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ABSTRACT

This paper presents the design research for Human Engineering to modify a 747SP aircraft for the Stratospheric Observatory for Infrared Astronomy. It summarizes the work of the SOFIA Layout of Personnel Accommodations (LOPA) Team at NASA-Ames Research Center in developing the specifications and project documents to define the mission crew work areas, including consoles, equipment racks, and astronomer/experimenter work areas and facilities. It covers several key areas, including the Project's assumptions about the SOFIA personnel complement and the aircraft's operational scenarios, based upon a systematic comparison to the SOFIA's predecessor, the Kuiper Airborne Observatory (KAO), a modified C-141.

The LOPA Team analyzed these complex assumptions, requirements and goals for improved Mission crew productivity to develop a Human Engineering Design Guideline. This Human Engineering Guideline follows a Crew-Centered Design Philosophy that takes four perspectives: crew members as occupants, crew members as individual operators, crew members as leaders, and crew as team members. This Guideline evaluates the role of automation in crew productivity. It suggests verification metrics through the design, development, and pre-operations phases of the SOFIA Program.

A key product of the LOPA Team activity was to develop several candidate layouts of the floor plan and console arrangements. These layouts derived from four considerations: LOPA requirements, physical and operational constraints upon the LOPA design, an architectural adjacency analysis, and a SOFIA-specific set of architectural design guidelines.

HUMAN ENGINEERING DESIGN APPROACH

An important component of the approach this guideline takes is to make the design reasoning process explicit. As Herbert Simon states:

> ... we as designers, or as designers of design processes, have had to be explicit as never before about what is involved in creating a design and what takes place while the creation is going on (Simon, Herbert, 1973).

Thus the Guideline goes to great pains to examine and articulate the assumptions and analyses that underlie its approach. The leading design driver for SOFIA Human Engineering and the interior architecture of the crew cabin is the ambitious set of human productivity goals.

A major key to the success of SOFIA is to maximize human productivity in all aspects of design for mission planning, preparation, operations, and ground support. By "maximize," the Human Engineering Guideline means that fewer mission crew members will oversee more tasks than their predecessors on the KAO. FIGURE 1 shows an artist's rendering of SOFIA. Please note the cavity door opening just forward of the tail. FIGURE 2 shows the KAO at Ames Research Center. Please note the cavity door opening just forward of the port wing.

MEASURES OF CREW PRODUCTIVITY - There are three principal measures of this productivity improvement: mission crew productivity, science crew productivity and ground crew productivity. This specification focuses upon crew productivity in general, which translates ultimately into science productivity.

Mission Operations Crew Productivity - The primary goal for crew productivity is to reduce the "Mission Crew" from the KAO baseline of 4 operators to the SOFIA baseline of 2 operators.

Please refer to the Table 1 for a comparison of the SOFIA and KAO baselines.

Science Crew Productivity - At the same time, the number of Principal Investigator Team members on SOFIA will increase above the KAO baseline. The primary goal for science productivity is to double the astronomical observation flight rate from the KAO baseline of 80 per year to 160 per year. A secondary goal is to increase the number of observation targets from the KAO range of 7 to 10 per flight to about 15 or 20 targets per flight for SOFIA. Ultimately through the use of advanced artificial intelligence systems such as an automated mission planner–scheduler–tracker–pointer, it may be possible to increase the number of targets to the 100 to 200 range. Along with the increase in infrared telescope size from .9m to 2.5m diameter, the telescope will provide approximately 10x the sensitivity and approximately 3x the spatial resolution of the KAO with a corresponding increase in science data. The SOFIA will also increase the observing time at ≥41,000 ft altitude from ~3 to 4 hours per flight to ~6 to 7 hours per flight. The larger crew cabin and on-board console area on the SOFIA will allow a larger science crew complement to fly on the aircraft to take advantage of the Science Instrument and its support systems.

Ground Support Crew Productivity - This measure of productivity encompasses mission preparation, mission simulation, telescope and focal plane instrument servicing. It EXCLUDES standard 747 aircraft servicing. Support crew productivity is essential to turning the SOFIA around in a timely fashion to accomplish the target rate of 160 science flights per year. The absence of a cargo door (available on the KAO C-141) to the SOFIA 747SP main cabin poses a potential bottleneck to achieving this productivity.

Ideally, the modularization of components to pass through the 42 inch (1.05m) crew doors will allow the ground crew to meet these goals. As the SOFIA flight rate doubles so that down days per flight available for maintenance decrease by 67% (as shown in TABLE 1), it may become necessary to increase substantially the ground support and maintenance crew shifts. The best way to measure such a shift relative to the KAO baseline remains to be seen. There should also be a reduction in TA and MCCS maintenance and servicing crew based upon better reliability and maintainability of the SOFIA mission system.

IMPACT OF CREW PRODUCTIVITY GOALS - Both the measures of mission crew productivity and science productivity make substantial demands upon crew efficiency, sustained performance, and the equipment upon which the crew must depend. Ground Support Crew Productivity depends similarly upon the equipment, but with reduced abilities to load and unload cargo due to the lack of a cargo door, and the fact that the 747 stands much higher off the tarmac than the KAO's C-141 aircraft.

TABLE 1 indicates that where four mission crew members performed a set of critical functions in KAO operations, only two mission crew members will perform the respective operations on SOFIA. The increase in flight rate means that the ratio of "down days" to observation flights for the KAO was ~3:1. For SOFIA, that ratio will be ~1:1, affecting all mission planning, preparation, and ground support operations both at SOFIA's home base and during deployments.

IMPLICATIONS OF CREW SIZE REDUCTION - This 50% mission crew reduction from the KAO to SOFIA places substantial demands upon the design of SOFIA's on-board mission control system, the Mission Control and Communications System (MCCS). To meet this goal will require greatly enhanced system availability, maintainability and reliability. Since SOFIA will require three mission crew teams of two each, eliminating six full time positions over the planned twenty year lifetime of the aircraft promises very significant savings in operational costs.

However this reduction by half in mission crew size places potentially much greater burdens upon the two remaining crew members. The crux of this burden is how to consolidate the four KAO crew roles between two crew members on SOFIA. On the KAO, the four crew positions were: Telescope Operator, Computer Operator, Tracker Operator and Mission Manager. On SOFIA, the approach is to combine the Telescope and Tracker tasks for one operator, and give the Mission Manager the computer and operating system as part of overall mission oversight and direction.

DESIGN FOR CREW PRODUCTIVITY - Design for human productivity in a technology-intensive situation such as SOFIA involves a complex of issues. These issues and the knowledge about how to handle them derive primarily from NASA's and the USRA team's human factors engineering experience in aviation and in space. The relevant components of crew productivity may include:

- application of anthropometry;
- avoidance, detection and prevention of human error;

- caution and warning systems; automation of routine and boring tasks such as checklists (Degani & Weiner, 1990; Palmer & Degani, 1991);
- crew resource management (Ginnett, 1993) such as task assignment and crew to crew communication;
- human-machine interfaces such as controls and displays -- including visual displays and data visualization(Ellis, Kaiser & Grunwald, 1993);
- human-environment interactions such as the layout of personnel accommodations;
- ergonomic modeling and analysis of work stations;
- auditory displays including data sonification (Kramer, 1994);
- perceptual and cognitive modeling of the knowledge domain;
- task cataloging and analysis;
- and workload prediction and verification.

All these specialties achieved sufficient maturity in recent decades that it is feasible to define how they should inform both the design process and the design product. In a few cases it is possible to cite design standards. More often it is more practical to state the goal and provide significant references for that specialty.

