NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC APOLLO 13 INVESTIGATION TEAM

REPORT
SUMMARIES

MAY 1970

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

REPORT SUMMARIES

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MSC APOLLO 13 INVESTIGATION TEAM

INTRODUCTION

INTRODUCTION

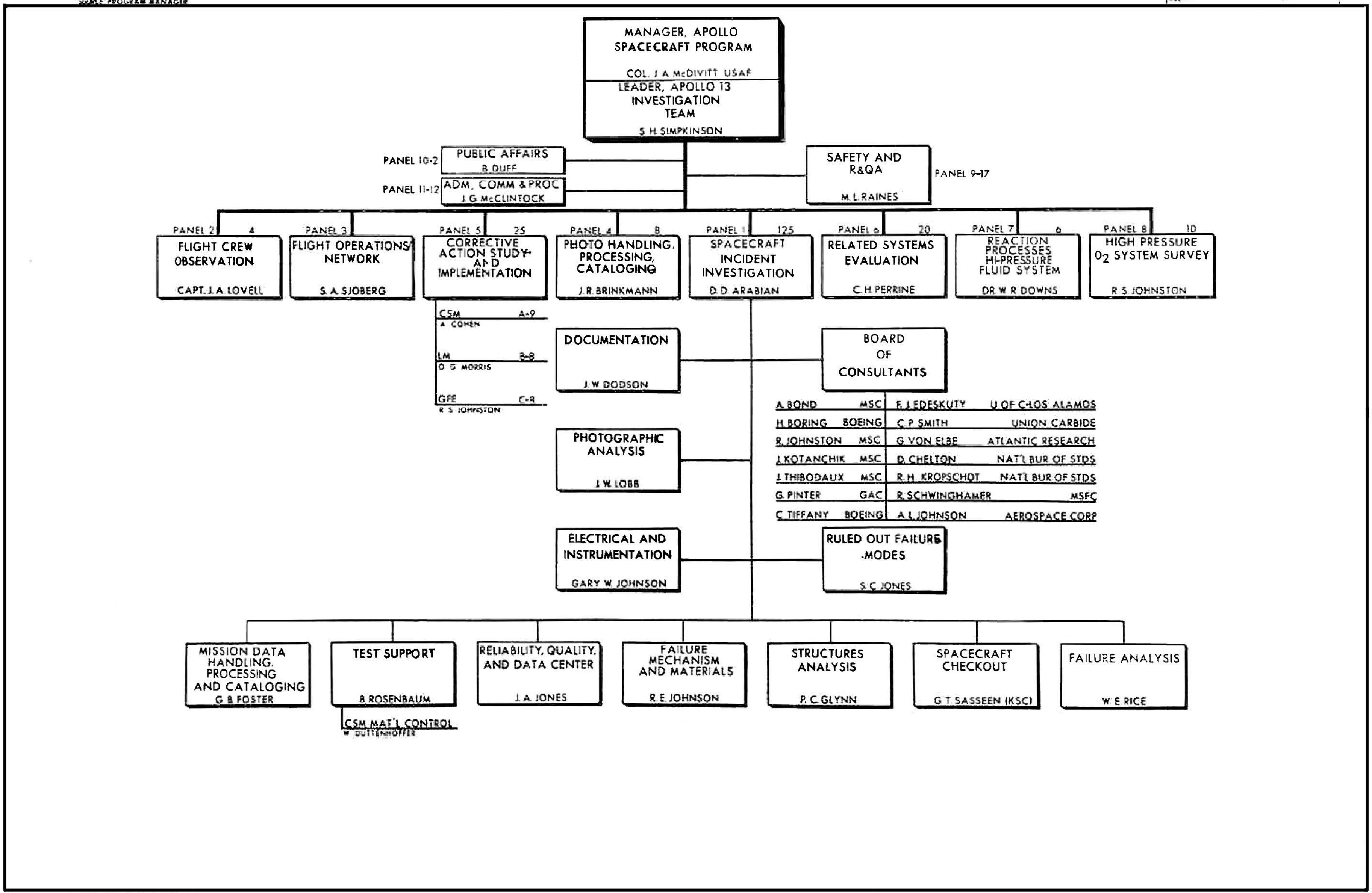
Immediately after the Apollo 13 crew and spacecraft were safely aboard the ship following splashdown, the Apollo Spacecraft Program Manager met with the Apollo Program Director and the Apollo 13 Mission Director to organize an investigation of the Apollo 13 mission failure. It was decided that the investigation would be performed following the guidelines set forth in the MSC/Apollo Mission Failure Investigation Plan.

As a result, an MSC Apollo 13 Investigation Team was organized under the leadership of the MSC Apollo Assistant Program Manager for Flight Safety. The team was comprised of eleven working panels as shown in Figure 1. Panel 1, Spacecraft Incident Investigation, took over the work that had been started immediately after the tank failed and set up a comprehensive approach comprising eleven subpanels, also shown in Figure 1. In addition, a board of 12 consultants was set up to oversee and guide the work of this panel.

After completion of their work, the first nine panels were requested to submit a report of their activity, including the findings and conclusions. Seven of these panels completed their work and will submit their final reports on or before June 2, 1970. Panels 5 and 6, however, are studying corrective action and related systems problems, respectively, and have not yet completed the work in these areas. This report, as published, contains the summaries extracted from the panel reports which were completed and should acquaint the reader with the activities of the MSC Apollo 13 Investigation Team.

MSC APOLLO 13 INVESTIGATION TEAM

SOURCE PROGRAM MANAGER



STATUS AS OF 21 MAY 1970

FIGURE 1

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PANEL 1

SPACECRAFT INCIDENT INVESTIGATION

DONALD D. ARABIAN
CHAIRMAN, PANEL I
MSC APOLLO 13 INVESTIGATION TEAM

CHAIRMEN OF SUBPANELS

Galloway B. Foster	Mission Data Handling, Processing, and Cataloging
Jack A. Jones	Historical Records Handling and Cataloging
Robert E. Johnson	Failure Mechanism and Materials
Philip C. Glynn	Structures Analysis
George T. Sasseen	Spacecraft Checkout
Bernard J. Rosenbaum	Test Support
W. Eugene Rice	Failure Analysis
John D. Lobb, Jr.	Photographic Analysis
Gary W. Johnson	Electrical and Instrumentation
Joseph W. Dodson	Documentation
Sidney C. Jones	Ruled-Out Failure Modes

PANEL 1

BOARD OF CONSULTANTS

Aleck C. Bond: Directorate of Engineering and Development, Manned Spacecraft Center

H. Boring: Boeing Company

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George Pinter: Grumman Aerospace Corporation

Robert Schwinghamer: Materials Division, Astrionics Lab, Marshall Space Flight Center

C. P. Smith: Union Carbide Corporation, Linde Division, Cryogenic Develop. Lab

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PANEL 1

SPACECRAFT INCIDENT INVESTIGATION

The loss of the cryogenic oxygen during the Apollo 13 flight was investigated from two aspects. First, what caused the flight failure? Second, could any factors during the ground history of the oxygen tank have contributed to the failure?

A problem in flight was first indicated when the quantity measurement in the tank suddenly increased to full-scale about 9 hours before the incident and remained there until nearly the time of the tank incident. This condition, in itself, could not have contributed to ignition in the tank because the energy in the circuit is limited to about 17 millijoules. This level of energy is at least an order of magnitude less than that found necessary to ignite any of the materials in the tank under the conditions existing at the time of ignition.

The electrical data provided the second indication of a problem when the fans in tank 2 were activated to reduce stratification which might have been present in the supercritical oxygen. Several short-circuits were detected, and these have been isolated to the fan circuits of tank 2. The first short-circuit could have contained as much as 300 joules of energy, which is within the current-protection level of the fan circuits. Tests have shown that an energy level two orders of magnitude less than this is sufficient to ignite the polytetrafluoroethylene insulation on the fan circuits in the tank. The evidence indicates that the insulation on the fan wiring was probably ignited by the energy in the short-circuit.

The burning in the tank then proceeded, causing the tank pressure to rise from about 890 psi to a peak value of 1008 psi, about half of the tank burst pressure. At that time the relief valve opened, as expected, and decreased the pressure in the tank to 995 psi. By this time, the burning had progressed to the point that all active electrical circuits to tank 2 had shorted and opened.

The next indication of a problem occurred when accelerometer traces in the Command Module showed vibration excitation which was greatest along the longitudinal axis. This was apparently at the time that the integrity of tank 2 was lost. The loss of tank pressure was probably caused by a failure in the wall of an electrical conduit between the inner shell and the outer shell when the fire progressed into the conduit. Tests under simulated conditions support this point of view. The only place the wiring nears or touches the walls of the actual pressure vessel is in the electrical conduit at the top of the tank.

Results to date indicate that there was probably no metal burning in the tank, and all tests with the physical configuration of the wire and hardware involved have resulted in burning only the insulation on the wire. To fail the tank at any location other than the electrical conduit, without burning metal, does not appear reasonable, particularly if only insulation was burning in zero g (with no convection).

