine the fraction of the fuel converted to carbon monoxide. For the first time, we have some hard data on where in the fire plume the chemical reaction is occurring. This same apparatus will be used by Mike Delichatsios to obtain measurements of air entrained in the plume--a technique very similar to that used by Professor Ed Zukoski from California Institute of Technology. This one apparatus will allow us to make these critical comparisons between theory and experiment, to validate models of plume combustion. Once this validation has taken place, we can go on to looking at the problem of the wall fire and developing integral models for wall fires.

The remainder of the first year we will be looking at formulating integral models for the wall/ceiling combustion configuration and extending the wall fire integral model to combustion under the ceiling. In the second year of the program, we hope to solve the ceiling flow combustion model and compare predictions from the theory with the experimental data. Finally, once we have the steady solution, we will formulate a transient under ceiling fire spread model by considering the transient case to be just a succession of steady burning situations. The integral solution could then be incorporated in existing zone models.

Task 2 of this NBS grant deals with the three-dimensional solution of fire heat transfer in an aircraft cabin. The situations we will be looking at are the radiant heat transfer from a pool fire outside the aircraft to the interior of the cabin where some penetration occurs (Figure 3). This is under quiescent wind conditions. With the outside pool fire and entrained air from the cabin, the flame has been drawn into the upper part of the cabin. The flame penetrates down the cabin and forms a hot ceiling layer going down the length of the cabin. We will be looking at the situation where we have flame penetration into a cabin, looking at the radiant flux and convective flux to arbitrary targets within the cabin.

Figure 4 shows the specific objectives of Task 2. In the first year, we do the first two subtasks and in the second year the last two subtasks. The first subtask is to calculate radiant heat transfer from external pool fires to arbitrary targets within the aircraft. We will develop both numerical solutions and approximate analytical solutions so that we can judge the accuracy of the approximate solution. These solutions will be in terms of parametric properties of the outside pool fires. In the remainder of the first year, we will be estimating heat transfer due to flame penetration.

TASK 2: THREE DIMENSIONAL SOLUTION FOR FIRE HEAT TRANSFER IN AN AIRCRAFT CABIN

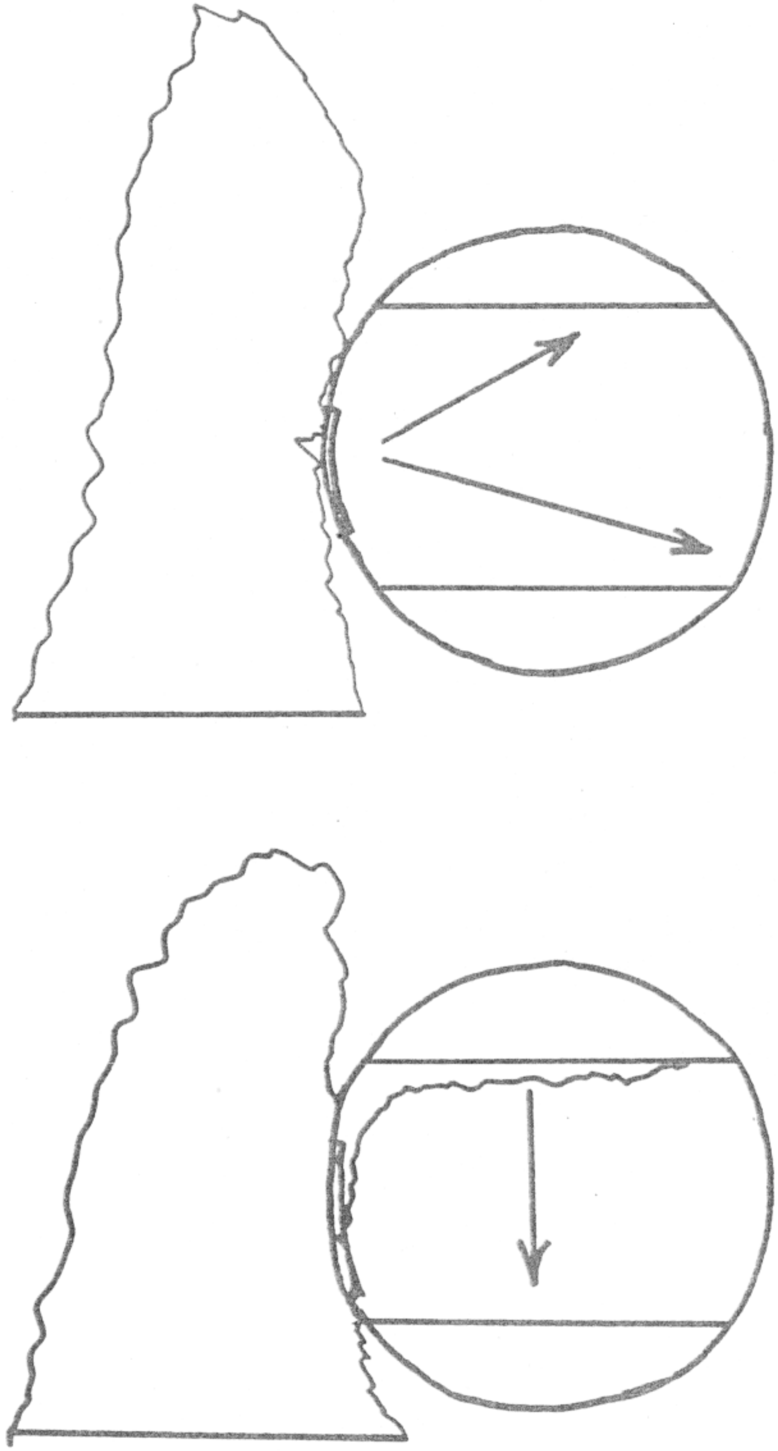


Figure 3

TASK 2: THREE DIMENSIONAL SOLUTION FOR FIRE HEAT TRANSFER IN AN AIRCRAFT CABIN

Radiant Heat Transfer from an External Pool Fire to an Arbitrary Target inside an Aircraft

Estimation of Heat Transfer due to Flame Penetration

Improved Calculation of Penetrating Flame Heat Transfer with Results from TASK 1

Computer Subprogram for Efficient Calculation of Heat Transfer Rates from Reacting Wall-Ceiling or Plume-Ceiling Flows to an Arbitrary Target within the Aircraft

Figure 4

The assumed geometries or thicknesses of the penetrating flame and the properties of the penetrating flame will be used to calculate the convective and radiant heat transfers to the ceiling and arbitrary targets in the aircraft. In the second year, based on calculations made in Task 1, we will be looking at ceiling layer combustion. We will predict properties of the layer, i.e., thicknesses of the layer and temperatures. We will use that information for improving the calculation of heat transfer to targets within the aircraft.

Finally, in the remainder of the second year, we will try to develop efficient subroutines for the calculation of heat transfer from either the penetrating flame or the ceiling layer flame or combustion products in the aircraft cabin to arbitrary products within the aircraft. This is our plan for this project.

We are just beginning and Mike Delichatsios has started work on the wall fire combustion problem and has made some real progress there.

QUESTION:

Are you going to attempt to work out a method of inserting the results that you get into a zone model?

RONALD ALPERT:

It would be very nice if we could do that. It depends on timing. If we have something developed on time during the contract period, I think we would look at it. We have the capability, for instance, for running the Harvard program at Factory Mutual.

QUESTION:

Why did you pick this particular geometry for the hull? You left out all the return flow problems. I realize that it makes life easier, but in a real hull, it might not be totally unimportant. There is some data that has been obtained that shows that you can actually get local air built up near the fire which would cause a couple of lengths of the hull to be completely afoul with smoke. There are problems of that sort that are associated with returning flow. Are you only interested in the very thin layer on the top?

RONALD ALPERT:

We wanted to tackle a problem and solve to a degree that we really believe the answer. We don't want to go out further than we think we can catch. We had enough problems with getting a combustion model working correctly. We had enough challenges with this one without taking on further challenges at this time.

QUESTION:

It seems to me you would want to address the problem of a pool fire outside the doorway. You are working on a piece of that. I wonder if you are going to address or consider, even when there is no wind acting on the fire plume, there is some sporadic intermittent penetration of that plume into the cabins. Have you made any consideration or will you address in your work or will you hope others will address some work on how to describe that phenomena--how do you see that related to your problem.

RONALD ALPERT:

I hope someone will describe that phenomena. I don't see that we are going to predict a random penetration of the plume. We may simulate it by saying we have a wall fire and a respectively black body source there or a wall fire on one side and then have a ceiling flow generated by that wall fire or have some assumed type of plume being a fraction of the pool fire.

ENCLOSURE MODELS APPLIED TO AIRCRAFT

HENRI MITLER

Research Associate, Division of Applied Science, Harvard University. Ph.D. in Nuclear Physics from Princeton University, 1960. Professor H. Emmons' coworker in designing computer fire code.

ENCLOSURE MODELS APPLIED TO AIRCRAFT

Henri Mitler
Harvard University

My discussion is going to very briefly explain the current status of the Harvard Computer Fire Code and how this is applicable to the ceiling jet problems of the FAA effort in general.