HUMAN ENGINEERING GUIDELINE - The LOPA team's main product, collectively known as the Human Engineering Guideline, was a set of three project documents:

1. SOFIA Project Office (1996, May) *Assumptions about SOFIA Personnel Complement and Operational Scenarios*, SOF-1021.

2. SOFIA Project Office (1996, May) *The Human Engineering and Ergonomic Design Specification*, SOF-1022.

3. SOFIA Project Office (1996, May) Design Guidelines for the Layout of Personnel Accommodation Requirements (LOPA), PD-2006.

The structure of this Guideline moves from the general to the specific. The first section establishes a general approach that applies to most parts of the SOFIA project with the notable exception of the existing flight deck (cockpit) on the 747 aircraft, and those portions of the ground support facility not directly concerned with aircraft, electronics, or telescope assembly servicing. The following sections apply to the human engineering design aspects of the Mission Command and Communications System (MCCS), Telescope Assembly (TA) and airborne support systems , Aircraft Modification and Refurbishment, and the Ground Support Systems.

ASSUMPTIONS ABOUT SOFIA PERSONNEL COMPLEMENT AND OPERATIONAL SCENARIOS

The purpose of this section is to make explicit the assumptions about the missions that SOFIA will perform. These assumptions include the personnel complement on SOFIA and the scenarios under which it operates. These assumptions extend to the designation of work stations in the crew cabin and the allocation of functionality among them.

TABLES OF ASSUMPTIONS - This section allows comparison between these assumptions through a set of tables. It suggests what the Layout of Personnel Accommodations must accommodate, and the ways in which to integrate these elements.

Changes from KAO to SOFIA - TABLE 1 shows the differences between Kuiper Airborne Observatory operations, to the plans for SOFIA operations. TABLE 1 describes and compares the "Normal Science Flight" for the two observatories. TABLE 1 recognizes the specific characteristics of SOFIA operations and their support setting as a key to develop and implement a successful design. However, the purpose of this comparison is not to show how SOFIA may resemble KAO, but rather how it must differ from the KAO. The major reasons for these differences appear in the heavy boxes. Perhaps the most significant among these reasons is the change in "down days" per observation flight. The KAO normally had three down days per observation flight, but the SOFIA aircraft will have less than one down day per observation flight.

SOFIA Teamwork Operational Analysis Matrix - TABLE 2 shows the correlation of SOFIA crew teams to the functions they perform, and the equipment they operate. This table conveys an intermediate analysis that links SOFIA from TABLE 1 to TABLE 3.

Five SOFIA Flight Scenarios - TABLE 3 illustrates five alternatives under which SOFIA may operate. In addition to the "Normal Science Flight" that TABLE 1 describes, SOFIA will fly a number of other missions that appear in TABLE 3: Normal Science, Engineering, Pilot Proficiency, Ferry, and Ferry–Science. TABLE 3 also breaks down the various roles and capacities in which crew members will fly on SOFIA. These capacities include the Mission Ops team, two Science teams, Engineering team, Educator Team, Other visitors (including engineering development for other projects) and Non-astronomical experimenters such as atmospheric scientists. TABLE 3 suggests the distribution of these teams or group members across the five SOFIA Flight Scenarios. TABLE 3 projects a census of the teams. The Normal Science flight is the primary focus of SOFIA activities, with the goal of achieving 160 science flights per year. The other four scenarios total 40 maximum "Program Support flights" including engineering, pilot proficiency, and ferry flights. Flights to commercially operated maintenance depots count as planned ferry flights.

Normal Science Flights - The personnel complement will vary in significant ways from one scenario to another. The Normal Science Flight will consist primarily of the Scientists on two or more teams, the Mission Ops Crew, and the Education Team. The Normal Science Flight is also the typical work regime for the Mission Crews. The optimal number of Mission crew members is two, but a few science instruments may require more than two Mission crew members to operate the Observatory successfully. In these cases, the additional Mission Crew member will apply the appropriate software key to the reserve crew console and perform his or her task.

Engineering Flights - Engineering Flights will serve a critical role in the on-going technology development program for SOFIA. As on the KAO, there will be an on-going and incremental development and upgrade process for SOFIA. The Engineering Flight will provide the opportunity to test and verify new facility hardware and software in the air, before the Principal Investigator teams come on board, to avoid interference with their limited and precious observing time. It is vital to plan to evaluate, test, and verify new technologies in the Engineering Development Flight environment, rather than trying for the first time during an actual observation flight. Engineering Flights are not redundant with the Instrument Test activities on normal science flights.

Pilot Proficiency Flights - Pilot Proficiency will be an essential part of safe operation for SOFIA. During pilot training flights, the 747 will be vacant except for flight deck crew members, typically consisting of pilot, copilot and flight engineers. It may include the "augmented crew" of additional pilots and flight engineers.

Ferry Flights - The Ferry flight is the scenario in which the SOFIA will operate most like the commercial passenger plane from which it derives. The pilots will fly point-to-point. Without a mission assignment to track any stars, the normal imperative to fly at night does not constrain the departure time. On Ferry flights, the mission crew and science teams will not perform any mission functions. In this role, TABLE 3 classifies them as "project support" personnel for Ferry Flights.

Ferry-Science Flights - The Ferry-Science Flight will be a hybrid activity that takes advantage of the fact that the aircraft is flying a particular route, to make whatever observations the opportunity presents. The host Scientists will select targets of opportunity along the flight path. Usually these observations will not derive from any particular grant proposal, but from the initiative of the host astronomer. Ideally, all Ferry flights will become Ferry-Science Flights.

TEAMWORK AS A BASIC UNIT OF ANALYSIS - The SOFIA Human Engineering Guideline recognizes teamwork as the primary unit of analysis for SOFIA design and mission and science operations. Individual operator work stations and operations servicing tasks play an essential role, but, in actual practice, they occur only in the context of a team effort. These teamwork analyses provide a more global framework for comprehending SOFIA.

The Mission Crew includes the Mission Manager and the "Telescope/Tracker Operator" mission specialist, with occasional back-up from another mission specialist serving as a "Computer Operator." These crew members sit at MCCS consoles where they have responsibility for all safety related functions and issues, including the physical operation of the Telescope. The Mission Crew oversee the functioning of the MCCS's computer operating system and interact with the Science Team to ensure that the P.I.'s experiment is working smoothly with the observatory.

The Principal Investigator Science Team consists of a Host Investigator -- who developed the instrument and provides the Experimenter science rack, and one or more Guest Investigators who propose experiments. Both the host and guest investigators may bring their own support people, including technicians and graduate students. The P.I. team may include teachers (as stated in the grant proposals), and involve them in science data acquisition and reduction. Generally, the Science Team works closely together in taking data from the instrument through the Science Rack(s). Their communication with the Mission Crew usually consists of the Host P.I. talking to the Mission Manager and the TA/Tracker Operator—Mission Specialist. The Principal Investigators control the handling of all science data.

The Outreach Team comprises a complex of activities including public and media relations and education. This team consists of one or more docents and several school teachers, such as the FOSTER program or other association with SOFIA. News media and other governmental visitors generally fall within the Outreach Team venue. The education dimension includes both the ideas of the "Flying Classroom" and the "Fly-in Classroom." The flying classroom presents an opportunity to videotape science operations or to broadcast them live, in the manner of "Live from the Stratosphere." The Fly-in Classroom refers to tours or seminars held on board SOFIA on the ground when on deployment to another airfield.

The Instrument Test Team includes members of groups involved in developing and testing new instruments, equipment, software or other systems for future flights. It typically includes both scientist and instrument designers. The manner of instrument testing generally involves securing a new instrument to the floor deck and measuring the background effects of the airborne environment.