Following the rupture of the conduit, tank 2 pressure remained above 880 psi to a point when all data were lost for approximately two seconds. If the tank had decreased below 880 psi, heaters in the tank would have come on automatically and they did not come on until during the 2-second data loss; therefore, up until the start of the data loss, only a small opening in the tank could have been present into the bay which housed the cryogenic tanks. A fraction of a second after the conduit failed, the pressure apparently increased rapidly in the bay and forced a panel off of the Service Module. The panel apparently struck the high-gain antenna, which was in a narrow-beam automatic tracking mode, resulting in a 2-second loss of data until the system automatically switched to a wide-beam mode. In this mode, a center horn is used which was not damaged and data were again usable. Thermal measurements show significant heating was present just before the panel separated, which indicated there probably was burning exterior to the tank. A ruptured tank that was dumping cold fluid would have caused chilling of the temperature sensors.

Many aftereffects resulted from the loss of tank-2 integrity. Most significant was the eventual loss of tank-1 pressure and the loss of electrical power from two of the three fuel cells after the shock of the panel separating caused two of the three oxygen supply valves to close. More important, however, was the fact that these closures were undetected, since a warning is only given to the crew when both the hydrogen valve and the oxygen valve to a fuel cell are closed. Oxygen tank 1 developed a leak either as a result of shock when the panel separated, or because of events associated with the failure of the tank-2 electrical conduit and the tank-2 vacuum-dome.

The exact conditions of tank 2 prior to flight are not known, but a reassessment of the history of that tank combined with further analysis and tests indicates that wires could have been damaged during assembly or ground tests that were not detected. This situation is inherent in the design. An incident when the cryogenic tank shelf was jolted during removal from a Service Module probably did not cause damage to the tank components. An extensive analysis shows the loads imposed as a result of the jolt were within the design capability. Tests are underway to determine if an unusual detanking operation at the launch site could have had any detrimental effect on the insulation of the wiring internal to the tank. These tests, to date, have shown negative results; however, they are continuing.

The analysis of test results and data associated with the incident led to the following conclusions:

1. A fire was started by electrical short-circuits in the wiring to the fan motors inside cryogenic tank 2 shortly after the fan circuits were energized.

2. Burning of the insulation probably continued for about 80 seconds before reaching the pressure vessel electrical conduit. The heat of the burning probably resulted in failure of the 1/2-inch diameter Inconel conduit, all of which ultimately led to failure of the vacuum-dome and subsequent separation of the bay-4 structural panel.

PANEL 2

FLIGHT CREW OBSERVATIONS

JAMES A. LOVELL
CHAIRMAN, PANEL 2
MSC APOLLO 13 INVESTIGATION TEAM

MEMBERS

John L. Swigert, Jr.

Fred W. Haise, Jr.

Thomas K. Mattingly

PANEL 2

Flight Crew Observations

At approximately 54:54:00 GET, a loud explosion occurred while the Command Module Pilot was in the left seat, the Commander in the lower equipment bay, and the Lunar Module Pilot in the tunnel. The noise was comparable to that noted in exercising the lunar module repressurization valve. The Command Module Pilot and Lunar Module Pilot also felt a minor vibration or tremor in the spacecraft.

Approximately 2 seconds later, the Command Module Pilot reported a master alarm and a main bus B undervoltage light. Voltage readouts from main bus B, fuel cell 3 current, and reactant flows were all found normal. It was concluded that a transient had occurred. The Command Module Pilot then initiated efforts to install the tunnel hatch.

The Lunar Module Pilot proceeded to the right seat and found the ac bus 2 and ac bus 2 overload lights on, with main bus B voltage, fuel cell 3 current, and fuel cell 3 reactant flows off-scale low. Inverter 2 was then removed from main bus B.

On switching ac electrical loads to ac bus 1, the main bus A undervoltage light illuminated, with a corresponding voltage reading of 25.5. A check of the fuel cells revealed fuel cell 1 reactant flow to be zero. At all times, fuel cells 1 and 2 were tied to main bus A and fuel cell 3 to main bus B, with the proper gray flags displayed.

Efforts to install the tunnel hatch were terminated when the Commander observed venting of material from the service module area. He then reported the oxygen tank 2 pressure was zero and oxygen tank 1 pressure was decreasing. This information pinpointed the problem source to within the command and service modules.

At ground request, fuel cells 1 and 3 regulator pressures were read from the systems test meter, confirming the loss of these fuel cells. AC bus 2 was tied to inverter 1, and the emergency power-down procedure was initiated to reduce the current flow to 10 amps. At ground request, fuel cell 1 and, shortly thereafter, fuel cell 3 were shut down in an attempt to stop the decrease in oxygen tank 1 pressure.

Lunar module powerup was handled quite efficiently by identifying selected segments of an existing procedure, the Lunar Module Systems Activation Checklist. However, the crew had to delete the VHF portion of the communications activation. This procedure also assumed suited operations, so the crew had to turn on suit flow valves and unstow hoses to establish air flow. This extended powerup blended well with the preparation for the subsequent midcourse maneuver to return to a free-return trajectory. A similar real-time update to the 2-hour activation section of the Lunar Module Contingency Checklist was also quite adequate.

Lunar module activation was completed at the time fuel cell 2 reactant flow went to zero because of oxygen depletion. The command and service modules were then powered down completely according to a ground-generated procedure. To form a starting base line for subsequent procedures, each switch and circuit breaker in the command module was positioned according to a ground-transmitted procedure.

Potable water was obtained by periodically pressurizing the potable tank with surge-tank oxygen and withdrawing potable water until the pressures equalized. This method provided potable water for crew use until 24 hours prior to entry, at which time the potable tank was exhausted.

The hatch, probe, and drogue were secured in the couches by lap belt and shoulder harness restraints to prevent movement during subsequent maneuvers.

PANEL 3

FLIGHT OPERATIONS AND NETWORK

SIGURD A. SJOBERG
CHAIRMAN, PANEL 3
MSC APOLLO 13 INVESTIGATION TEAM

PANEL 3

Flight Operations and Network

The Apollo 13 flight was essentially following the nominal flight plan prior to 55 hours 53 minutes ground elapsed time (GET). The center engine on the S-II stage of the Saturn launch vehicle shut down about 2 minutes early, but this had no effect on insertion into earth orbit or on translunar injection. The Saturn S-IVB stage had been successfully targeted toward the planned lunar impact area near the Apollo 12 seismometer. The launch vehicle debriefing with the crew had been completed, and entry into the lunar module (LM) had been made about 3 hours early to inspect the supercritical helium pressure in the descent propulsion system. This pressure was satisfactory, and no further action was contemplated.

At 55:53 GET, a command module computer restart was observed, followed by a report from the crew that a main bus B undervoltage had occurred about the same time as a "loud bang." There was a short period during which the Control Center and the crew sorted out the false indications from the true anomalies, but it quickly became apparent that one of the two cryogenic oxygen tanks and two of the three fuel cells had been lost. The command module (CM) systems were configured to protect the entry capability. Efforts were concentrated on attempting to save the remaining oxygen tank. These efforts proved to be futile, and at 57:35 GET, the commander and lunar module pilot were entering the LM to establish communication and life support functions. The LM guidance system was powered up and aligned to preserve a maneuver capability and at 58:40 (GET), the command and service module was completely powered down. About 20 amp hours had been used from the total of 120 amp hours available in the CM entry batteries.

Once the systems situation had stabilized, the attention of the Control Center turned to the trajectory plan. The current status was that the spacecraft was on a nonfree-return trajectory which would require a significant maneuver to change to satisfactory entry conditions. A direct return to earth with landing time of 118 hours GET was possible only by using the service module propulsion system and jettisoning the LM. This option was unavailable for obvious reasons and reduced the considerations to either of the following: (a) Execute an immediate 40 fps midcourse correction to a free-return trajectory (landing at 152 hours GET in the Indian Ocean). There would then be an opportunity to reduce the transearth coast time by making a maneuver about 2 hours after flying by the moon. (b) Wait to make the first maneuver until about 2 hours after flying past the moon.

The plan adopted (and which was essentially unchanged) was to execute an immediate midcourse correction to a free return trajectory, evaluate the consumables with the intention of keeping the LM guidance system powered up through major maneuvers if at all possible, and executing a major LM descent engine burn about 2 hours after passing the moon (79:30 GET).

The primary effort for the remainder of the mission was directed towards establishing the various procedures required for the many non-standard operations, for example, CM battery charging from LM batteries, CM LiOH cannister use on LM environmental control system, no-optics alignment for maneuvers, water transfer from CM and portable life support system tanks to LM tanks, service module jettison, and many others.