The Harvard Computer Fire Code is a deterministic model of fires burning in enclosures. At the moment, the enclosures that we are considering are rectangular (i.e., a room) which has a number of vents (limited to five). We can also handle the behaviors of up to five objects, at least one of which is burning and the rest are to be considered targets. The floor will be considered an object.

The math model is deterministic. The computer program is modular so that we can remove a subroutine if we wish and substitute an even simpler one or a better one or a more complicated one. This includes not only physical subroutines but also numerical subroutines. We have basically two numerical subroutines. One is a successive substitution method of solving an enormous set of simultaneous equations. Another is, as C. MacArthur pointed out, a Newton-Raphson technique.

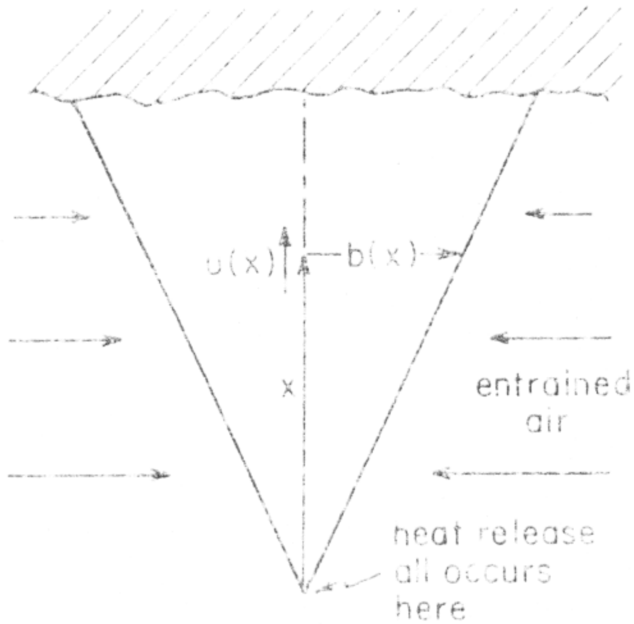
The fires we are looking at are pre-flashover fires. Harvard Computer Fire Code Version Five of this model is about to come off the drawing board. A tape of version five should be made soon and if anyone is interested in obtaining that tape, please see me. This model can handle several types of fires. One is a growing fire, such as igniting a piece of polyurethane foam or a mattress or anything else and watching this thing grow. Moreover, a fire can be set initially and can be ignited at some point down the road either by autoignition due to the charring surface of the flammable target reaching an ignition temperature or by contact with the flame. We model flames, vent flow rates, plume, species production, the spread rate for a growing fire, convective heat transfer, etc.

Figure 1 shows a schematic of the enclosure fire. A flame is modeled by a cone of hot gas which is assumed to be a grey emitter with uniform properties. The flame temperature is chosen by the user. We modeled it with an optical absorption coefficient of 1.55 reciprocal meter. We also have a plume model for the hot gases rising from the flame. We used the Morton-Taylor-Turner point source plume model shown in Figure 2. A virtual point source is located below the fire surface and the plume itself will assume either a top hat model, which is actually what I use now, or a Gaussian profile. It makes very little difference. The radius of the plume is in effect the radius of the fire at the burning base. A virtual part of the plume is below the fire base and the real part of the plume has an air entrainment coefficient which is assumed constant. Nevertheless, in spite of the simplicity, the plume model has worked quite adequately.

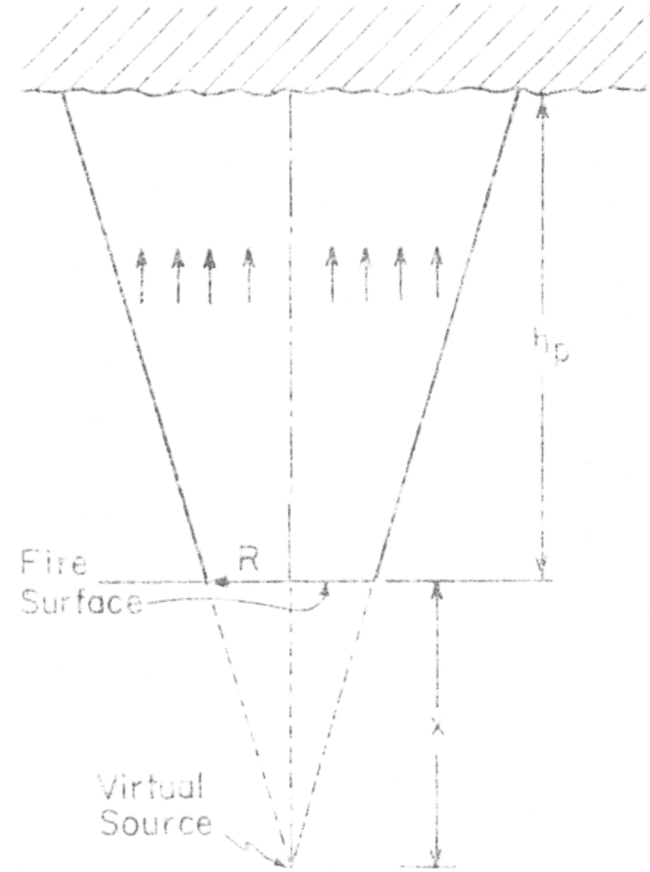
The flow rate of hot gas and air are shown in Figure 1. The flame and plume go up to the ceiling and form a hot layer which gets deep in time; then buoyancy carries it out. We solved the ventilation equation effectively the same way as C. MacArthur pointed out to you. In fact, we have drawn independently exactly the same basic equations.

We model the species concentration by assuming that any particular object gives rise to a constant mass fraction of carbon monoxide, carbon dioxide and smoke which consists of mostly soot and possibly hydrocarbon. One source of these mass fraction data is burning polyurethane foam by Tewarson. I used the numbers that he developed. It is a very simple approximation with single numbers. Nevertheless, the results are reasonable for all the species except carbon monoxide.

We have to use experimental results for the flame spread rates. We could not get the spread rate from first principles. It is possible to have an expression which gets the correct spread rate for the open flame, but then corrects for the effect of the feedback radiation from the hot layer, hot ceiling, the walls, etc. Again, we get quite reasonable results by doing that.



Schematic of point-source plume. At any height x above the source, the plume radius is b(x) and the upward fluid-flow velocity on the axis is u(x). The horizontal arrows indicate the flow of air which will be entrained. The shaded region is the hot layer.



Schematic of area-source plume. Plume height is given by h_p, and R is the radius of the fire base. The geometry is as in fig. 4.