Ground Support Teams consist of people connected to the Mission Command and Control Systems, Telescope Assembly, Mission Simulator, and Aircraft System who perform maintenance, repair, and reconfigurations when the SOFIA aircraft is on the ground.

EXCLUSION: Flight Deck Crew - This framework of assumptions excludes the flight deck crew (pilot, copilot, flight engineer), who execute the Science Flight Plan and who have overall responsibility for SOFIA aircraft safety.

THE SOFIA HUMAN ENGINEERING AND ERGONOMIC DESIGN SPECIFICATION

The heart of the in-house human engineering effort was the Human Engineering Specification. This Specification defines the Human Engineering goals in the context of improvements over the existing, 20 year old Kuiper Airborne Observatory (KAO). These goals include crew safety, maximum crew productivity and SOFIA System-wide human performance requirements. The Human Engineering Specification includes references for many types of human-machine interfaces.

SYSTEM-WIDE ENGINEERING REQUIREMENTS - The Human Engineering Specification levies several system-wide requirements on all portions of SOFIA design and operations except for those portions specifically exempted. The design conforms to MIL-STD-1472D (1989) and the Human Engineering design process must conform to MIL-STD- 46855 (1979). In addition to these two references, the specification focuses upon three specific requirements: safety, preventing human error and sustaining human performance. The Specification expresses these three requirements in terms of several analyses described below.

The Human Engineering Design for SOFIA systems promotes safety in all mission, flight, and ground operations. A key to ensuring safety is to prevent or minimize human error and to minimize the impact of human error upon system safety. Human error may occur from a variety of causes including: mistaken or inadvertent operation of controls, misunderstanding of display data, miscommunication with other crew members, lack or misuse of vital information, physical or mental strain, fatigue, or misinterpretation of a caution or warning. It is a design goal to prevent such human errors from occurring by the ground crew and flight crew. The design supports sustained, high levels of human performance over every time interval by which SOFIA operations are measured: observation leg, observation flight, focal plane instrument installation cycle, and deployment cycle.

APPROACH TO THE OPERATIONAL SETTING - While there are broad, generic components to human engineering and ergonomics, the specific characteristics of SOFIA operations and their support setting are key to developing and implementing a successful design. The Human Engineering Management Plan embodies this approach as required in Mil-STD-46855. This Human Engineering Plan includes the following analyses for Teamwork, Tasks, Architectural Adjacency, Situation Awareness, Cognitive Aspects, Task Allocation between Humans and Machines, Workload, Flight Schedule and Fatigue.

Teamwork Analysis - This specification recognizes teamwork as the primary unit of analysis, both for SOFIA design and operations. Certainly, individual operator work stations and individual servicing tasks play an essential role. However, in actual practice, they all occur only in the context of a team effort. While it is essential to design work stations, tasks, functions, and decision-making responsibilities for individual crew members, the Teamwork analysis shall provide a more global framework for comprehending SOFIA operations. These teamwork analyses shall include team forming, team decision-making, communication, and shared situation analysis (Kanki, B. G., & Foushee, H. C., 1990; Kanki, B., 1992). The teamwork analysis shall include the role of automation as a "team player," (Malin, J. T., et. al., 1991, September)

Task Inventory and Analysis - The Human Engineering Specification requires a task inventory and analysis on all tasks that the SOFIA flight crew performs. For each team for which the SOFIA Project designs or provides accommodations and equipment, a task analysis is essential. This pre-design task analysis shall utilize an analytical software tool such as Activity Catalog Tool (ACT), (Segal, 1993). A competent, adequate, professional, and complete task analysis is essential to the cognitive restructuring of tasks for teams that are downsizing from the KAO baseline to the SOFIA goals.

Architectural Adjacency Analysis - The Specification asks for architectural adjacency analyses showing the requirements for locating the equipment on board the aircraft and in the mission simulation ground support facility. The adjacency analysis indicates which pairings of elements require close proximity, which require separation, and those for which proximity versus separation is not important (Callendar, J. H., 1992; Woodson, W., Tillman, B., & Tillman P., Edt, 1992; Ramsey & Sleeper, 1994). A preliminary architectural adjacency analysis appears in FIGURE 1 and TABLE 4.

Analysis of Situation Awareness The design of SOFIA, all its systems and subsystems should support a high level of situation awareness for the flight crew and ground support crew. Situation awareness affects crew decision-making, productivity and safety. (Orasanu, J. M., 1995).

Cognitive Analysis - The System Provider shall perform a cognitive analysis that captures the knowledge domain of the Mission Operations Crew to facilitate the restructuring of this team to a smaller number of operators. This analysis addresses the key questions of "What do the mission crew members need to know and when do they need to know it?" The cognitive analysis should cover the role of training, and the design of data displays in fostering shared mental models among team members and between different operational teams (Orasanu, J. M., 1990; Orasanu, J. M., & Fischer, U., 1991). This analysis includes the effects of high altitude on crew cognitive performance (Lieberman et al., 1994).

In sum, the cognitive analysis to design for the SOFIA MCCS must address two questions: What is the mental workload -- especially for the Mission Crew? Also, what is the model of teamwork for SOFIA to best support the operators to handle the workload and carry out the mission successfully?

Analysis of Task Allocation between Humans and Machines - The design process should evaluate the allocation of tasks between human crew members and machine crew members also known as automation (Billings, 1991). This evaluation includes full consideration of automation failure modes and their effects (Palmer, E., 1995; Malin et al., 1991).

Workload Analysis - The System Provider shall evaluate the proposed workload -- both physical and mental -- for SOFIA crew members, and adopt a consistent empirical method both for planning and measuring that workload (Vidulich, M. A., 1989). Workload Analysis for the flight crew should consider several perspectives on assessing workload, including: cumulative workload, peak workload, demands upon attention, workload effects of communication demands, and interaction with training (Donchin, E., Hart, S. G., and Hartzell, E. J., 1987). Workload analysis for the ground support crew should consider physical ergonomic factors, subjective mental workload factors, the effects and interaction of training upon workload, and other aspects or workload.

Flight Schedule and Fatigue Analysis - Fatigue and degraded judgment due to rotating shiftwork account for a significant incidence of workplace accidents and mishaps (Gold, D.R. et al., 1992, July). Fatigue can make a particularly profound effect in the Aviation environment (Rosekind, M. R., et al., 1994). Fatigue becomes a factor for planning especially on long-haul routes (Connell, L., Graeber R. C., and Schreiber, H., 1987).

DESIGN - The Design of SOFIA systems encompasses a wide range of disciplines and expertise. The Specification points out critical philosophical and methodological concerns for those disciplines. The design of SOFIA systems implies a conscientious approach to the design of the training techniques and operational procedures for the crew members who will use those systems (Chappell, S. L., 1991). This section on DESIGN brings together the most current research, design methods, and guidelines for work stations and crew accommodations. This section identifies the source and requirements for detailed human engineering design considerations.

Because crew productivity is so vital to the success of SOFIA, all Human Engineering should follow the crew-centered design philosophy that Bill Rouse advocates (Rouse, W. B., 1991). This approach is "crew-centered" because it begins with the crew capabilities, responsibilities, roles, and tasks. It reasons from the crew to the equipment and environment necessary to support them. This specification does not address crew accommodations or work stations in isolation from the people they must support. It follows the format that Michael T. Palmer et al. (1995) developed, addressing the

Crew as occupant,
Crew as operator,
Crew as leader,
Crew as team.