The consumable situation continued to improve and stabilize to the point where it was feasible to leave the LM guidance system powered up until the descent engine maneuver with every expectation that the systems could easily be managed to stay within the consumable quantities available. This proved to be the case and, after the major manever at 79:30 GET, the usage rates had dropped to be clearly compatible with the landing time. Sufficient workaround procedures had also been established to provide margins should there be subsequent loss of batteries, water tanks, or oxygen tanks in the LM.

There were several options available for the maneuver at 79:30 GET (2 hours after lunar flyby). These included jettisoning the service module before the burn and burning the descent engine to near depletion. The consumables status did not justify going to either of these extremes, and the maneuver was targeted to reduce the landing time from 152 hours GET to 142 hours GET and change the landing area from the Indian Ocean to the Pacific Ocean. This allowed a comfortable propellant margin for future midcourse corrections.

The transearth coast portion was devoted to getting the ground developed procedures up to the crew at the proper times and in executing two small midcourse adjustments to the trajectory. The consumable status had continued as predicted, and the LM was powered up early to help warm up the crew and allow them a better chance to rest. This early power-up also allowed a LM Primary Guidance and Navigation System alignment, which was later transferred to the CM Guidance System saving several minutes in the critical preentry phase.

The service module was jettisoned about 4-1/2 hours prior to entry interface (EI) and the CM power-up procedure started at EI - 2 hours 30 minutes. The CM Guidance System was fine-aligned and the LM was jettisoned at EI - 1 hour. All CM systems functioned properly during entry and the landing could be seen from television on board the recovery ship. The crew were recovered in 45 minutes and were in good condition.

PANEL 4

PHOTOGRAPH HANDLING, PROCESSING, AND CATALOGING

JOHN R. BRINKMANN
CHAIRMAN, PANEL 4
MSC APOLLO 13 INVESTIGATION TEAM

MEMBERS:

E. Jack Ottinger
Taylor W. Moorman
Carlos Ramirez
Ludy T. Benjamin
George C. Collins
Noel T. Lamar
John Denman

PANEL 4

Photograph Handling, Processing, and Cataloging

Eleven rolls of Apollo 13 flight film arrived at the MSC Photographic Technology Laboratory (PTL) at 8:45 a.m. on April 19, 1970. While the film was being downloaded for processing, the radiation level was being checked by measuring the dosimeter included in the film transportation box. Radiation level was less than 0.5 rads and considered satisfactory. There was no detectable effect of radiation on any of the processed film.

Priority processing proceeded on Magazine N (70-mm color film, type SO-368), Magazine R (70-mm black-and-white film, type 3400), and Magazine FF (16-mm color motion-picture film, type SO-368). These three magazines contained the only photography of the damaged service module in flight. The 70-mm color still photographs were shot by Astronaut Swigert using a Hasselblad camera with a 250-mm lens. Exposure was reported to be 1/250 second at f/8, but this exposure cannot be confirmed by the crew. The camera Swigert used was originally to be used in the command module but was taken to the lunar module by Swigert to photograph the damaged service module. The 70-mm black-and-white still photographs were shot by Astronaut Lovell using a Hasselblad camera with an 80-mm lens. Exposure was reported to be 1/250 second at f/8--again, unconfirmed by the crew. The 16-mm color motion-picture film was shot by Astronaut Haise using the data-acquisition camera with a 3-inch focal-length lens. Exposure was reported to be 1/250 second at f/8 at a 12-frames-a-second rate. This exposure also was not confirmed by the crew.

The decision to use SO-368 color film and type 3400 black-and-white film to photograph the damaged service module in flight was made by a committee comprising Helmut Kuehnel (Missions Operations), James Peacock (Apollo System Engineer), John Brinkmann, Richard Underwood, and Mark Weinstein (PTL), and spacecraft designers.

The color SO-368 was selected because of the possibility of color stain on the service module which could help define the cause of the accident. The black-and-white type 3400 was chosen to give best resolution and latitude to record details and account for any exposure deviations.

When the film arrived at PTL, it was decided that the SO-368 would be processed normally so that correct color balance would be maintained. The SO-368 was processed first to determine spacecraft orientation, lighting, and validity of exposure used. Analysis showed that the color film had been slightly underexposed, and most of the critical areas were in shadow.

The black-and-white type 3400 film therefore was processed to gain as much film speed rating as possible to obtain maximum information available in the shadow areas. The process cycle selected produced the ultimate amount of shadow detail possible and yielded a high gamma product with a wide range of densities. With this high-gamma original, the slower speed duplicating stock required a long exposure with low-gamma processing employed to insure best shadow detail.

None of the resulting imagery was optimum with respect to sharpness or lighting. The lack of picture sharpness is attributed to the fact that the cameras were focused at approximately 100 feet by instruction from ground control and the actual distance of the service module was later estimated to be 269 meters for Magazine N and an average of 125 meters for Magazine R. With the longer focal length lenses on the color film cameras, the service module was apparently not within the acceptable limits of depth of field range. However, with the shorter focal length lens on the black-and-white film camera and the closer distance of the service module, the photography was more within the depth of field range and the images were fairly sharp.

The distance of the service module from the camera resulted in a very small image on all of the frames--both motion picture and still. The image on the 70-mm color frame was at a 1:1077 scale and on the 70-mm black-and-white frame averaged a 1:1500 scale. This meant that, in addition to lack of sharpness of focus, enlargement of the photographs resulted in image deterioration because of film grain structure.

Since image enhancement was obviously needed, 11 still photographs were selected from Magazines N and R for enhancement attempts. The 11 frames comprised frames 8462 and 8464 from Magazine N and frames 8500, 8501, 8510, 8511, 8512, 8513, 8530, 8531, and 8534 from Magazine R. Visual examination was made of the Magazine FF 16-mm color motion-picture film, and a determination was made to concentrate on still picture enhancement only since the motion-picture film had no additional information in it.

Further study resulted in the selection of two color 70-mm frames from Magazine N (frames 8462 and 8464) and two black-and-white 70-mm frames from Magazine R (frames 8500 and 8501) for concentrated enhancement attempts. The two black-and-white frames were usable as a stereo pair when properly oriented.

In addition to immediate in-house enhancement attempts, the two 70-mm black-and-white frames were reproduced to the best possible masters; and sets were sent for additional enhancement work to Data Corporation in Dayton, Ohio, McDonnell Douglas Astronautics in Huntington Beach, California, Jet Propulsion Laboratory in Pasadena, California, and LogEtronics, Incorporated, in Springfield, Virginia.

The two color frames from Magazine N were studied in-house on optical instruments only because what little information there was beyond that already available on the black-and-white frames could not be reproduced.

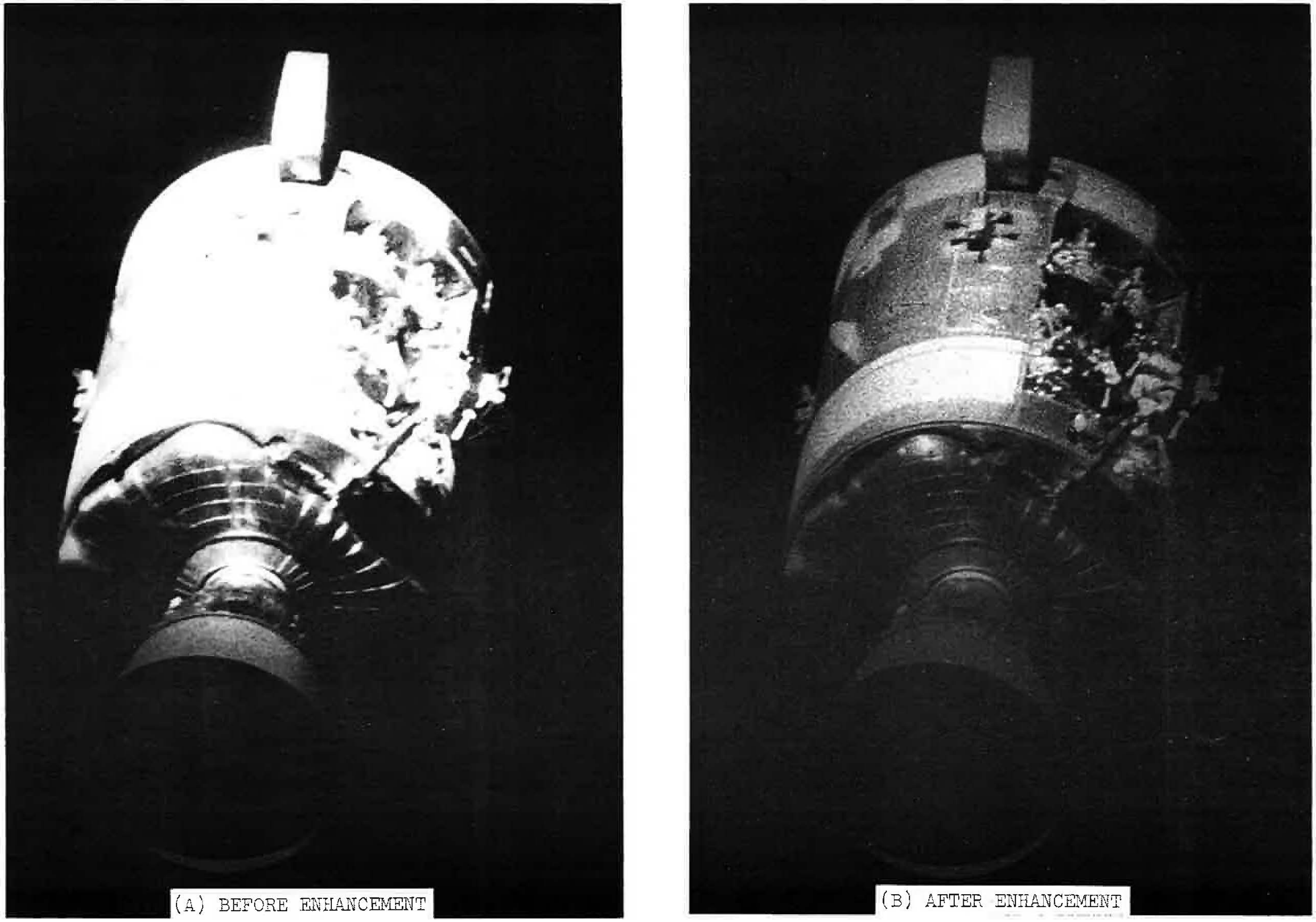
The final results of all enhancement attempts have been received at MSC. All efforts to date, both in-house and out of house, have reached approximately the same level of enhancement; and all products have been shown to Board and Panel members for their evaluation and judgment.