Figure 2

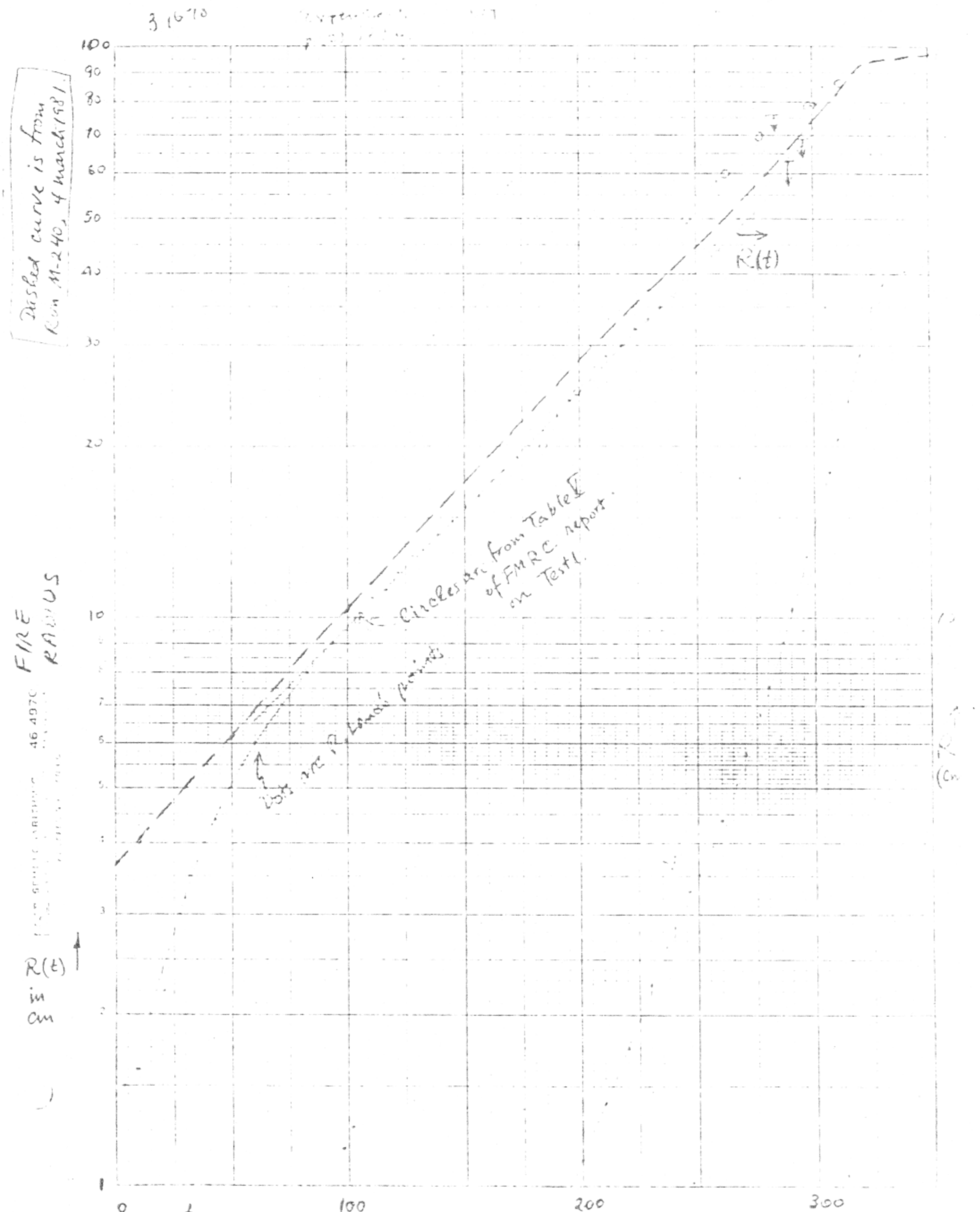

Dashed curve is from Run 11-240, 4 March 1981.
FIRE RADIUS
R(t) in cm
t →
R(t)
Circles are from Table V of FMRC report on Test 1.
Dots are P. Lund's points
0
100
200
300
100
90
80
70
60
50
40
30
20
10
3
1

Figure 3

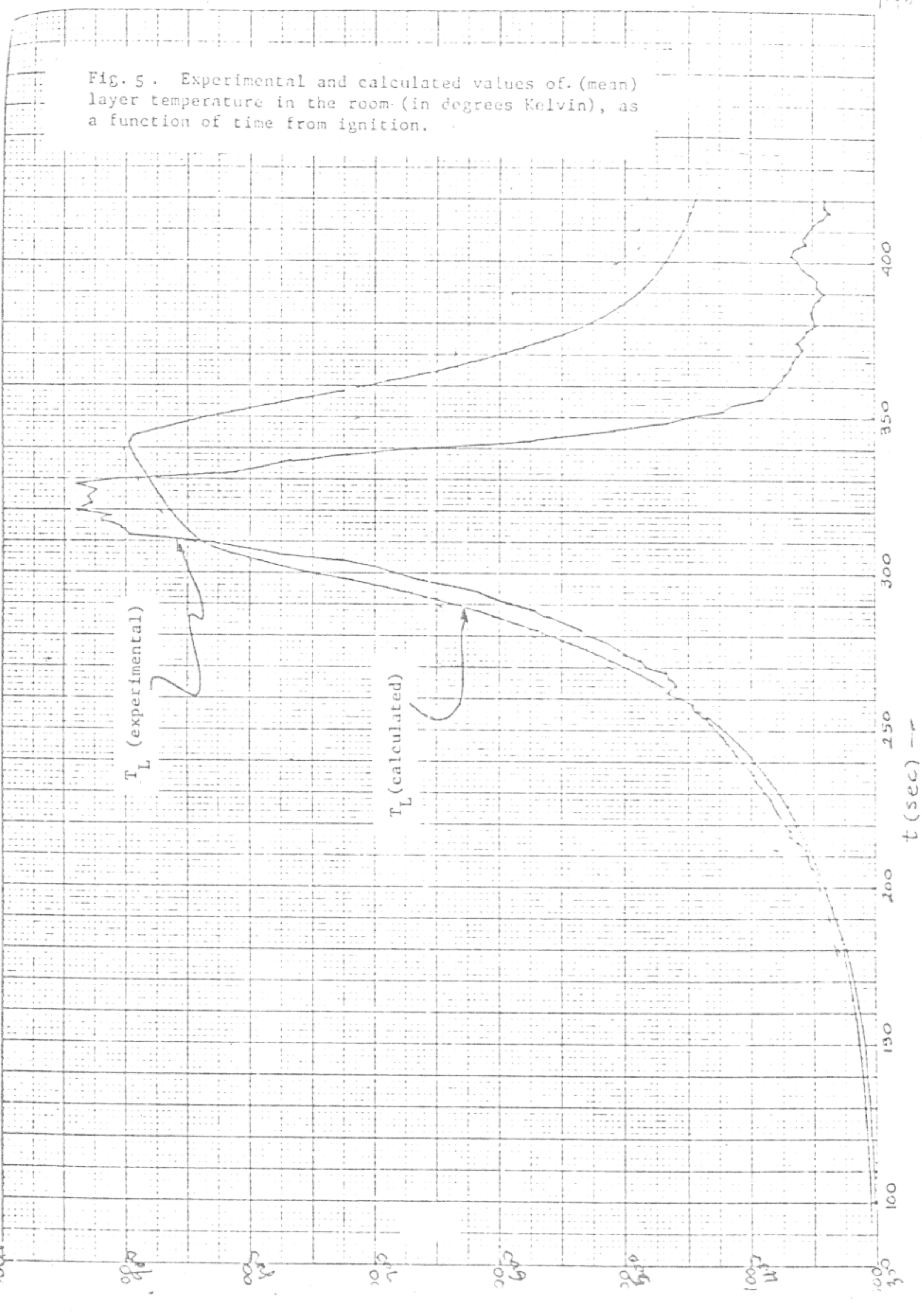


Fig. 5. Experimental and calculated values of (mean) layer temperature in the room (in degrees Kelvin), as a function of time from ignition.