Crew Members as Occupants - The design of the SOFIA environment may have a profound effect upon crew comfort, performance, and safety. The design supports the needs of the crew as humans in a potentially hazardous work environment. SOFIA is a workplace -- like any other -- where people will spend eight to twelve hours at a stretch trying to be productive in creating something useful, in this case, scientific data. The Working Environment conditions and amenities must support and enhance this productivity. Working environment conditions that the Specification addresses are: the cabin atmosphere, the emergency oxygen system, emergency egress and ground access, control of noise, temperature and humidity, lighting, ergonomic design of consoles and seating, architectural design of the cabin interior, accessibility for disabled persons (Americans with Disabilities Act, 1990), education accommodations, and associated safety provisions.

Crew Members as Individual Operators - Each of the mission **crew members** has a seat assigned in front of a display console, including the Mission Director. Similarly, the P.I. supervises several operators working with the P.I.'s experimenter rack and the P.I. console. The design of SOFIA and its systems support sustained, reliable crew operations (Dhillon, 1986). The major design considerations for the crew as operators include operator involvement in tasks or functions, the design of procedures, controls and displays, input and output devices and methods, and the information content of displays. The design of the MCCS system should be consistent with mission objectives, and is realistic in terms of the crew's shared conceptual models and operations capabilities.

Crew Members as Leaders - The Mission Director and the Principal Investigator play the role of leader for the mission crew and the science crew respectively. Overall, the Mission Director is responsible for operational safety and "bringing home the data in a briefcase." The Mission Director has access to all critical information concerning the status of the Aircraft, and its systems, the Telescope Assembly, the focal plane instrument and other scientific instruments, the status of the mission, and the progress of the flight. The Mission Director enjoys exclusive access to the SOFIA pilot and flight deck crew.

However, the Mission Director's access to science data is only at the discretion of the Principal Investigator. The Principle Investigator manages all science data and supervises the science crew. The P.I. supervises all dynamic science functions and task allocations among the science crew. The P.I. acts as the primary liaison with the Mission Director.

Crew Members as a Team - The SOFIA team consists of mission crew, science crew and their associated automated systems. To some degree, the mission crew & science crews operate as separate teams. The automated systems include the SOFIA Data Management & Acquisition System (DMACS), and other computer systems to support the Telescope, other mission equipment, and to support the science equipment. A successful design should incorporate the automated systems to serve as team members (Malin, et al., 1991). The Specification addresses these key aspects of teamwork for SOFIA: operator awareness, communication among operators, dynamic allocation of task functions, potential interference among tasks, error handling, designed capabilities and shared situation awareness.

HUMAN-CENTERED AUTOMATION - Automated systems should follow the principles of Human-Centered Automation set forth in Billings (1991). The automation designer should abide by Charles Billings' caveat "Do not automate any function without a good reason for automating it." Automation shall be: accountable, subordinate, predictable, adaptable, comprehensible, flexible, dependable, informative, error resistant, error tolerant, and shall be simple enough for the human operators to understand.

The conception and design of automation can provide a great boost to human productivity or may undermine it with the need to make constant adjustments and exceptions not needed for manual operations. The guiding principle of Human Centered Automation shall be to implement systems that will make the crew most productive at higher level activities and functions -- not simply to automate those functions that appear easiest to automate or to segregate from other functions. Ideally, automation should increase productivity by relieving crew members of boring, routine, or repetitious tasks that are prone to errors or omissions because of their intrinsic nature OR that would diminish the crew's situation awareness, distracting them from vital responsibilities. Automation should become more active with increased workload on the crew off-loading lower level tasks from the crew, and become less active with decreased workload on the crew, passing tasks back to the crew.

VERIFICATION - This Specification includes an approach to Test and Verification that involves a three stage method. The first stage occurs during the design process when the System Provider models its proposed design solutions with the designated human factors analysis and design tools. The proposed design shall meet the requirements of the analytical tools to verify that it complies with this specification at the design stage. The second stage occurs after construction of hardware prototypes to simulate tasks and functions experimentally in the Ground-based Mission Simulation Facility. The third stage will be a regimen of rigorous flight testing to empirically validate the design. This test and verification procedure ensures that the System Provider delivers the design modeled during the design process and simulated on the ground.

THE LAYOUT OF PERSONNEL ACCOMMODATIONS (LOPA)

The layout of personnel accommodations for SOFIA encompasses virtually all aspects of the architectural design of the crew cabin to accommodate the on-board mission control system and associated functions. The LOPA is where the SOFIA designers pass the crucial test of translating the complex assumptions, analysis, guidelines and requirements into a physical and functional reality that will perform the airborne astronomy mission. The key design considerations for the LOPA include the floor plan, modularity of consoles and equipment racks, *interpreting the assumptions about personnel* complement, and the application of human engineering. The LOPA design must cope with several constraints. These constraints include mounting seats, consoles and racks on the existing 747SP seat tracks and obeying their load limits, and balancing these masses with the aircraft's center of gravity. The LOPA also accommodates the science instrument on the Nasmyth tube end of the telescope, including its dynamic range of motion.

ARCHITECTURAL ADJACENCY ANALYSIS - A key step in designing the SOFIA LOPA is to interpret the requirements into an architectural adjacency analysis. The project documents include several such analyses, but one will illustrate the method here. A key method for understanding these layout requirements for crew work stations, consoles and seating is the architectural adjacency matrix with related bubble diagram. TABLE 5 shows this adjacency matrix for the SOFIA LOPA. The bubble Diagram appears in FIGURE 3. A key feature that emerges in these bubble diagrams is that the Host P.I. plays a pivotal role in establishing all the adjacencies. The Mission Director plays a pivotal role also, but the Host P.I. is primary. Personnel positions often translate into work stations of the same name, but this translation is neither automatic nor always the case. Perhaps the most prominent exception is the Guest P.I., who most likely sits with the Science Team at the P.I. Rack, and does not have a separate work station or console. Similarly, outreach personnel will mingle with the crew members doing the science and taking data; other than the single seat education console, there is no work station labeled for the outreach activities.

ARCHITECTURAL DESIGN GUIDELINES - The SOFIA Interior crew cabin comprises the envelope for the human-environment interface. This environment encompasses a wide range of systems that support human life, safety, and mission operational abilities. These guidelines derive from the interpretation of the above Top Level Requirements and the adjacency tables and bubble diagrams.

Access to the Telescope Assembly (TA) - Visual and physical access to the TA is the single most significant design driver for the LOPA. Key crew members shall be able to obtain a clear view to the TA from their work station seats. Scientists especially must be able to observe and monitor the performance and behavior of the focal plane instrument mounted upon the Nasmyth Tube. The minimum clear aisle width for physical access to the TA is 1.25m (50 inches). This center aisle also provides the preparation and alignment area for *ground support crew to lay out and attach large focal* plane instruments to the Nasmyth Tube. The clearance zone on the floor deck around the TA floor cut-out allows easy, convenient and safe crew access to the TA and focal plane instrument. This zone incorporates consideration of the crew member's ergonomic reach envelope to touch and adjust the TA. Crew safety in working around the floor cut-out requires a safety railing to protect crew members from falling into the "lower lobe" of the former aft cargo bay.

Mission and Science Operations Floor Area - The LOPA provides sufficient floor space for crew members to stand behind seated console operators and science team members taking data at the P.I.

Science Racks. This arrangement shall facilitate "over the shoulder" observation and team participation. The effective distribution of utilities is vital to the successful operations and locational flexibility of crew consoles and science racks. These utilities include power distribution, data cables and control cables.