The Photographic Analysis Group of Panel 1 reports that, considering the marginal characteristics of the original photography, the blowups are quite remarkable. The processing produced, on hardcopy, photographic information which previously could only be viewed on a transparency through a magnifier. However, obtaining this information required mentally combining the presentations of each of the three color layers. The process, of course, cannot duplicate the color acuity and flexibility of focus of the eye.

Additional information on exterior placement of the loosened Mylar was more evident in the blue-layer prints, more contrast in the red layer, and more interior definition with the green layer when compared with the blue and red. The processing did not provide a clear image of the no. 2 oxygen tank.

Photographs are attached showing the result of image enhancement attempts and the service module mockup photographed with lighting duplicating inflight condition.

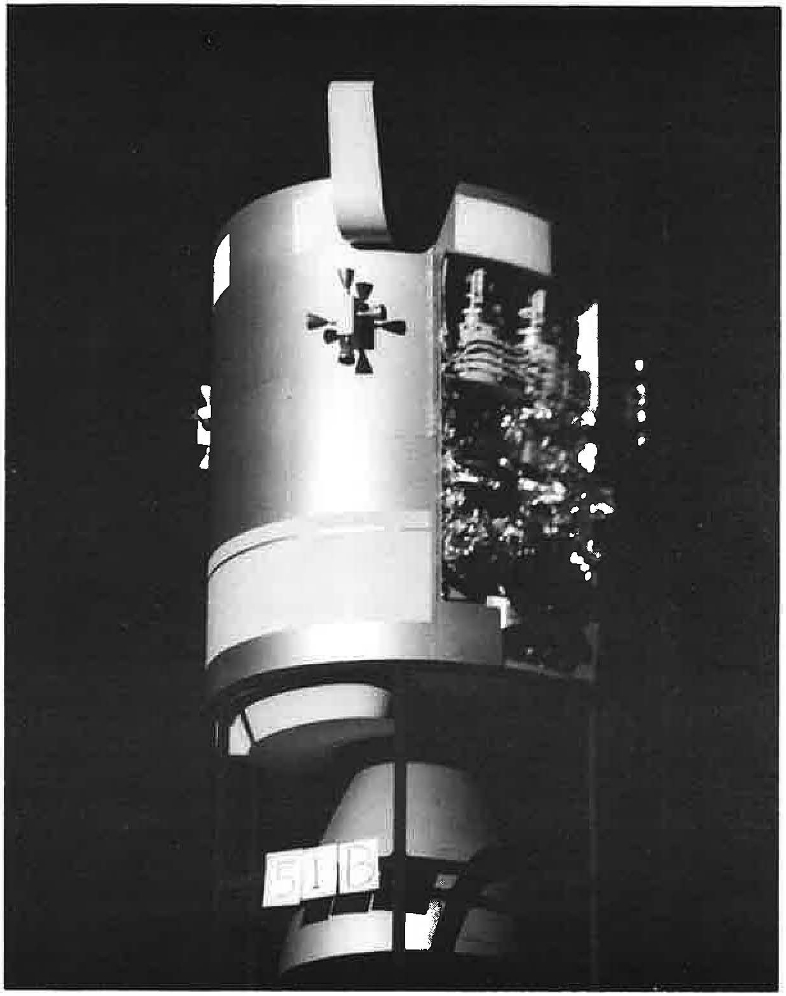
Enclosures 2



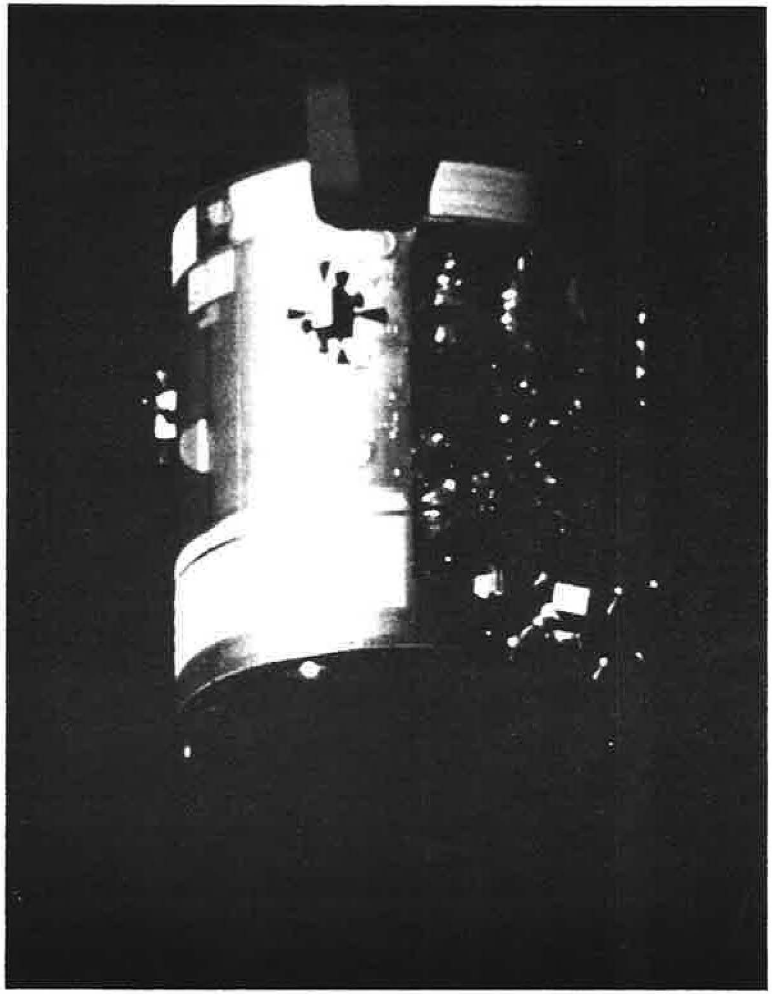
(A) BEFORE ENHANCEMENT

(B) AFTER ENHANCEMENT

APOLLO 13 SERVICE MODULE PHOTOGRAPH
(MAGAZINE R, FRAME 8500)



APOLLO 13 SERVICE MODULE MOCKUP AT MSC WITH LIGHTING DUPLICATING THE IN-FLIGHT CONDITIONS OF MAGAZINE N, FRAME 8464



APOLLO 13 SERVICE MODULE INFLIGHT, MAGAZINE N, FRAME 8464

PANEL 5A

CORRECTIVE ACTION STUDY AND IMPLEMENTATION

COMMAND AND SERVICE MODULE

AARON COHEN
CHAIRMAN, PANEL 5A
MSC APOLLO 13 INVESTIGATION TEAM

MEMBERS:

Richard B. Ferguson
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Wilburne F. Hoyler
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Charles N. Rice
R. E. Bobola
Don L. Teegarden
Robert C. Hood
George B. Merrick, North American Rockwell

PANEL 5A

Corrective Action Study and Implementation
Command and Service Module

Panel 5A worked closely with Panel 1 and considered three areas of activity within their responsibility.

1. Study and implementation of corrective action associated with the cryogenic oxygen system failure which occurred on Apollo 13.

2. Establishment of the as-flown configuration of SM 109 Bay IV and identification of differences within the bay between SM 108, SM 109, and SM 110.

3. Assessment of the feasibility and implementation of corrective action for potential problems identified by the Related Systems Evaluation Panel (Panel 6).