8/6/71 CO, CO2, and Smoke concentrations, July 6 1971 test @ FMRC

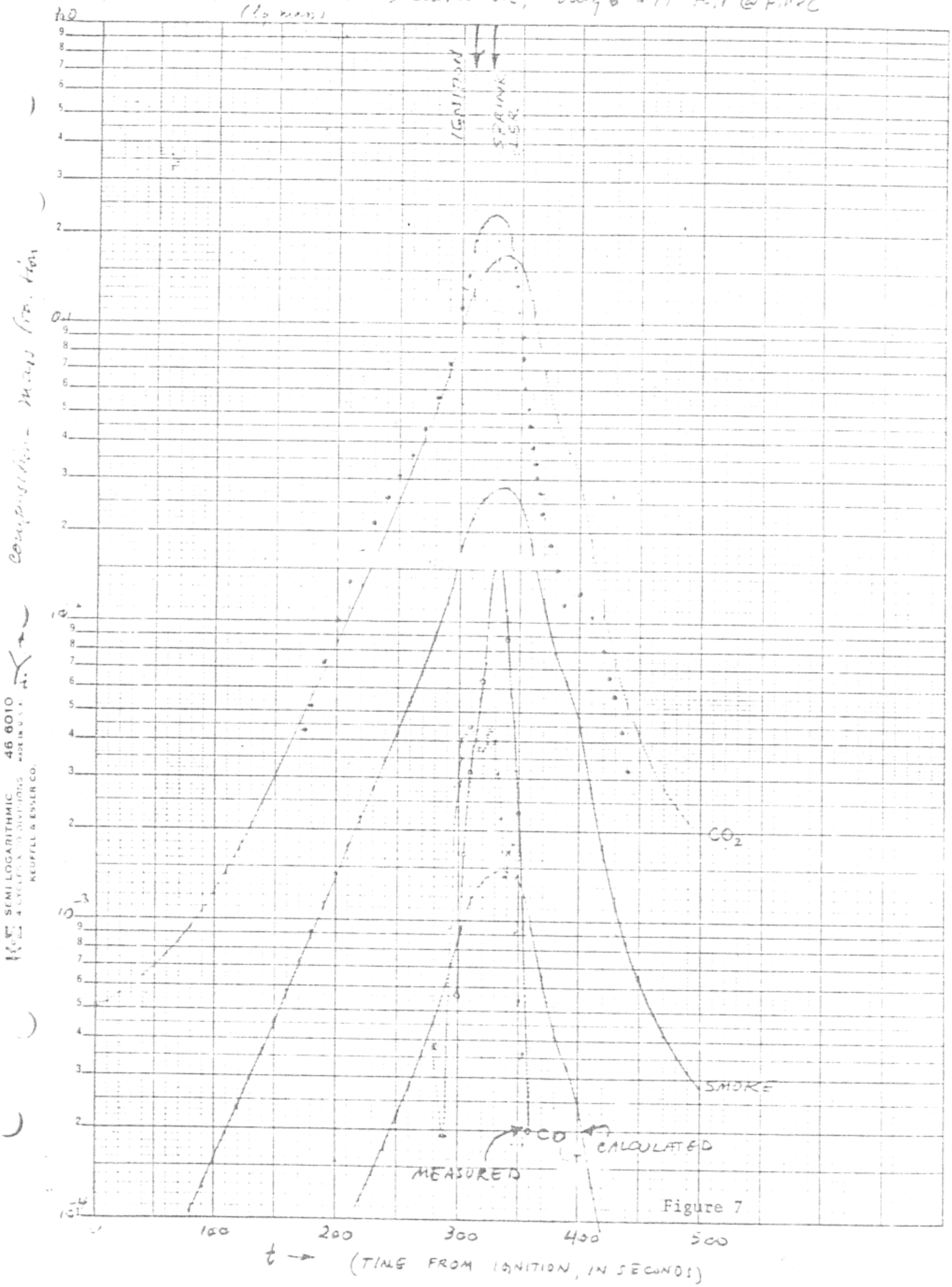


Figure 7

3/6/81. κ in a standard run

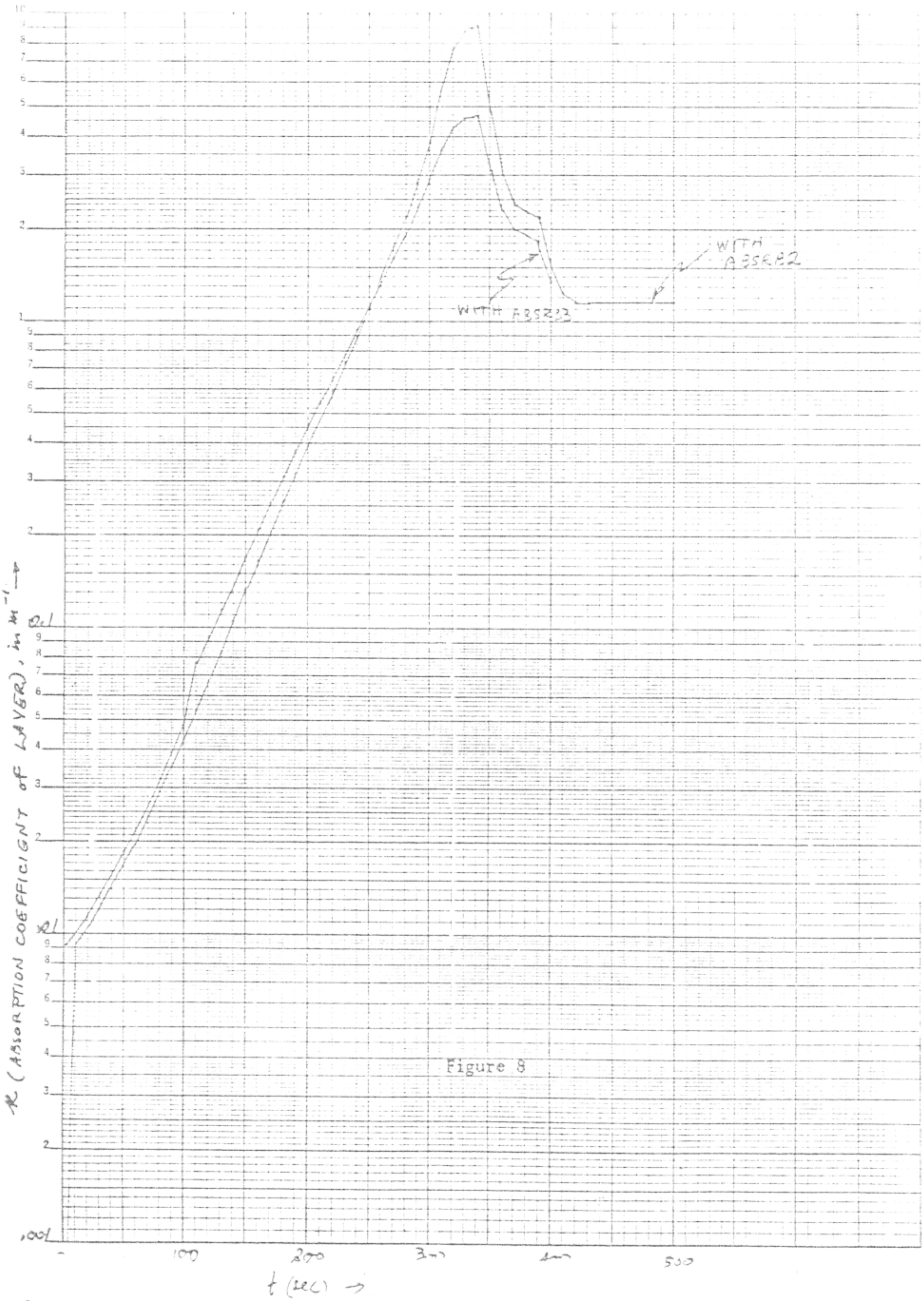


Figure 8

make it much more robust and it works very well. Another part of the numerical package is that I try to avoid using the Newton technique as much as I can because of the large amount of work involved in solving the Jacobian. I use the Newton technique when necessary and then I immediately shift out of that to a grid-size where I don't change the Jacobian.

QUESTION:

Have you used double precision on the VAX?

H. MITLER:

Yes and no. I have not. John Randall, a graduate student working with us, has used double precision. He finds that sometimes double precision is needed in solving the Jacobians and has to go with double precision.

QUESTION:

You make some comparisons between the computed upper layer temperature and the experimental upper layer temperatures that should be interfaced. How do you compute this from your experimental data?

H. MITLER:

There are three racks of thermocouples (front, middle and rear). Each rack has a dozen or more thermocouples. We weighed the numbers in some reasonable way for all those temperatures and took an average of those numbers. We are also working on a couple of equations which tie them together.

THERMOCHEMICAL MODELING OF AIRCRAFT INTERIOR POLYMERIC MATERIALS

PLAN OF THIS PRESENTATION

1. OBJECTIVES AND BASIC APPROACH
2. BACKGROUND AND INFORMATION AND REPRESENTATIVE RESULTS
3. SPECIFIC TASKS IN FY'80 FOR THE FAA
4. SYNERGISM AND COOPERATION WITH OTHER EFFORTS (EX: NASA ARC)
5. FUTURE PLANS (FY'81 AND BEYOND)