Crew Comfort and Working Environment - The design of the SOFIA crew cabin shall ensure crew comfort, to support sustained human performance, and to promote crew productivity as defined above. The design of the crew cabin interior employs professional standards of architectural, industrial, and engineering design to create an environment that supports the accomplishment of SOFIA mission goals. The design and placement of crew consoles and seating conform to the ergonomic design standards and guidelines. The design of furnishings and outfitting in the cabin supports peripheral activities that relate to the mission objectives. These activities include preparing crew manifests, completing paperwork, making public address or intercom announcements, providing video feeds, and eating and drinking at the consoles.

The SOFIA LOPA - The Layout of Personnel Accommodations(LOPA) seeks to achieve maximum efficiency in the allocation and use of floor area and volume. The design of the crew cabin layout reflects the logic of team organization and teamwork. Within each team, the LOPA facilitates the individual activities of each team member at his or her respective work station. The LOPA provides all required crew operational and maintenance access to equipment in the crew cabin. However, no maintenance access in the MCCS areas on the aircraft or in the mission simulation ground facility shall necessitate floor area dedicated exclusively to that maintenance access. All maintenance access shares floor area with other common functions such as work stations, "standing room" zones behind the crew seating, and general circulation areas. This requirement applies wherever feasible to the TA support equipment behind the aft bulkhead and in the below deck "lobes." This requirement implies that there should be no secondary "access corridors" behind equipment racks.

The ***Configurability*** of the consoles and seating is a key to the SOFIA LOPA meeting its many and diverse mission scenarios and variations in crew complement. A comparison of FIGURE 4, the Minimum Configuration; and FIGURE 5, the Maximum Configuration illustrates this property of configurability. Thus, the number of seats or consoles neither predetermines the crew complement nor does it equate to the number of Mission Crew members. Instead, the consoles are configurable to match the crew composition for each mission and the tasks before them.

FIGURE 6 provides a view of the entire main crew cabin of the SOFIA 747SP, forward of the cavity pressure bulkhead. It shows the relative position of all the major equipment including the telescope, crew consoles, seating, conference tables and equipment racks, plus other crew accommodations such as galley, lavatory, and passenger seating. This LOPA is subject to on-going revision by the members of the SOFIA project.

SOFIA WORKING ENVIRONMENT - The focus of the entire Human Engineering effort is to produce a working environment that enables the crew to meet their productivity goals safely and reliably. The LOPA in all its architectural attributes is the major vehicle for implementing these objectives.

CONCLUSION

The SOFIA Human Engineering Guideline takes an innovative approach to the human factors and ergonomic design. By emphasizing clarity of the fundamental assumptions of the project and the analysis necessary to define the design problem, this approach makes the design requirements accessible and comprehensive. The preliminary architectural design approach flows from this design reasoning.

DEFINITIONS

Aircraft System: The Boeing 747-SP, as refurbished and modified to accommodate the Telescope Assembly in a full diameter cavity, and to accommodate the crew and all the mission operations and science equipment.

Comfort: To conduct all flights in a manner that maximizes passenger and crew health, comfort, and productivity (Billings, 1991).

Configurability: The ability to change or rearrange the crew consoles, seats, and science racks in a modular fashion.

Console: The primary work station for SOFIA crew members. All consoles are identical or "universal," but operate in modes determined by the software keys issued to the various crew members.

Crew: "Crew" or "crew member" means any person on board the aircraft or working in ground support functions.

Ergonomics (or Human Factors Engineering): A discipline concerned with designing machines, operations, and work environments so they match human capabilities and limitations (Miller, 1994, attributed to A. Chapanis, 1965).

Experimenter (P.I.) Rack: A "half-height," mobile science rack that the Experimenter integrates at his or her home institution to support the focal plane instrument, and brings to SOFIA.

KAO: Kuiper Airborne Observatory, a .91m infrared telescope installed in a C-141 in 1975, now being retired after 20 years of successful operation.

LOPA: Layout of personnel accommodations, refers to the architectural plan for the crew cabin, including consoles, racks, seating, stowage, and amenities.

MCCS: Mission Control & Communications System (MCCS), the airborne mission control center to operate the SOFIA 2.5m telescope.

Observatory Rack: An equipment rack permanently installed in the SOFIA Aircraft. The facility racks are the primary installation location for permanent (hard-wired and hard-plumbed) equipment for operating the observatory facility.

Principal Investigator (P.I.): A scientist, typically an astronomer, who leads the science team in using the SOFIA capability to collect scientific data.

Situation Awareness: The perception of the elements in the environment within a volume of time and space, the comprehension or their meaning, and projection of their status into the near future (Endsley, 1994).

System Provider: The performing organization that does the work to build SOFIA and its systems; University Space Research Association (USRA).

Team: A unified "multi-person system" that performs like an operator: it works to a mission requirement, performs tasks, receives feedback, holds goals in common, and adjusts its behavior to changing demands. (Meister, David, 1976).

Telescope Assembly (TA): The 2.5m infrared telescope with balance, bearing, pointing and focal plane instrument mounting system, to be provided by DARA, the German space agency.

USRA: University Space Research Association, the prime contractor for SOFIA.

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TABLE 1. Changes from KAO to SOFIA: Conditions for "Best" and "Worst" Cases
Major impacts appear in heavy boxes.

Item	KAO	SOFIA	Change %
Observation Flights per year	80	160	+100
Support Flights per year	20	<40	+100
Down Days per year	265	<165	-40
Down Days / Observation Flight	~3:1	<1:1	-67
Focal Plane Instruments / Flight	1	1*	~0
Maximum Viewing Targets / Flight	10 dim~ 100 bright	10 dim~ 200 bright	+100
Maximum Mission Crew	4 to 5	2 to 3	-25 to -50
Mission Crew Trainees (as required)	~2	~2	+0
P.I. Teams / Flight (maximum, including host & guest teams, plus instruments for background tests)	2	2 to 3	0 to+50
P.I. Team Members (including supporting technicians)	4 to 6	6 to 15	0 to +275
P.I. Racks	1 to 2	4 to 5	+100 to 250
Outreach/Educators with Docent	3	6	+100
Media Guests (incl. foreign observers)	2	4	+100
Engineering Development Personnel	2	2	0
Cargo Doors to the Main Cabin	1	0	-100
Other Seats Vacant or removed During normative observation flight	0	12 to 18	∞
Total Personnel During Science Operations	18	~26 to 30	+44 to +77

* SOFIA Level I Requirements mandate not precluding use of more than one instrument on a SOFIA Flight.

TABLE 2. SOFIA Teamwork and Task Analysis

Crew Teams	Mission Planning & Prep.	Install Consoles & Racks on Aircraft	Install New Focal Plane Instrm't. on TA	Service Telescope Assembly	Annual Maint.	Normal Science Flight	Conduct Deploy-ment Ops
Mission Ops Team	√	√				√	√
Science (P.I.) Team	√	√	√			√	√
Outreach/ Education Team	√					√	√
Instrument Test	√	√				√	
Ground Support Team		√	√	√	√		√

TABLE 3. Five SOFIA Flight Scenarios

Values indicate the number of crew members on board SOFIA.

Crew Flying in SOFIA Cabin	Normal Science Flight		Engineering Flight		Pilot Training		Ferry Flight		Ferry — Science Flight	
	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.
Mission Ops. Crew Members	3	2	3	2	0	0	1	1	3	2
Scientists (in two teams)	15	6	10	0	0	0	0	0	12	6
Engineers / Technicians	3	0	12	5	0	0	0	0	3	0
Educators **with** Docent	6	3	0	0	0	0	0	0	6	3
Instrument Test	5	0	5	0	0	0	0	0	0	0
Other (Press, visiting dignitaries, etc.)	10	0	0	0	0	0	0	0	6	0
Augmented Flight Crew	0	0	0	0	3	3	3	0	3	0
Maintenance Crew	0	0	0	0	0	0	8	2	8	2
Trainees (Mission Ops)	2	0	2	0	0	0	0	0	2	0
"Project Support"	0	0	0	0	0	0	43*	0*	36*	0*
Other Experimenters (e.g., Atmosphere. or Earth Science.)	3	0	0	0	0	0	0	0	1	0
TOTAL in cabin	44**	8	29	6	3	3	44*	1	44*	10*
Nominal Census	30	10	30	10	3	3	44	1	44	10

* Depending upon cargo load. **Not a sum but a top limit

FIGURE 1. Artist's rendering of the Stratospheric Observatory for Infrared Astronomy (SOFIA) in flight.