The panel activities were initiated immediately after the completion of the Apollo 13 flight. The initial efforts have been aligned towards alternate design approaches to correct the anomalies as identified by Panel 1.

The investigation being conducted by Panel 5A will not be considered complete until the findings and recommendations of the Apollo 13 Review Board have been received and assessed for the need for further corrective action.

PANEL 5B

CORRECTIVE ACTION STUDY AND IMPLEMENTATION

Lunar Module

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MSC APOLLO 13 INVESTIGATION TEAM

MEMBERS

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Philip M. Deans
James J. Shannon
Edison M. Fields
Norbert B. Vaughn
Donald J. Markarian - Grumman Aerospace Corp.

PANEL 5B

Corrective Action Study and Implementation
Lunar Module

Panel 5B was created to conduct studies of corrective action and proposed hardware implementation for the lunar module, as required. The panel reviewed the results of other panels primarily Panel 1, The Spacecraft Incident Investigation, and the Related Systems Evaluation conducted by Panel 6. Considering the material available to the panel at this time, no specific recommendations have been made for lunar module hardware change. However, it is apparent that some items will require further study.

The investigation being conducted by Panel 5B will not be considered complete until the findings and recommendations of the Apollo 13 Review Board have been received and assessed for the need for further corrective action.

PANEL 5C

CORRECTIVE ACTION STUDY AND IMPLEMENTATION

GOVERNMENT FURNISHED EQUIPMENT

RICHARD S. JOHNSTON
CHAIRMAN, PANEL 5C
MSC APOLLO 13 INVESTIGATION TEAM

MEMBERS

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Dean F. Grimm
John H. Langford
E. Jones
Chester E. McCullough, Jr.
Norbert Vaughn
James W. Thompson

PANEL 5C

Corrective Action Study and Implementation
Government Furnished Equipment

The scope of the GFE Panel activities was limited to the compilation of a list of pressure vessels in GFE, review of the criticality ratings for GFE end items, and review of the acceptability of the design of Criticality I equipment. The pressure-vessel data were required to support an in-depth review by another panel of all Apollo spacecraft pressure vessels. Evaluation of GFE materials and electronic circuit elements were not considered, based on the extensive equipment review and redevelopment which resulted from the Apollo 204 investigation and the continual review of the use of nonmetallic materials, their proximity to ignition sources, and other safety aspects by all levels of program management.

The investigation being conducted by Panel 5B will not be considered complete until the findings and recommendations of the Apollo 13 Review Board have been received and assessed for the need for further corrective action.

PANEL 6

RELATED SYSTEMS EVALUATION

CALVIN H. PERRINE, JR.
CHAIRMAN, PANEL 6
MSC APOLLO 13 INVESTIGATION TEAM

SUBPANEL CHAIRMEN

Jerry W. Craig	Lunar Module
Richard A. Colonna	Command and Service Modules
John R. Sevier	Government Furnished Equipment
David W. Camp	Ground Support Equipment

PANEL 6

Related Systems Evaluation

The purpose of the investigation was to reevaluate the Apollo systems design in light of the failure of the CSM cryogenic oxygen tank which caused the abort of the Apollo 13 mission. The evaluation included all CSM, LM, GFE, and GSE pressurized subsystems. Within each system, consideration was given to the tank or container, the line components with electrical interfaces, and line components without electrical interfaces. Potential sources of subsystem failure were considered including electrical failures, materials incompatibilities, mechanical failures, thermal problems, and manufacturing and process discrepancies. The panel also considered the potential consequences of failure. Primarily, emphasis was placed on oxygen and oxidizer systems and electrically induced modes of failure.

The findings of this panel will be in four volumes.

Volume I	Summary
Volume II	Lunar Module
Volume III	Command and Service Module
Volume IV	Government Furnished Equipment and Ground Support Equipment

The investigation being conducted by Panel 6 is continuing and will not be considered complete until the panel has had an opportunity to review the findings and recommendations of the Apollo 13 Review Board and assessed their impact on other systems within the spacecraft.

PANEL 7

REACTION PROCESSES IN HIGH-PRESSURE FLUID SYSTEMS

DR. W. R. DOWNS
CHAIRMAN, PANEL 7
MSC APOLLO 13 INVESTIGATION TEAM

Members:

Dr. Robert C. Ried, Jr., Deputy Chairman
Quintin T. Ussery
Robert F. Fletcher
Dr. M. E. Taylor

PANEL 7

Reaction Processes In High-Pressure Fluid Systems

This summary presents the results of several physical, chemical, and thermodynamic surveys which have been made on the high-pressure tank and plumbing systems of the Apollo spacecraft. These systems comprise the pressurized oxygen, hydrogen, nitrogen, propellant, and helium tanks and related plumbing. The purposes of the surveys are to lend support to the Apollo 13 investigation, to provide review and extend knowledge of spacecraft pressure systems, and to contribute to the safety of future manned space flight. To achieve these objectives, descriptive data for all tanks were collected, a metallurgical survey and a comprehensive physical chemical survey of all systems were made, and some detailed thermodynamical calculations were performed.

Descriptive data for all tanks on the Apollo command module, service module, and lunar module have been collected, collated, and tabulated. A listing was made of tank numbers, location, and dimensions. Materials of construction, design pressure, normal operating pressures, actual operating pressures, temperatures, and fluid flow rates are tabulated for all tanks in the spacecraft.

The oxygen, hydrogen, and hypergolic propellant tanks have been examined in detail for contaminants and incompatibilities that could be potentially dangerous. Mechanisms for failure by contaminants, incompatible materials, and physical processes have been postulated for the supercritical hydrogen tank, supercritical oxygen tank, propellant tanks, and oxygen ground service equipment. The mechanisms considered are (1) brittle fracture failure (below material yield strength) caused by pre-existing flaw (mode-fragmentation or leakage) and (2) tank rupture at material ultimate strength caused by pressure increase where the mode is fragmentation resulting from combustion of polymeric and metallic materials interior to the tank, from combustion of fluid impurities after segregation and concentration, and from catalytic decomposition of tank contents.

Metallurgical assessment addressed itself to inherent metallurgical characteristics of the various tank materials with respect to metal combustion, stress corrosion, and fracture mechanics evaluation of a tank's integrity. Assuming the fabrication and use of the tanks are not violated, and provided approved fluids and procedures associated with the tank usages are maintained, unexpected combustion of metals from impact or abrasion appears remote, and stress corrosion appears unlikely. The only instance of metallurgical incompatibility noted is in the hydrogen tanks, where tin-lead solders and brass (containing zinc) and iron in the fan assemblies are of doubtful service in liquid hydrogen. These metal systems require further investigation, since it is known that lead and zinc are incompatible with liquid hydrogen but no known data exist which can resolve the questions of the solder, brass, or iron compatibilities.

Descriptive data on the high-pressure systems and the information obvious from the Apollo 13 accident required a physical chemistry survey of the several tank systems. This survey indicated the following results:

Polytetrafluoroethylene, when heated, decomposes (unzippers) into the monomer (C_2F_4), elemental fluorine (F_2), fluoro-methane (CF_4), and other fragments. If oxygen is present, the monomer oxidizes to COF_2. If metals in suitable physical state for reaction are present, the metal is converted to its fluoride (and oxide if oxygen is available). If ceramics, such as silicates and glass are present, reaction to silicon fluoride and metal fluorides occurs. Oxygen, fluorine, and hydrogen all react with polytetrafluoroethylene at about 650°C (1202°F) for virgin unfilled polymer and at about 430°C (806°F) for filled polymer, dependent on fillers used. The basic reactions are as follows:

$(-CF_2-)_n \longrightarrow C_2F_4 + (F_2 + CF_4 + C)$ Unzippering

$(-CF_2-)_n + O_2 \longrightarrow COF_2$ Oxidation by oxygen

$(-CF_2-)_n + H_2 \longrightarrow HF + C$ Hydrogenation

$(-CF_2-)_n + F_2 \longrightarrow CF_4$ Incipient combustion from pyrolysis

$(-CF_2-)_n + OF_2 \longrightarrow CF_4 + O_2$ From sparks and arcing

$(-CF_2-)_n + Al \longrightarrow AlF_3 + C_2F_4 + CF_4$

Safe usage of PTFE involves preventing high-temperature environments (above 500°C (932°F)) for unfilled virgin polymers and 400°C ((752°F) for filled polymers) from occurring within the polymer structure. Polytetrafluoroethylene (PTFE), a thermodynamically reactive material, can react rapidly and destructively with a variety of materials dependent on only a few triggering mechanisms. Knowledge of the triggering mechanisms is imperative. Prevention of excessive heating on external PTFE surfaces and elimination of mechanisms for sparking, arcing, and high-pressure induced shocking is mandatory for its safe use in high-pressure systems.