NECESSARILY BRIEF MORE INFORMATION AVAILABLE

Figure 1

INTERRELATIONS WITH OTHER'S WORK

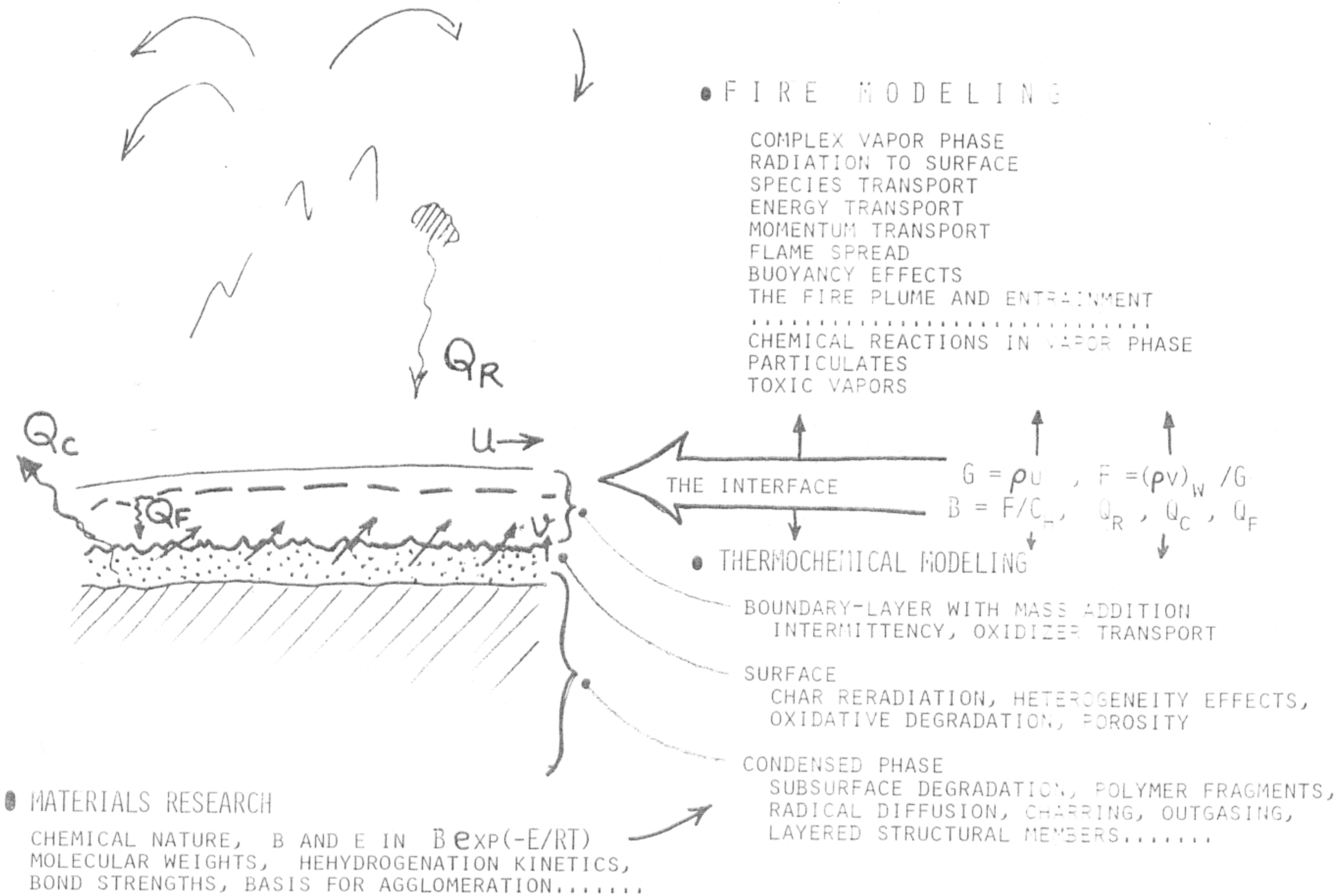


Figure 3

FRAGMENT SIZE VAPORIZING

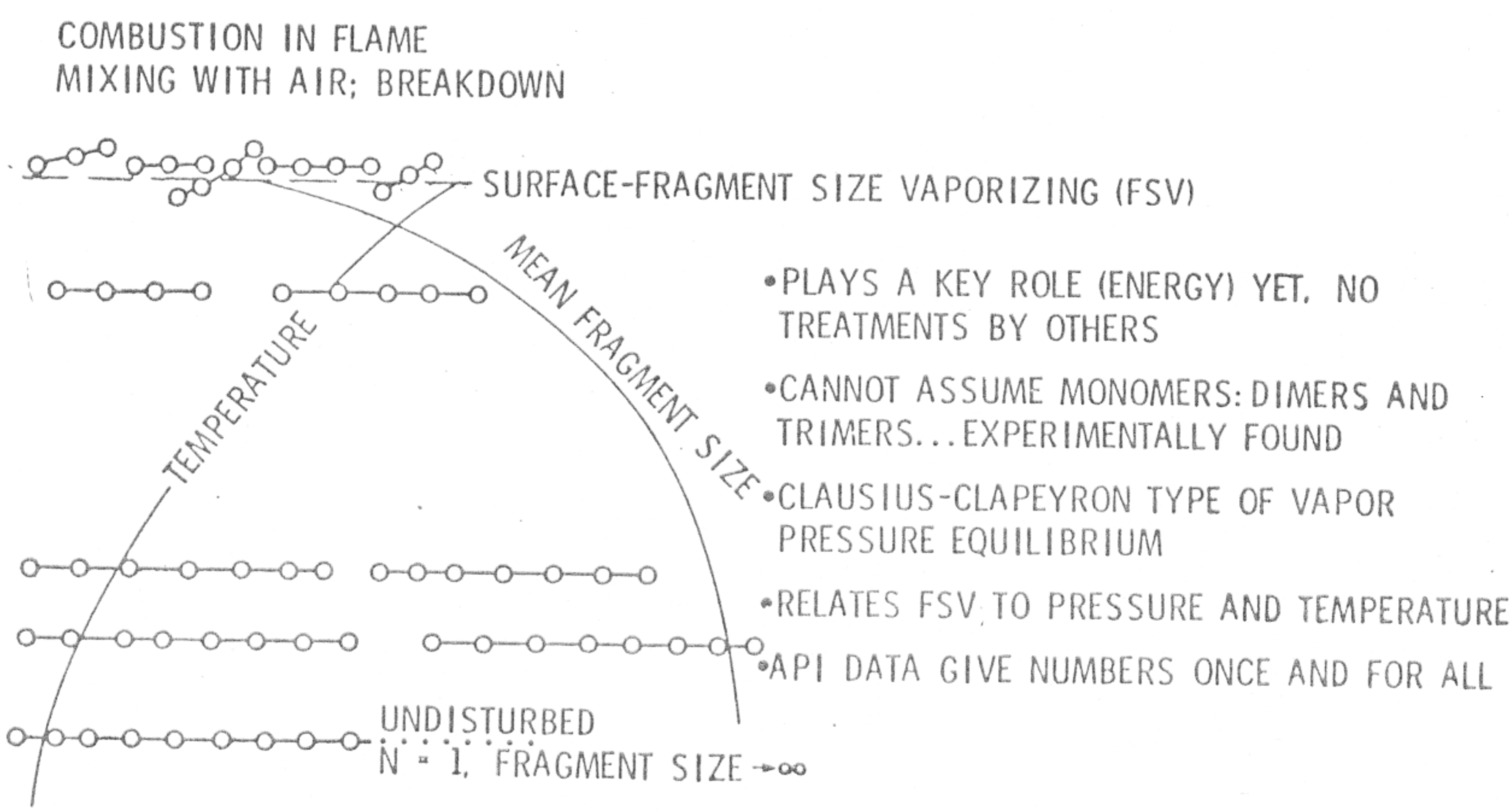


Figure 4

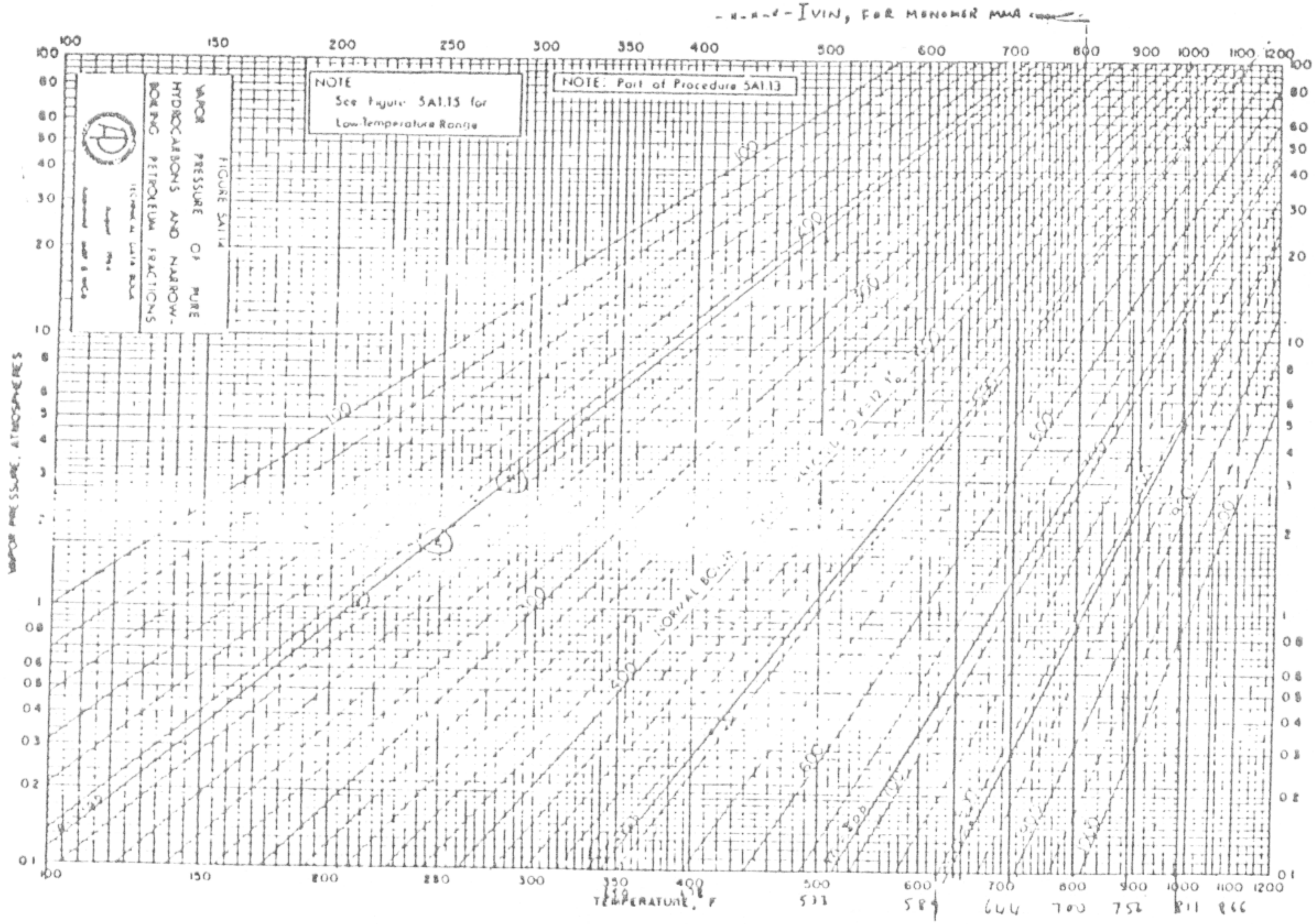
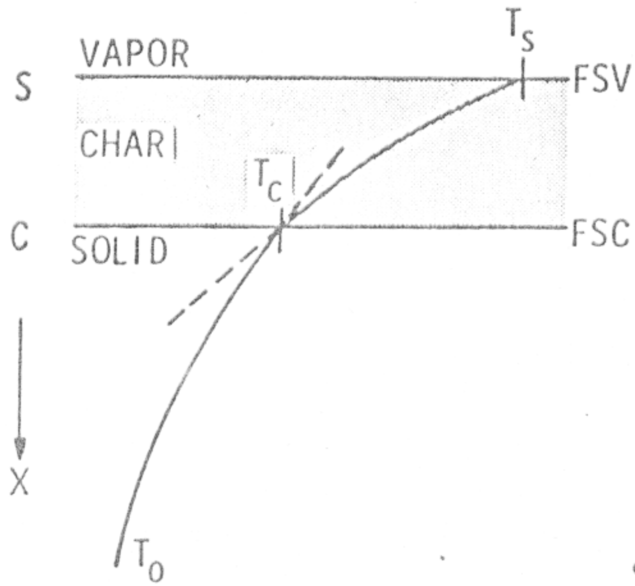