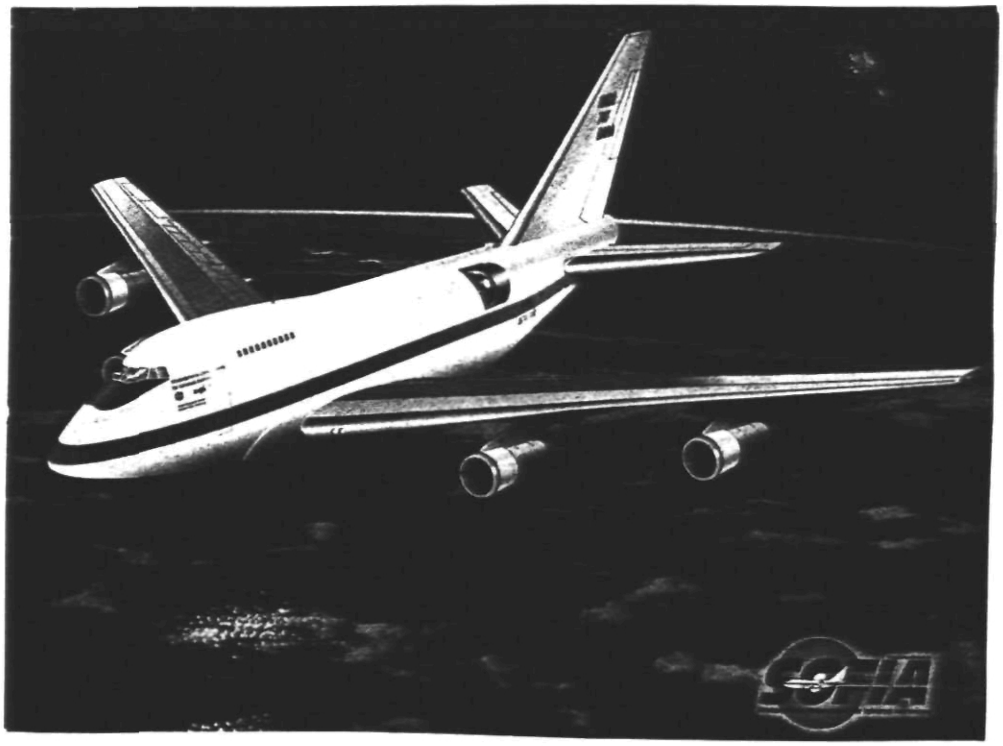


FIGURE 2. The Kuiper Airborne Observatory (KAO) -- predecessor to SOFIA -- at Ames Research Center.

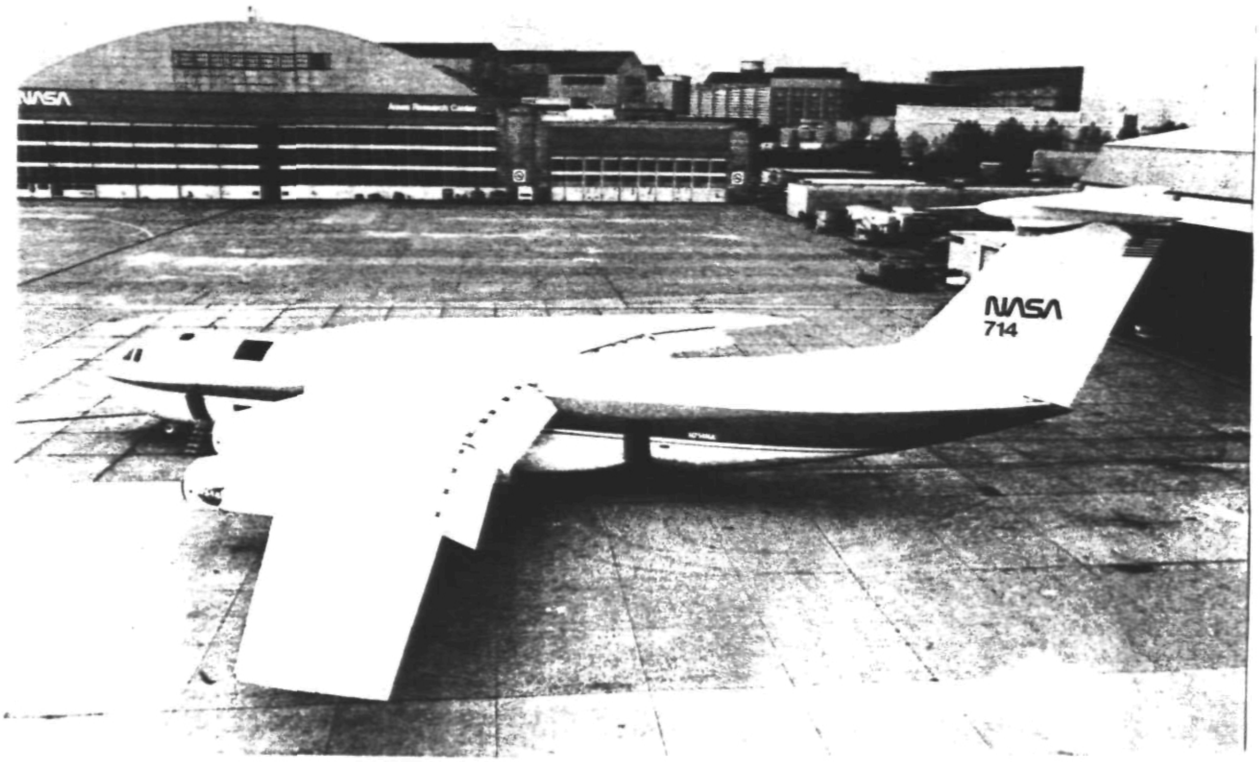
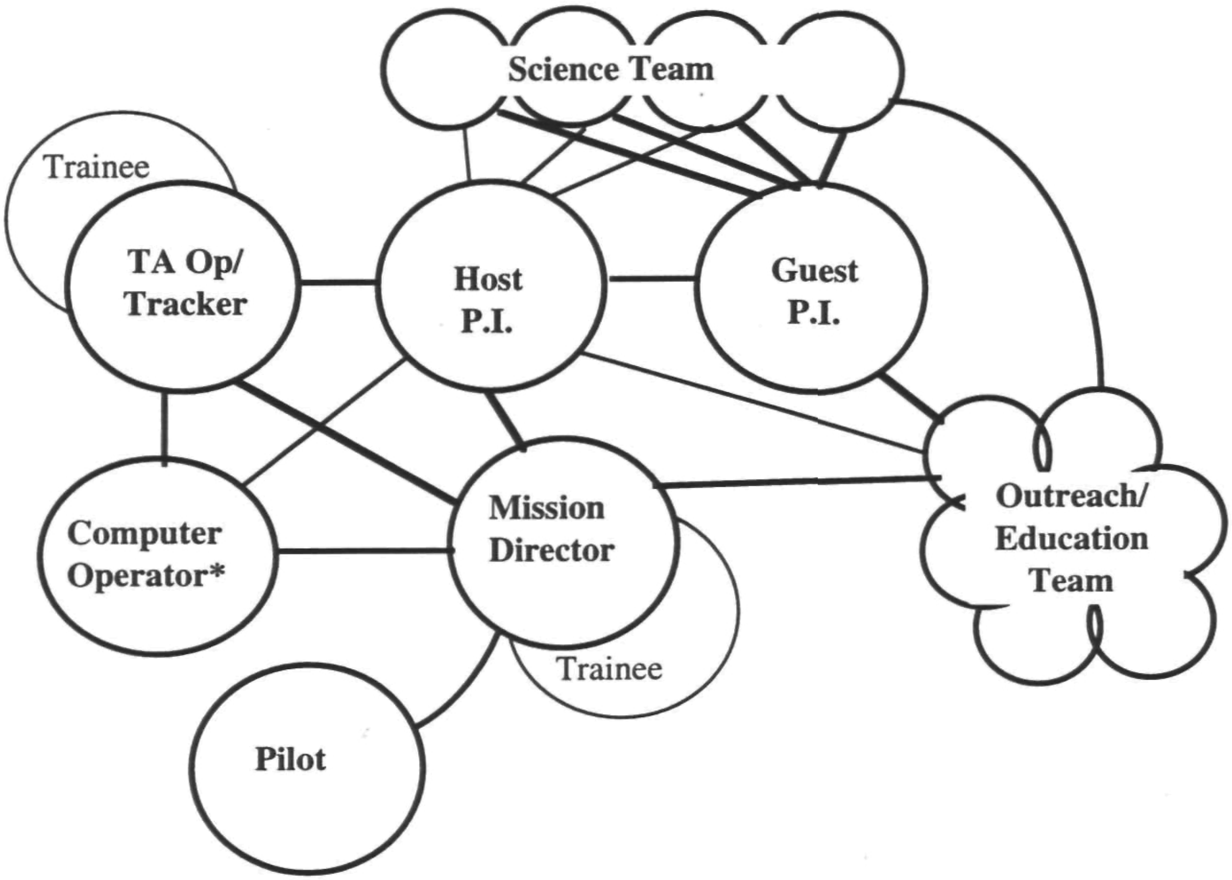