To avoid chemical reactions due to surface charging inside high-pressure tanks and plumbing, impurities and high flow rates must be excluded from oxygen systems where potential combustibles such as PTFE exist. Water as ice crystals in a high-pressure system is especially hazardous. Only an experimental program can establish the magnitude of the limits of impurities and flow rates in critical systems well below those which by experience have not been sufficient to cause difficulties.

Polytetrafluoroethylene is degraded for electrical and chemical service when the polymer contains inorganic chemical fillers, fibers, and coloring agents to the extent that its resistance to thermal effects may drop as much as 300°C (from 733°C to 430°C, 1351°F to 806°F). Treatment of PTFE parts with halocarbons will degrade the polymer for nitrogen tetroxide service. No hazards are expected in using PTFE components in high-pressure oxygen or nitrogen tetroxide service provided the following conditions maintain:

1. Unpigmented virgin polymer is used where physical conditions permit.
2. Temperatures are not permitted above 430°C (806°F).
3. Electric sparks and arcing at polymer sites cannot occur.
4. Halocarbon cleansing agents are completely removed.

Catalytic acceleration of chemical reactions in the spacecraft pressurized containers has been reviewed, and the following areas have been identified as regions where significant catalytic action may occur:

1. Reactive degradation of fluorocarbons -- It has been noted that the reactivity of PTFE varies markedly, dependent on the fillers, coloring dyes, and contaminants contained in the structure. Such fillers and dyes may act catalytically to induce decomposition of the polymer. This is the case with metals which may come in intimate contact with PTFE and with particulate contaminants which can impinge the surface of the polymer. For spacecraft systems, the use of halocarbons for cleaning high-pressure PTFE parts for nitrogen tetroxide service should be avoided because of catalytically induced reactivity.

2. Reaction between fluids and impurities -- Strict attention to standards of purity in the fluids and in the fluorocarbons is important to avoid unexpected catalytic effects. Rigorous application of present knowledge to purification and surface preparation would increase safety, while research into reaction mechanisms would be desirable for long-range improvements.

3. Catalytic effects of impurities on crack propagation -- Liquid oxygen, hydrogen, and nitrogen have very low dielectric constants. They are not electrolytes and the effect of dissolved impurities is expected to be additive. The results of a recent NASA-sponsored research program point out that Ti-5Al-2.5Sn is adversely affected at ambient temperatures by the hydrogen environment. Although the risk has obviously been considered before the selection of this particular alloy for the hydrogen tanks, this alloy as well as its surface treatment should be reviewed.

The hypergolics are electrolytes, and impurities in this case must be expected to act as powerful catalysts. Some research on impurity effects on the corrosivity of N_2O_4 was done and incorporated in the specifications. The influence of impurities on corrosivity and crack propagation in the case of monomethyl hydrazine and Aerozine-50 apparently has not yet been investigated. Each flight batch, however, is tested with surface flawed specimens to indicate no metal fluid incompatibilities.

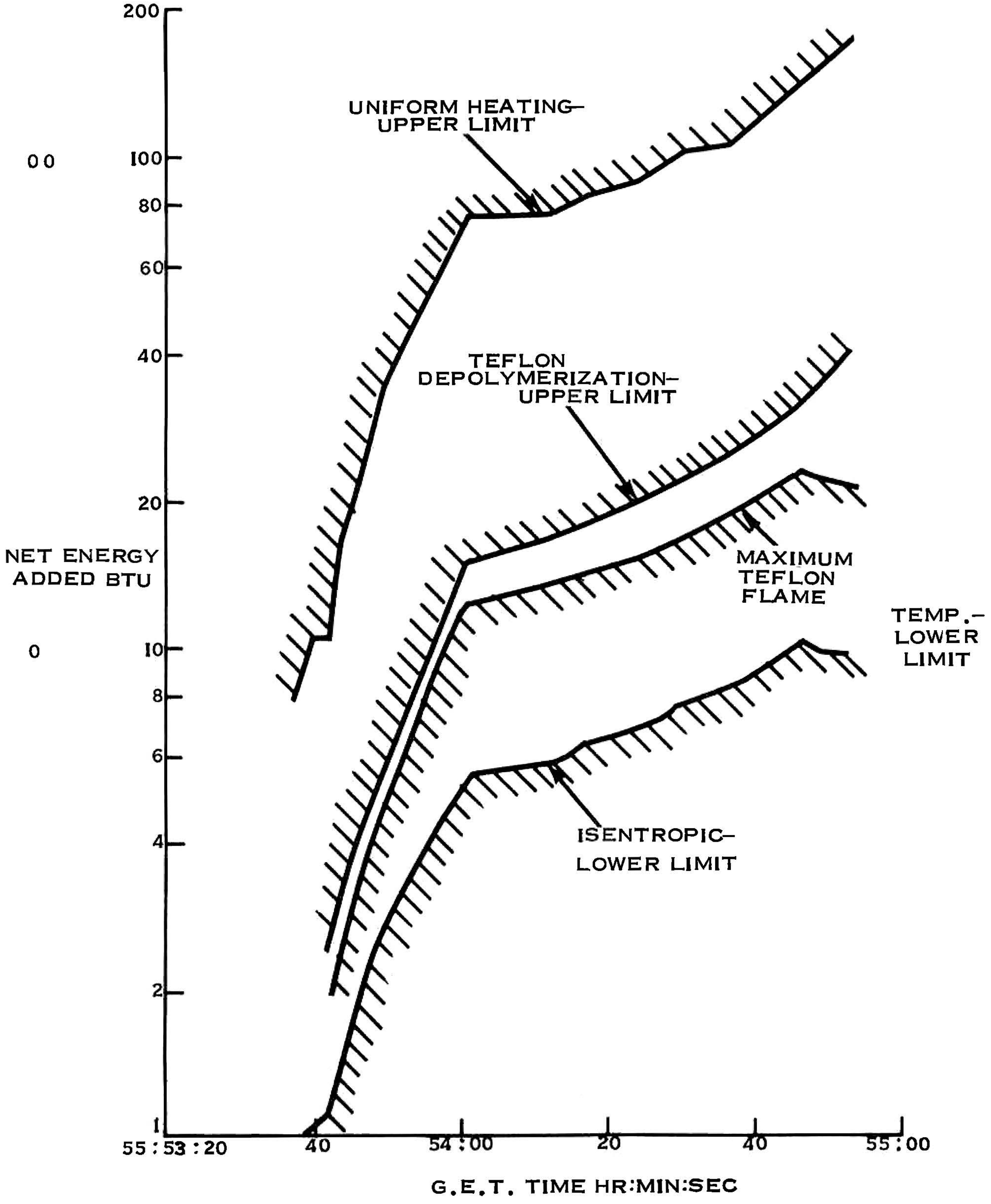
Extent of polymer degradation upon exposure to (a) high-pressure shock treatment, (b) oxidation, (c) catalytic influence, and (d) hydrogenation can be followed by using electron microscopy techniques. Degradation induced by fillers or coloring agents, as well as by aging, can be delineated by correlating size and numbers of voids in PTFE structure with known histories of specimens of virgin composition.

The thermodynamic limitations on the net energy added to the oxygen in the Apollo 13 No. 2 tank are shown on the attached figure. The limits have been established under the constraints of the measured pressures and temperatures, the tank volume, and the oxygen mass. The calculations include nominal mass usage, nominal heat leak, and the work which the fluid performs on the tank. The ultimate limits of uniform heating and an isentropic process have previously been reported. The isentropic limit has been lowered due to increased accuracy obtained in the calculation procedures. This lower limit is, however, within the accuracy of knowledge of the thermodynamic properties of supercritical oxygen.

Because of the extremely low thermal conductivity of supercritical oxygen and the zero-gravity state, it is reasonable to describe the distribution of energy within the oxygen by a two-fluid model. The two-fluid model establishes very sensitive temperature distributions, which in turn allow a very close specification of the energy added to the oxygen. Since the ultimate limitations are well within the energy available from the PTFE combustion, the characteristics of PTFE burning have been used to establish peak temperature limitations and therefore energy addition. The lower limit is obtained by assuming that the peak temperature in the reaction zone is equal to the theoretical limiting flame temperature for a stoichiometric reaction. The upper limit is established by the constraint that the peak temperature had to be high enough to allow the PTFE to undergo depolymerization. This is only a limit to the energy added to the oxygen and does not include energy which may have gone into heating structural components of the tank. Details of this analysis are presented in the final report.

Panel 7 is indebted to the following individuals for their help: Dr. Alan W. Smith, the Boeing Company, for his study of electrostatic effects; Dr. Hans Brunner, the Boeing Company, for his work in catalysis and solid state physics and fracture mechanics effects; Mr. Robert E. Johnson and Mr. Glenn W. Ecord, MSC, for their help in metallurgical review of the spacecraft fluid systems; Dr. Winston D. Goodrich and Mr. Michael A. Gibson, MSC, for their help in the thermodynamic calculations; Dr. C. A. Krier and the Boeing/SMD organization for helpful suggestions; Mr. Joseph N. Kotanchik, MSC, for his beneficial comments and reviews; Dr. Hans Mark, ARC, for his help in physics and insight into mechanisms; and Dr. Wayne D. Erickson, LRC, for his assistance in thermodynamics.