IVIN, FOR MONOMER MMA
FIGURE 5A1.14
VAPOR PRESSURE OF PURE HYDROCARBONS AND NARROW-BOILING PETROLEUM FRACTIONS
NOTE
See Figure 5A1.15 for Low-Temperature Range
NOTE: Part of Procedure 5A1.13
VAPOR PRESSURE, ATMOSPHERES
TEMPERATURE, F
100
150
200
250
300
350
400
500
600
700
800
900
1000
1100
1200
533
584
644
700
752
811
866

Figure 6

SOME DETAILS OF SOLUTION



- ENERGY EQUATION IN TWO REGIONS
- HEAT FLUX MATCH: $k_l \left(\frac{dT}{dX}\right)^- = k_h \left(\frac{dT}{dX}\right)^+$
- $k \frac{d^2T}{dX^2} + \rho c r \frac{dT}{dX} = DB \rho e^{-E/RT}$
- NON DIMENSIONALIZE:

$$P \frac{dP}{d\tau} + P = (h + P + \tau) \Lambda e^{-\theta_a [1 + \chi (1 - \tau)]}$$

- SOLUTION: SIMULTANEOUS IN
  BURN RATE OF MATERIAL
  FRAGMENT SIZE AT CHAR LAYER
- T_s DETERMINED FROM HEAT FLUX
- ITERATE ECONOMICALLY ON ALGEBRAIC EQUATIONS

Figure 8

SPECIFIC TASKS IN FY'80 FOR THE FAA

MATERIAL: AIRCRAFT CARPET AND SEAT CUSHION

BURNING BEHAVIOR WITH:

1. INCIDENT RADIATION
2. SELF-SUSTAINING FLAME
3. TREATMENT WITH FLAME RETARDANT
4. THERMAL/PHYSICAL THICKNESS
5. SPALDING "B" NUMBER
6. AMBIENT PRESSURE

Figure 9

REACTION RATES OF CARPET DEDUCED FROM TGA

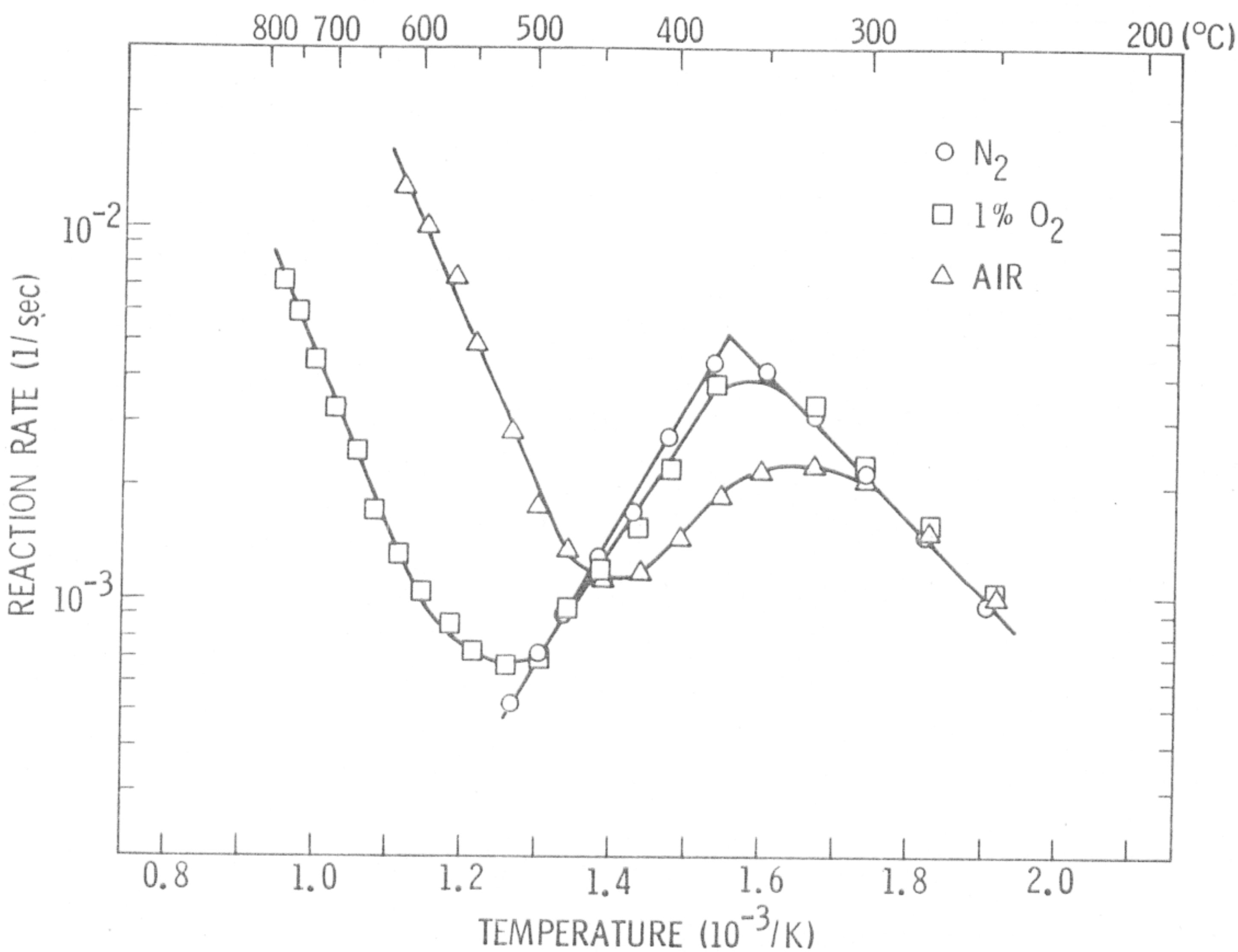


Figure 11

from the material flame for sustaining the combustion. The material surface under radiative flux could raise the surface temperature and become self-ignited. The burning rate for self-ignition is low. The flame actually starts moving farther and farther out as the burning rate goes up and heat flux from the flame decreases. If no outside heat flux is supplied, the burning rate will be diminished and extinguished.

The specific tasks in FY'81 for the FAA are summarized in Figure 13. The material to be tested is multilayered polymer such as honeycombed panels, polyurethane foam-neoprene blocking layer with wool and nylon as seat covers. We plan to extend the analytical thermochemical model to a multilayered system to predict burning behavior under various heat flux conditions. Different sizes of layer thickness will be tested to obtain an optimum combination of multiple layers. More experimental work is also planned. A NBS smoke density test chamber will be used to compare the model predictions. The material samples will be tested under varying incident radiative flux and the weight loss and temperature profile in the sample material will be recorded. The experimental data will be compared with data from NASA/ARC. It is expected that cooperation with other fire researchers will produce satisfactory results.

ENCLOSURE FIRE DYNAMICS MODEL FOR INTERIOR CABIN FIRES

J. BELLAN - Combustion modeling and numerical formulation

L.H. BACK - Group leader

C.P. BANKSTON - Experimental and analytical

K.G. HARSTAD - Computer program

J.R. RADBILL - Numerical techniques

C.S. WONG - Computer programming

Jet Propulsion Laboratory

March 1981

Figure 1

PLAN OF PRESENTATION

1. BACKGROUND AND FORMULATION

2. PROGRESS AND STATUS

3. FUTURE PLANS

Figure 3

DIFFICULTIES IN ESTABLISHING A DETAILED ENCLOSURE FIRE MODEL

1. GEOMETRICAL ASPECTS
2. TURBULENT ASPECTS

   LACK OF TURBULENT TRANSPORT DATA
3. COMBUSTION ASPECTS

   LACK OF KNOWLEDGE ON DETAILED, OR EVEN OVERALL CHEMICAL MECHANISMS
4. DESCRIPTION OF THE COUPLING BETWEEN COMBUSTION AND TURBULENCE
5. RADIATION ASPECTS

   VIEW FACTORS, GAS PHASE ABSORPTION AND TRANSMISSION
6. BOUNDARY CONDITIONS AND WALL EFFECTS

   DIFFICULTY TO CORRECTLY APPROXIMATE BOTH WALL AND CORE PHENOMENA WITHIN REASONABLE CONSTRAINTS OF MONEY, TIME AND COMPUTER TIME
7. LACK OF THERMOPHYSICAL AND THERMOCHEMICAL CONSTANTS FOR VARIOUS AIRCRAFT MATERIALS

Figure 5

and 7. We assume that Lewis number and Prandtl number equal to one, and one-step chemical reactions represent the complex fire chemistry. With these approximations, we can eliminate from all but one equation the reaction term so that our equations are simple to solve.