TABLE 4. SOFIA LOPA Architectural Adjacency 3 Value Matrix of All Positions

	Host P.I.	Guest P.I.	Mission Director	Tracker/ TA Op.	Computer Operator*	Science Crew	Outreach/ Education Team
Host P.I.							
Guest P.I.	2						
Mission Director	2	0					
Tracker/ TA Op.	2	0	1				
Computer Operator*	1	1	2	2			
Science Crew	1	1	0	0	0		
Outreach/Ed Team	1	2	2	0	0	1	

* The Computer Operator is a transitional position during SOFIA operations start-up.

FIGURE 3. SOFIA LOPA Architectural Adjacency Bubble Diagram for 3 Value Matrix of All Positions. The Computer Operator is a transitional position during SOFIA start-up, that falls to the Mission Director.



Stratospheric Observatory for Infrared Astronomy

SOFIA

Layout of Personnel Accommodations

LOPA

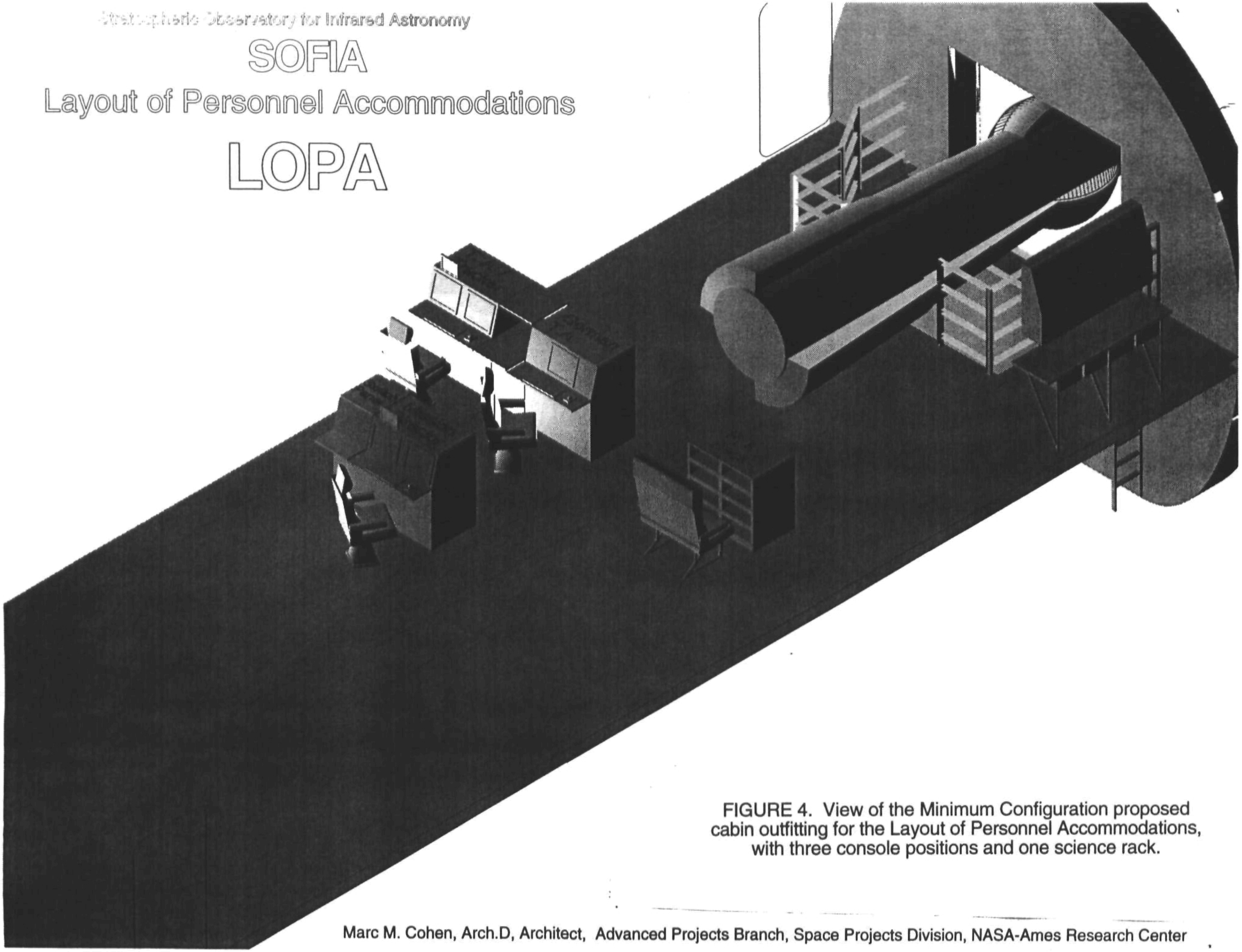


FIGURE 4. View of the Minimum Configuration proposed cabin outfitting for the Layout of Personnel Accommodations, with three console positions and one science rack.