THERMODYNAMIC LIMITATIONS TO THE NET ENERGY ADDITION TO THE 2 OXYGEN TANK



PANEL 8

HIGH-PRESSURE OXYGEN SYSTEMS SURVEY

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MSC APOLLO 13 INVESTIGATION TEAM

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PANEL 8

High-Pressure Oxygen Systems Survey

The objective of Panel 8, "High-Pressure Oxygen Systems Panel" of the MSC Apollo 13 Investigation Team was primarily to conduct a comprehensive survey of the state of the art in aircraft and commercial oxygen systems. Although there was very limited time available, the panel also included low-pressure gaseous and liquid oxygen systems in its scope to make the survey as complete as possible. Secondary objectives of this survey were considered by the panel to be:

1. The identification of differences, if any, in technology between various oxygen systems.

2. Identification of new technology which is not in general practice and should be considered for application across the industry.

3. The review of various standards and criteria used in the manufacture, service, use, and control of oxygen systems.

Panel 8 was established on April 17, 1970, by the Apollo Program Manager to conduct the stated survey. Several administrative meetings were held during the week of April 20, 1970, to develop the survey approach, the overall panel makeup, and worksheet questionaires. To maintain the survey in manageable proportions, the panel selected typical oxygen systems from each of several industries and conducted a detailed review of these systems. The typical systems selected were chosen to be representative of commercial aviation, military aviation, submarine, spacecraft, aircraft carrier, hospital, and altitude chamber breathing oxygen systems in use today. During the week of April 27, 1970, representatives of the Boeing, McDonnell-Douglas, and AiResearch Companies and the Naval Research Laboratory prepared data packages and presented information on their respective oxygen systems to the panel. Presentations and system reviews generally covered the topics listed below:

1. Design standards and system features
2. System performance requirements
3. Component design
4. Test philosophy and experience
5. Process controls and standards
6. Materials control and listings
7. Failure experience
8. Parts lists and suppliers

Information from the presentations and general discussions which followed and answers to the questionnaires were used to make system comparisons.

Because of variations in design, performance requirements and operating characteristics, it was not possible to make a direct comparison of the systems. The general characteristics of these systems are summarized in table 1. The presentation and discussion of the various oxygen systems revealed a number of differences between the design methods and needs of the different commercial and governmental groups. However, a common concern for safety was very much in evidence. Discussions of safety considerations indicated that one major concern of each group was the control of fuel (combustible material) and ignition sources. Fuel was considered to be both metallic and nonmetallic system materials and contaminants in the presence of the oxidizer. Ignition sources were considered to be any phenomenon which could cause a material to reach its ignition temperature.

In design considerations, the hospital, altitude chamber, and shipboard systems are not greatly restricted by size, weight, and volume as are the aircraft and spacecraft systems. Therefore, for these groundbased systems, design margins for strength and fire resistance are greater. All systems employed relief valves or burst disks to protect lines against overpressure. Only the hospital and altitude chamber systems had all relief lines vented out of the buildings or use area. Static electricity was considered as a potential danger, and all systems required electrical grounding during operation and servicing. Contamination control in regard to cleaning, oxygen procurement specification, and particulate filtering was common to all systems but varied greatly in requirement, application, and certification. All systems are cleaned at the time of installation or manufacture except for the hospital which utilized precleaned pipe. All systems except the hospital utilize particulate filtering at the service point as a minimum.

The interfacing of electrical systems to the oxygen system was one of the major ignition sources considered by the various groups. It was found that the military aircraft, the Gemini supercritical tanks, and the MSC altitude chamber had requirements for electrical equipment within the oxygen environments. The military aircraft LOX converter contains a capacitance probe in the LOX tank as does the Gemini cryogenic tank. The altitude chamber, which is similar in some test configurations to spacecraft crew compartments, requires many electrical system interfaces. Wire sizing to load, individual wire fusing, close control of wire insulation and connector potting, and isolating of circuits and power consuming devices by hermetic sealing or nitrogen blanketing are a few of the techniques employed in chamber design. All except the Navy systems contain transducers, remote alarms, solenoid valves, and other electrically operated devices which are not directly in the oxygen environment. In the event of a failure in these components, the internal electrical section of the device could be overheated or exposed to oxygen. The commercial aviation system reviewed requires that all interfacing electrical devices, as mentioned above, be tested to simulate an overvoltage failure. It is required that this type of failure will not

Table 1.–

TABLE OF OXYGEN SYSTEMS

SYSTEM	TYPE O_2	OPERATING PRESSURE psig	OPERATING TEMP. Deg.F	PIPING AND TUBING MAT'L	OTHER METALLIC MATERIAL USED	NONMETALLIC MATERIAL USED	MAT'L AVOIDED	ELECT. (Electrical System from O_2 Environ.)	ENVIRON QUAL. TEST	ACCEPT. TESTING	PERIODIC MAINT.	PERIODIC CLEAN.	SINGLE POINT FAIL.	
													Redundant Systems	Redundant Components
MSC CHAMBER:														
Source	GOX	2200	Ambient	s.s.	Bronze & Brass	Teflon, Viton	Ferrous Metals Hydro-carbons	NO	NO	YES	YES	NO	YES	NO
Distribution	GOX	100	Ambient	s.s., Cu	Bronze & Brass	Kel-F, neoprene		NO	NO	YES	YES	NO	YES	NO
Use	GOX	3.5–20 psia	0 to 100	Al, s.s., Cu	SAME	Beta, PBI Webbing	SAME	YES	NO	YES	YES	NO	YES	NO
MILITARY AIRCRAFT:														
Source	LOX	85	−320	s.s	s.s. Cu-Ni s.s. Al Brass	Teflon, Kel–F, Viton, Silicone Rubber	Carbon, Steel, Neoprene	YES	YES	YES	YES	YES	YES	NO
Distribution	GOX	72	-297/90	Al				NO	YES	YES	YES	N/A	YES	NO
Use	GOX	3.5–15 psia	Ambient	Al			N/A	YES, Crew Microphone	YES	YES	YES	N/A	NO	NO
HOSPITAL SYSTEM:														
Source	LOX	70	−290	s.s., Al	Cu, Bronze, silver solder, Aluminum	Teflon, Neoprene, Cellulose Acetate	Ferrous Metals Hydro-carbons	NO	NO	YES	NO	NO	YES	NO
Distribution	GOX	60	Ambient	Cu				NO	NO	YES	NO	NO	NO (2)	NO
Use	GOX	Ambient	Ambient	Cu, Brass				YES	NO	YES	NO	NO	NO (2)	NO
GEMINI O_2 BOTTLE:														
Source (1)	Super–Critical GOX	900	−290	s.s.	718 Inconel Press. Vessel	Silicone Rubber	N/A	YES	YES	YES	YES	NO	YES	NO
SUBMARINES:														
Source	GOX	3000	Ambient	Monel	s.s., pressure vessel, Cu Bronze Brass	Teflon, Kel–F Fluorocarbons Teflon, Nylon	Ferrous Metals Hydro–carbons Rubber Plastics	NO	N/A	YES	YES	YES	YES	NO
Distribution	GOX	100	Ambient	Monel				NO	N/A	YES	YES	YES	YES	NO
Use	GOX	Ambient	Ambient	Monel				NO	N/A	YES	YES	YES	YES	NO
AIRCRAFT CARRIERS:														
Source	LOX	85	approx. −300	s.s.	Cu, Monel Bronze	Teflon, Kel–F	Ferrous Metals Hydro–carbons Rubber Plastics	NO	N/A	YES	YES	YES	YES	NO
Distribution (3)	LOX	85	SAME	s.s				NO	N/A	YES	YES	YES	YES	NO
Distribution (6)	GOX	35	Ambient	s.s.				NO	N/A	YES	YES	YES	YES	NO
COMMERCIAL AVN.														
Source	GOX	1850	Ambient	s.s.	Bronze, Al, Brass, Yellow Chromium, Cu, Carbon Steel	Kel–F, Teflon, Nylon, Silicone Rubber, Vinyl Plastic, Silicone Rubber	Titanium Magnesium Rubber Hydro–carbons	NO	YES	YES	YES (4)	YES (4)	NO (2)	NO
Distribution	GOX	150–600	Ambient	s.s.				NO	YES	YES	YES (4)	YES (4)	NO (2)	YES (7)
Use	GOX	0 to 150	Ambient	Al				NO	YES	YES	N/A	N/A	NO	YES

(1) Other sections of Gemini oxygen system not considered
(2) Portable bottles available.
(3) Carrier use is by military aircraft.
(4) Periodic maintenance and cleaning performed by aircraft user.
(5) N/A: Data not available
(6) LOX converted to high pressure gas.
(7) Redundancy provided in system actuation only.

result in a loss of integrity of the oxygen system. The panel found no formal government or industry standard which controls electrical interfaces.