The boundary conditions are listed in Figure 8. The inert wall conditions determine the species and the energy counts at the surface. At the entrance we have forced ventilation and all the species and temperatures are prescribed. At the exit we are going to compute temperatures and species by forward extrapolation. Finally, we are assuming in the first stage of the model that the pool fire is burning and wind velocity is zero in axial direction. The fuel evaporates in the pool. I want to point out that the equation we are using here has a transient operation. It has an evaporation equation rather than equilibrium equation. It has been found that there are important discrepancies between models that use conventional thermodynamic equilibrium and this type of equation for this time duration.

Finally we have here a boundary equation that gives us the energy balance and the surface of a pool fire. Again, we make a thin wall approximation that relates to latency of the evaporation and enthalpy that evolve from the surface in the gas flow.

The turbulent transport modeling term is shown in Figure 9. The equations that I have given you previously are correct equations; however, they don't isolate turbulent transport. In order to isolate turbulent transport, it is a well-known procedure that all the dependent variables are expressed as a sum of mean gradients plus turbulence. A solution for the mean values is sought and the correlation terms are modeled. These are practical eddy-diffusion types of models with all the density variations neglected. The laminar transport variations are increased by turbulent contributions. The Lewis and Prandtl numbers are assumed equal to one. It is sufficient to specify only one of the transport terms. We chose to do it for the diffusivity because we do have an analogy of a turbulent jet.

BOUNDARY CONDITIONS

WALLS (INERT)

$$u = 0\ , \quad v = 0$$

$$\rho u_n Y_i - \rho D_n \frac{\partial Y_i}{\partial \vec{n}} = 0 \ ; \qquad \begin{array}{l} \vec{n} \text{ is the direction perpendicular to the wall} \\ u_n \text{ is the velocity perpendicular to the wall} \end{array}$$

thin wall assumption

$$\delta_w \rho_w C_w \frac{\partial T_w}{\partial t} = h_w (T_g - T_w) + \dot{q}_{\substack{net \\ rad}} + \delta_w \frac{\partial}{\partial \vec{s}} \left(k_{s_w} \frac{\partial T_w}{\partial \vec{s}} \right) \ ; \qquad s \text{ is the direction along the wall}$$

ENTRANCE ($x = 0, \ ; \ y_1 < y < y_2$)

$$A \overline{\rho u} = \dot{m}_{air} \quad \text{(forced ventilation)}$$

$$v = 0$$

ρ, T, Y_F, Y_{O_2}, Y_{N_2}, Y_{CO_2}, Y_{H_2O} given

EXIT ($x = L \ ; \ y_3 < y < y_4$)

ρ, u, v, Y_F, Y_{O_2}, Y_{N_2}, Y_{CO_2}, Y_{H_2O}, T are found by forward extrapolation

POOL SURFACE ($y = 0, \ x_1 < x < x_2$)

$$u = 0$$

$$\rho v \ Y_F - \rho D \frac{\partial Y_F}{\partial y} = \dot{M}_F$$

$$\rho v \ Y_i - \rho D \frac{\partial Y_i}{\partial y} = 0 \qquad i = O_2, \ N_2, \ CO_2, \ H_2O$$

$$\dot{M}_F = a \ P_{atm} \left\{ e^{\frac{L_g}{R_u}\left(\frac{1}{T_b} - \frac{1}{T_l}\right)} - \frac{Y_F}{w_F} \frac{1}{\sum \frac{Y_i}{w_i}} \right\} \left(\frac{w_F}{2 \pi \tilde{R} T_l} \right)^{1/2}$$

thin wall assumption

$$\delta_l \rho_l C_l \frac{\partial T_l}{\partial t} = h_l (T_g - T_l) + \dot{q}_{\substack{net \\ rad}} - \frac{\dot{M}_F}{w_F} L_g + \delta_l \frac{\partial}{\partial x} \left(k_{x_l} \frac{\partial T_l}{\partial x} \right) - \rho Y_F v C_P \ (T_g - T_{ref})$$

Figure 8

Now, we are coming to a very important part which is the turbulence combustion shown in Figure 10. It is a very controversial subject and that is why we decided that in our model we are not going to specify whether combustion rate is either controlled by kinetics or by diffusion alone. We are going to have to choose one of two processes depending on which one is a slower process.

For the kinetic one we have a practical one-step reaction model and for the diffusion one we have a reaction proportional to the quantities that are defined here. They are the mean square of fuel, pure oxygen mass and enthalpy. Our definition of diffusivity and length scale are also defined for the diffusion controlled process. Going back to our computation equations we can write the equations for the g's. The problem can be solved and in order to solve it we need additional modeling. In order to find an easy way, we are making the assumption of local equilibrium of the flow which means that transient convection and diffusion terms are going to be small in respect to the production and dissipation. We can then solve the equation in the right form. I don't want to go any further than that except to point out that contributions of different terms are involved.

For the quantities that are related to the mass fraction, we have production due to turbulence transport which is divided by the dissipation due to turbulence and sink due to combustion. I would like to point out that the combustion terms have not been modeled before and we are going to compare the calculations with data. The enthalpy equation has in the numerator terms for turbulence transport and buoyancy, and in the denominator terms for turbulence, combustion, radiation and pressure effect.

The description of radiation model is shown in Figure 11. Radiation in a turbulent flow is a very important thing. In order to model radiation, we find the solution of the intensity equation and assume

<u>RADIATION IN THE GAS</u> - PROCEDURE TO FIND $\nabla \cdot \vec{q}_r$

a. FIND THE SOLUTION OF THE INTENSITY EQUATION

b. ASSUME THAT ATTENUATION OF RADIATION BY GASES IS SMALL

c. ASSUME THAT THE EMISSIVE POWER OF THE ENCLOSURE SURFACES IS NEGLIGIBLE WITH RESPECT TO THAT OF THE GASES, PARTICULARLY THE FLAME

THEN

$$-\nabla \cdot \vec{q}_r = -4a\sigma T^4$$

RADIATION IN A TURBULENT FLOW

$$-\nabla \cdot \vec{q}_r = -4a\sigma \bar{T}^4 - 24a\,\sigma\,\bar{T}^2\, g_H \left(\frac{\Delta H}{C_p}^2\right) \qquad (\bar{T}'^3\ \bar{T}'^4 \ll \bar{T}'^2)$$

WHERE a IS FOUND FROM MODAK'S PROGRAM BY INVERTING $\alpha = 1 - e^{-a\ell}$

<u>RADIATION TO SURFACES</u>

FOR AN OPAQUE SURFACE i

$$\dot{q}^i = \frac{e_b^i - B^i}{(1-\epsilon)/\epsilon} \quad \text{WHERE} \quad e_b^i = \sigma (T^i)^4$$

FOR NONISOTHERMAL SURFACES, NEGLECTING THE EMISSIVE POWER OF THE SURFACES WITH RESPECT TO THAT OF THE GASES

$$B^i = \epsilon^i e_b^i + \tilde{\rho}^i \pi \sum_{n=1}^{N} \left[\left(\sum_{in=1}^{m} \overline{{}^i tg_{in}}\ \overline{\alpha_{in}} \right) F_{i-n} \right]$$

Figure 11

UNCOUPLING AND QUASILINEARIZATION OF THE EQUATIONS

- GENERAL TYPE OF SYSTEM OF DIFFERENTIAL EQUATIONS

$$\mathscr{L}_i(x,y,Z_j,t) = \frac{\partial Z_i}{\partial t} + \sum_{k=1,2} A_k(x,y,Z_j,t)\left(\frac{\partial^2 Z_i}{\partial x_k^2}\right)^{n_k} + B(x,y,Z_j,t)\left(\frac{\partial^2 Z_i}{\partial x \partial y}\right)^p + \sum_{k=1,2} C_k(x,y,Z_j,t)\left(\frac{\partial Z_i}{\partial x_k}\right)^{m_k} + D(x,y,Z_j,t) = 0$$

WHERE

$$Z_i = \rho,\ u,\ v,\ \Gamma_{Oi},\ \Gamma_{OT},\ Y_{O_2} \quad ; \quad x_1 = x,\ x_2 = y$$

AND FOR EACH Z_i, $Z_j = \rho,\ u,\ v,\ \Gamma_{Oi},\ \Gamma_{OT},\ Y_{O_2}$

- DESIRED FORM OF THE SYSTEM OF DIFFERENTIAL EQUATIONS

$$L_i(x,y,Z_i,t) = \frac{\partial Z_i}{\partial t} + \sum_{k=1,2} A_k(x,y,t)\frac{\partial^2 Z_i}{\partial x_k^2} + B(x,y,t)\frac{\partial^2 Z_i}{\partial x \partial y} + \sum_{k=1,2} C_k(x,y,t)\frac{\partial Z_i}{\partial x_k} + D(x,y,t)\,Z_i + E(x,y,t) = 0$$