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Stratospheric Observatory for Infrared Astronomy

SOFIA

Layout of Personnel Accommodations

LOPA

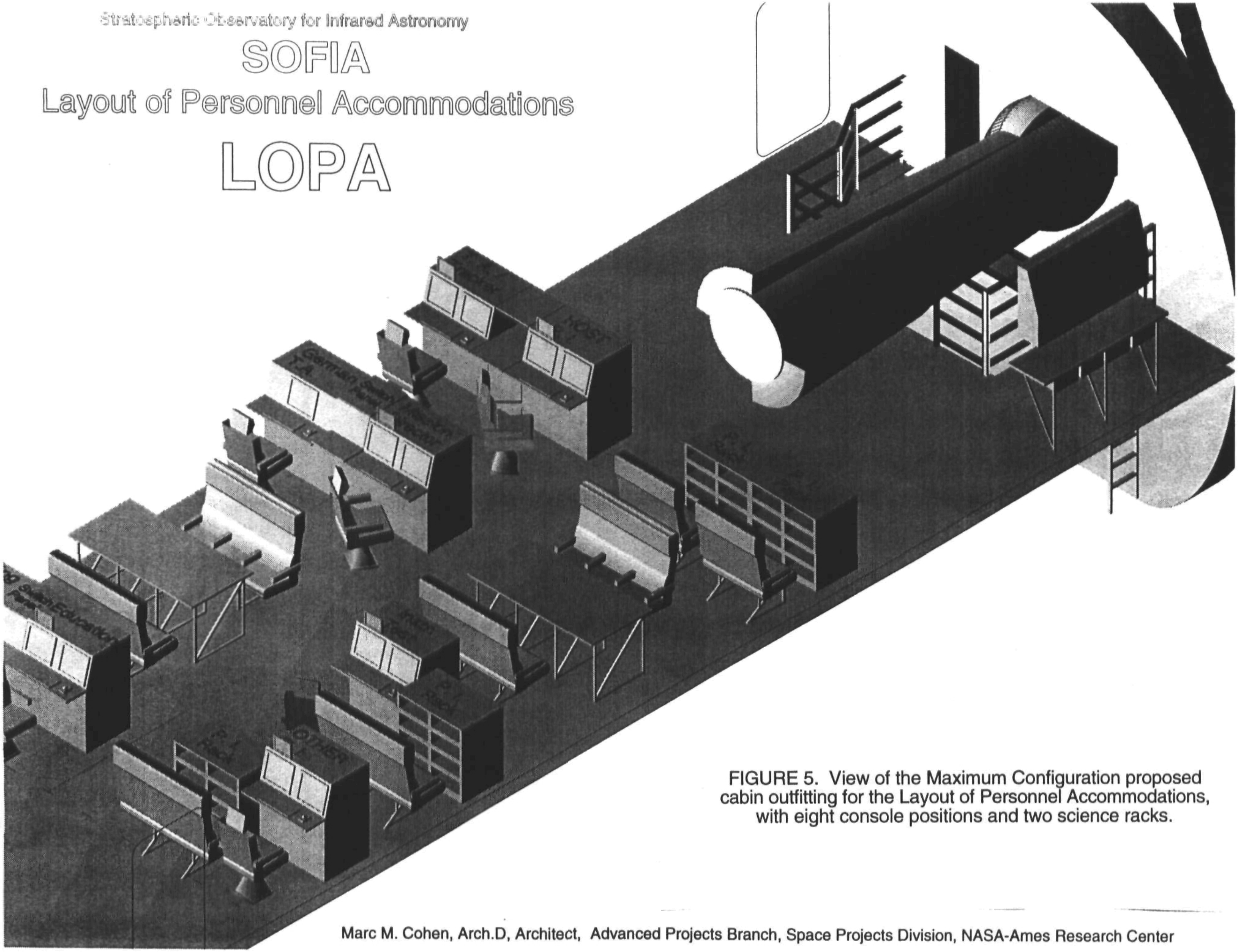

FIGURE 5. View of the Maximum Configuration proposed cabin outfitting for the Layout of Personnel Accommodations, with eight console positions and two science racks.

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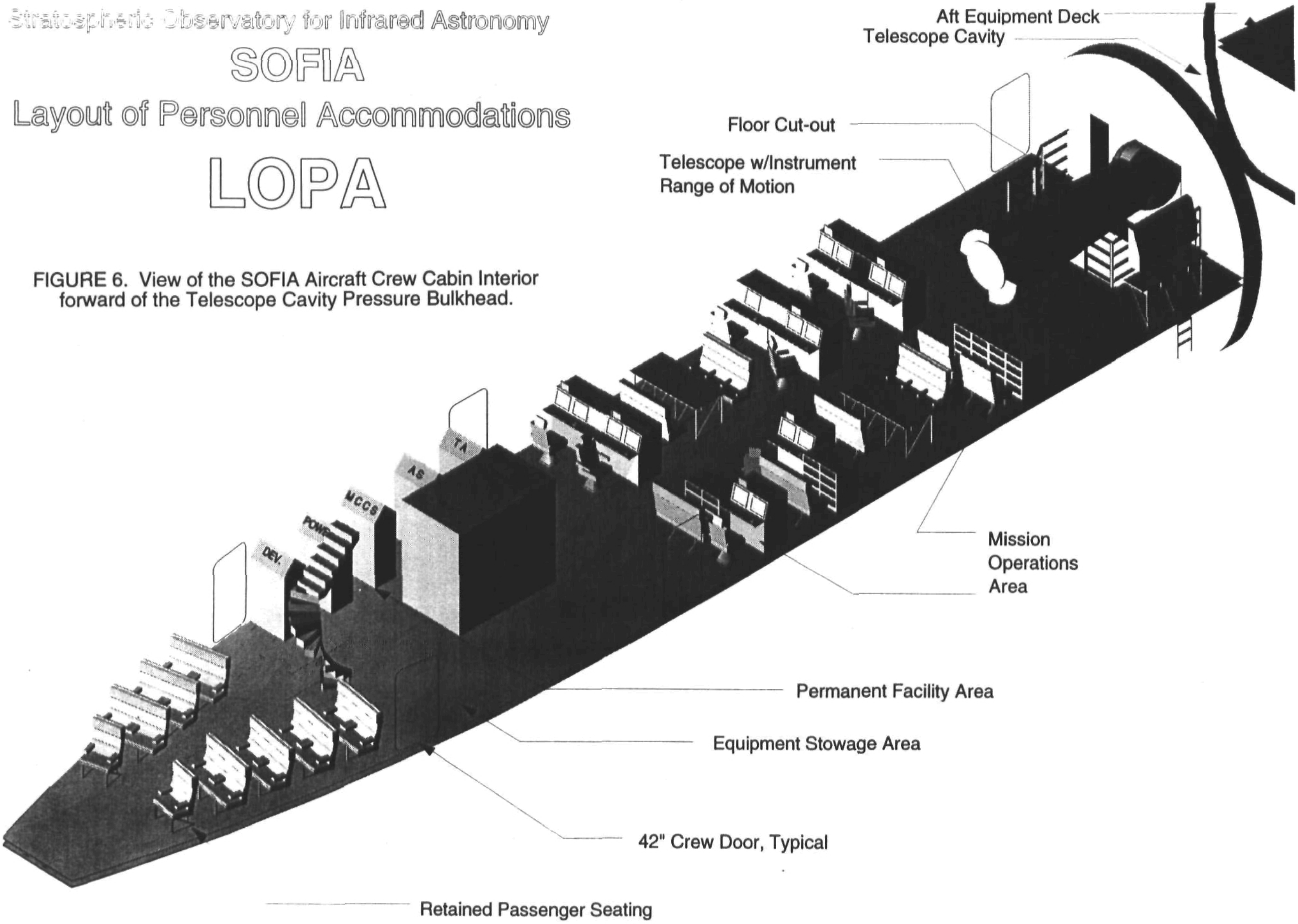
Stratospheric Observatory for Infrared Astronomy

SOFIA

Layout of Personnel Accommodations

LOPA

FIGURE 6. View of the SOFIA Aircraft Crew Cabin Interior forward of the Telescope Cavity Pressure Bulkhead.



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