In all systems reviewed it is required that vendors perform acceptance testing of the component prior to shipment to the major contractor or use facility. Some organizations perform component bench tests prior to system installation. However, all organizations perform installed systems tests for leakage and function although the extent of the functional test varied greatly. Environmental qualification tests are unique to the military and aerospace industry. Periodic maintenance and cleaning are generally not the rule and, primarily, maintenance is performed only as required for failure correction. All systems require batch sampling of the supply oxygen prior to system filling. Only the altitude chamber requires periodic sampling from the use ports. The Navy discussed a problem which it has experienced and was related to sampling. It was found, in some instances, that oxygen sampled from the aircraft LOX converter did not meet specifications although the carrier supply was within specification. It was determined that some contaminants would remain in the liquid oxygen when the system is not in use and with repeated partial refilling of the converter, would tend to increase in concentration within the converter. The Navy now requires that each converter be cleaned every 30 days.

The subject of failures was discussed briefly. Although many failures are known, few were of a catastrophic nature and failures were generally related to improper servicing procedures and handling methods. The methods for analyzing for failures vary greatly. Critical design reviews, failure modes and effects analysis and experience record for similar systems are used to assure reliability and safety.

The subject of nonmetallic material use was discussed, and it was generally accepted that this area needs standardization of testing and selection criteria. The system participants indicated that both the government and prime contractors purchase component parts from vendors with experience in manufacturing oxygen system components and great reliance is made on these vendors to choose "oxygen compatible" nonmetallic materials. Also, no adequate vendor, contractor, or government list of acceptable materials was presented or known. Much of the time, material selection was based upon experience or limited test data. The use of nonmetallics is often compensated by the selection of metals which will contain fire should it occur in the nonmetallic material as a result of heating from without or within the system. For some new designs nonmetallic material selected for commercial aircraft use cannot have a burning temperature which could result in the ignition of the surrounding metal. It should be noted that one commercial airplane manufacturer has undertaken a development program to eliminate all nonmetallic material interfacing the flow stream of the high pressure portion of the oxygen system. Also tests are being developed to demonstrate that a reasonable amount of contaminant can be ignited within components without burning through their housing.

No unique design elements or features were found; however, a device used on some commercial aircraft should be mentioned. This device is called a thermal compensator and it is used before each valve having a nonmetallic seat which could be subjected to rapid pressurization. Rapid repressurization can cause temperatures to increase by compression to the ignition temperature of contaminants which could then lead to burning of the nonmetallic materials. The thermal compensator absorbs and conducts heat from the gas to the surrounding plumbing, thereby preventing the high gas temperature. The device is simply a chromium copper alloy wire brush configuration, approximately 5 inches long, which is placed inside the plumbing at the dead end. This device may be useful to provide additional safety margins for rapid pressurization heating.

The conclusions of the panel were as follows:

1. No great technology differences exist among the fields reviewed.

2. Breathing oxygen systems utilized today have been quite successful in meeting their intent. The majority of the relatively few failures which have occurred have been traced to poor handling practices.

3. The success of today's designs has been the result of designing by experience, largely without thorough scientific understanding.

4. Improvement in and standarization of specifications and guidelines are needed in the following areas.

   a. System design requirements as a function of pressure and use.

   b. Materials requirements and a suitable list of materials for specific applications.

   c. Materials test methods which will verify suitability of materials for the given applications.

   d. Accurate testing methods for determination of a given systems contamination level.

   e. Allowable contamination levels and materials, including particle sizes, for the various system pressure levels.

PANEL 9

SAFETY, RELIABILITY AND QUALITY ASSURANCE

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SUPPORT TO PANEL 7

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SUPPORT TO PANEL 8

John W. Conlon

SUPPORT TO PANEL 11

William L. Baldwin

PANEL 9

Safety, Reliability and Quality Assurance

The Safety, Reliability and Quality Assurance (R&QA) Panel (9) of the MSC Apollo 13 Investigation Team was established to provide the following functions:

1. Act in an advisory capacity to the Team Manager
2. Provide specific documentation and documentation control
3. Provide technical support to Panels 1, 5, 6, 7, 8, and 11 and to the members of the Investigation Board

This report summarizes these activities and presents Safety and R&QA Panel findings.

The Safety and R&QA Panel provided support to Panels 1, 5, 6, 7, 8, and 11. This support was furnished by personnel from NASA Safety and R&QA elements, from Boeing Company and General Electric Company support contractors, and by appropriate hardware contractor personnel. It is estimated that at the peak of the activity the Safety and R&QA Offices had more than 200 personnel directly supporting the investigation.

In addition to the technical support referenced above, approximately two thousand documents were retrieved, reproduced, or otherwise made available to the panels and to members of the Investigation Board.

During the Apollo 13 mission, the planned Safety and R&QA support was set up to review flight anomalies as they occurred and to provide related data, information, and recommendations through the Safety and R&QA representatives on the Mission Monitoring Team. At the time of the cryogenic tank incident, the Safety and R&QA organization furnished supporting data and information related to the incident and reviewed changes in flight plan and flight procedures as they related to hardware capabilities to assure safe recovery. Data, information, and recommendations from these activities were furnished in real-time to the Mission Monitoring Team. Immediately after splashdown, an effort was initiated to collect data on certification and problem history and KSC checkout activities on problem-related hardware. In addition, timelines and other basic information were studied in preparation for the formal team activities. Safety and R&QA support continued as the Apollo 13 Investigation Team was being organized. The following support was furnished to the panels of the Investigating Team during the investigation.

Panel 1, Spacecraft Incident Investigation

1. Compared previous safety-related flight and test anomalies with Apollo 13 flight data
2. Reviewed previous safety assessments of Apollo 7 to 13
3. Evaluated test results and test analyses
4. Provided Data Centers to enable the following:
    a. Control of pertinent historical documents, records, and data
    b. Security of data
5. Reliability/Quality Records/Evaluation
    a. Prepared history and reevaluated certification test data for cryogenic O_2 tank
    b. Prepared synopsis of test procedures used at Beech Aircraft Corporation on the cryogenic O_2 tank number 2 and all associated equipment
    c. Provided failure history of electrical connectors used on the cryogenic O_2 tank

Panel 5, Corrective Action Study and Implementation

1. Analyzed safety impact of recommendations
2. Evaluated alternatives relative to previous safety assessments
3. Evaluated test requirements and results
4. Assisted in establishing qualification requirements for possible cryogenic O_2 tank redesign
5. Evaluated alternative designs

Panel 6, Related Systems Evaluation

1. Analyzed proposed revisions for reliability and safety considerations
2. Evaluated alternatives relative to previous safety assessments

3. Assessed nonmetallic material compatibility of all oxygen, fuel, and oxidizer tank assemblies and line components with the exception of cryogenic oxygen tanks

4. Provided information on contamination requirements

5. Reviewed and assessed certification and failure history, failure mode and effects analysis, single-point failure summaries, and limited life requirements.

6. Provided R&QA inputs to Systems Engineering team members

7. Provided inputs on emergency backup modes

8. Provided information on pressure-vessel explosion protection

9. Provided information on pyro initiator debris

10. Provided circuit breaker data

11. Reviewed and provided inputs into final report

12. Determined energy levels of the effect of faulted electrical components oxygen and oxidizer interfaces with the exception of the cryogenic O_2 tank

Panel 7, Reaction Processes in High-Pressure Fluid Systems

1. Furnished documentation relative to LOX compatibility of materials

2. Listed and reevaluated two waivers against Apollo 13 on O_2 fluid cleanliness

Panel 8, High-Pressure Oxygen Systems Survey

1. Gathered and reviewed information on fires and/or explosions in O_2 enriched environments of greater than ambient pressures

2. Assembled applicable design standards and safety criteria

3. Furnished procedures used at MSC for cleaning of facility O_2 equipment

Panel 11, Administration, Communications, and Procurement, had no significant requirement for support.

The findings were as follows:

1. The existing system for control of the hardware certification test programs and assessment of completion is adequate.

2. Formal closeout and recurrence control of reported hardware problems is adequate.

3. The current MSC method for R&QA and Engineering review of hardware nonconformances and material review board actions is adequate.

4. Adequate background information on both specific and related generic hardware is contained in the record system.

5. There is a comprehensive spacecraft cabin materials control program. The area of materials compatibility in high-pressure fluids is not completely understood.

The Safety and R&QA Offices concur with the findings and corrective action defined to date relative to the Apollo 13 cryogenic tank failure, although certification and acceptance test requirements of the new tanks have not yet been completely defined.

Disposition of the recommendations submitted by Safety and R&QA representatives through their assigned panels has been satisfactory.

MSC APOLLO 13 INVESTIGATION TEAM

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