- TWO-STEP APPROACH
  1) UNCOUPLING OF THE EQUATIONS FOR DIFFERENT VARIABLES
  2) QUASILINEARIZATION

$$\mathscr{F}(Z_i) = \mathscr{F}(Z_i^0) + \sum_{i=1}^{I} \left(Z_i - Z_i^0\right)\frac{\partial \mathscr{F}}{\partial Z_i}\left(Z_i^0\right) + O\left(|Z_i - Z_i^0|^2\right)$$

WHERE $\mathscr{F}$ IS <u>ANY</u> FUNCTION OF Z_i

Figure 12

(LINEAR) FINITE ELEMENT METHOD
APPLIED TO A SECOND ORDER
PARTIAL DIFFERENTIAL EQUATION

- GENERAL FORM OF THE MINIMIZATION STATEMENT FOR A SECOND ORDER P.D.E.

$$<\mathcal{F}_r , \varphi_{kn}> = \sum_{\substack{i=1\\j=1}}^{I,J} \frac{dZ^r_{ij}}{dt} <\varphi_{ij} , \varphi_{kn}> + \sum_{s=1,2} \sum_{\substack{p=1\\q=1}}^{I,J} \sum_{\substack{i=1\\j=1}}^{I,J} A^s_{pq} Z^r_{ij} <\varphi_{pq} \frac{\partial^2 \varphi_{ij}}{\partial x_s^2} , \varphi_{kn}>$$

$$+ \sum_{\substack{p=1\\q=1}}^{I,J} \sum_{\substack{i=1\\j=1}}^{I,J} B_{pq} Z^r_{ij} <\varphi_{pq} \frac{\partial^2 \varphi_{ij}}{\partial x \partial y} , \varphi_{kn}>$$

$$+ \sum_{s=1,2} \sum_{\substack{p=1\\q=1}}^{I,J} \sum_{\substack{i=1\\j=1}}^{I,J} C^s_{pq} Z^r_{ij} <\varphi_{pq} \frac{\partial \varphi_{ij}}{\partial x_s} , \varphi_{kn}>$$

$$+ \sum_{\substack{p=1\\q=1}}^{I,J} \sum_{\substack{i=1\\j=1}}^{I,J} D_{pq} Z^r_{ij} <\varphi_{pq} \varphi_{ij} , \varphi_{kn}>$$

$$+ \sum_{\substack{p=1\\q=1}}^{I,J} E_{pq} <\varphi_{pq} , \varphi_{kn}>$$

- CHOOSE $<,>$ TO BE THE SCALAR PRODUCT IN (X, Y) SPACE, NAMELY THE INTEGRAL
- NOTE THAT, FOR EXAMPLE, $<\varphi_{ij} , \varphi_{kn}> = <\varphi_i , \varphi_k><\varphi_j , \varphi_n>$
- TYPE OF INTEGRALS TO BE EVALUATED ARE

$$\phi_{oo} (i, k) = \int_0^1 \varphi_i(s) \varphi_k(s) \, ds$$

$$\phi_{ono} (p, i, k) = \int_0^1 \varphi_p(s) \frac{d^n \varphi_i}{dx^n}(s) \varphi_k(s) \, ds \quad , \quad n = 0, 1, 2$$

WHERE s is either x or y

Figure 14

(LINEAR) FINITE ELEMENT METHOD
APPLIED TO A SECOND ORDER
PARTIAL DIFFERENTIAL EQUATION
(Cont'd)

$$\phi_{00}(i,k) = \begin{cases} \dfrac{\Delta s_k + \Delta s_{k+1}}{3} & \text{if} \quad i = k \\ \dfrac{\Delta s_k}{6} & \text{if} \quad i = k-1 \\ \dfrac{\Delta s_{k+1}}{6} & \text{if} \quad i = k+1 \\ 0 & \text{otherwise} \end{cases}$$

$$\phi_{000}(p,i,k) = \begin{cases} \dfrac{\Delta s_k + \Delta s_{k+1}}{4} & \text{if} \quad p = i = k \\ \dfrac{\Delta s_k}{12} & \text{if} \quad p = k,\ i = k-1 \quad \text{or} \quad \text{if} \quad p = k-1,\ i = k \\ \dfrac{\Delta s_{k+1}}{12} & \text{if} \quad p = k,\ i = k+1 \quad \text{or} \quad \text{if} \quad p = k+1,\ i = k \\ 0 & \text{otherwise} \end{cases}$$

$$\phi_{010}(p,i,k) = \begin{cases} 0 \quad \text{if} \quad |i-k| \geqslant 2 \quad \text{or} \quad |p-k| \geqslant 2 \quad \text{or} \quad |p-i| \geqslant 2 & \\ \dfrac{1}{6}\,(2i-p-k) & \text{otherwise} \end{cases}$$

$$\phi_{020}(p,i,k) = \begin{cases} 0 & \text{if} \quad |i-k| \geqslant 2 \quad \text{or} \quad |p-k| \geqslant 2 \quad \text{or} \quad |p-i| \geqslant 2 \\ 0 & \text{if} \quad i \neq k \\ -\dfrac{1}{\Delta s_{k+1}} - \dfrac{1}{\Delta s_k} & \text{if} \quad p = i = k \\ \dfrac{1}{\Delta s_k} & \text{if} \quad p = k-1,\ i = k \\ \dfrac{1}{\Delta s_{k+1}} & \text{if} \quad p = k+1,\ i = k \end{cases}$$

Figure 15

FUTURE PLANS

1) APPLICATION OF MODEL AND SOLUTION TECHNIQUE TO A NO-COMBUSTION PROBLEM THAT HAS ENERGY AND MASS ADDITION ONLY

NEEDED FOR SOLVING ABOVE

- CODING THE GLOBAL BALANCE EQUATIONS
- THERMOCHEMICAL, THERMOPHYSICAL, AND TURBULENCE RELATED PARAMETERS
- CRITERION FOR CONVERGENCE
- ACCESS TO A VERY FAST COMPUTER

  CDC-CYBER 203 FROM LANGLEY RESEARCH CENTER

  - PIPELINE VECTOR MACHINE
  - HIGH SPEED COMPUTER
  - LARGE VIRTUAL MEMORY
  - ACCESSIBLE AT ANY TIME DURING THE DAY THROUGH A REMOTE JOB ENTRY TERMINAL AT JPL OVER MODERATE SPEED PHONE LINES

Figure 17

APPENDIX A
(Concluded)

3:30 - 3:50	Enclosure Models Applied to Aircraft Henri Mitler, Harvard University Cambridge, Massachusetts
4:00 - 4:20	Thermochemical Modeling of Burning Aircraft Materials Kumar Ramohalli, Jet Propulsion Laboratory Pasadena, California
4:30 - 5:00	Enclosure Fire Dynamics Model for Interior Cabin Fires Josette Bellan, Jet Propulsion Laboratory Pasadena, California
5:00 - 5:30	Discussion
March 25, 1981	Director's Conference Room 4th Floor Technical Building
9:00 - 12:30	Tours of FAA Fire Test Facilities
12:30 - 1:30	Lunch
1:30 - 5:00	Ad Hoc Committee (Plumes)
March 26, 1981	Director's Conference Room 4th Floor Technical Building
9:00 - 5:00	Ad Hoc Committee (Plumes)
March 27, 1981	Director's Conference Room 4th Floor Technical Building
9:00 - 5:00	Ad Hoc Committee (Smoke Movement)

APPENDIX B
(Continued)

Raymond Friedman
Director of Research
Factory Mutual Research Corporation
1151 Boston-Providence Turnpike
Norwood, Massachusetts 02062

Marilyn K. Goldberg
Information Analyst
DOT/TSF - Raytheon Service Company
31 Grand View Road
Arlington, Massachusetts 02174

D.M. Kanury
Department of Aerospace/
Mechanical Engineering
University of Notre Dame
Notre Dame, Indiana 46556

Edward L. Lopez
Research Specialist
Lockheed-California Company
24827 Quigley Cyn Road
Newhall, California 91321

Charles D. MacArthur
Research Physicist
University of Dayton Research
Institute
300 College Park
Dayton, Ohio 45469

Henri E. Mitler
Research Fellow in Applied
Mechanics
Harvard University
Engineering Science Laboratory
Oxford Street
Cambridge, Massachusetts 02138

Peter C. Owzarski
Senior Research Engineer
Battelle-Northwest
P.O. Box 999
Richland, West Virginia 99352

Jay S. Parish
Senior Project Engineer
Underwriters Laboratories, Inc.
1088 Randville Drive
Palatine, Illinois 60067

William J. Parker
Physicist
Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

Kumar Ramohalli
Jet Propulsion Laboratories
4800 Oak Grove Drive
Pasadena, California 91109

George E. Reagan
Senior Scientist
Bolt Beranek & Newman, Inc.
15721 Singletree Lane
Dumfries, Virginia 22026

Ronald Rehm
Mathematician
Administration A302
National Bureau of Standards
Washington, D.C. 20234

Robert L. Rodgers
Electrical Engineer
U.S. Army Aviation Research
& Development Command
Applied Technology Laboratory
Attn: DAVDL-ATL-ATS
Fort Eustis, Virginia 23604

William Shepherd
Program Scientist
AAM-550
Federal Aviation Administration
800 Independence Avenue, S.W.
Washington, D.C. 20591