NASA CONTRACTOR REPORT

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AN EXPLORATORY STUDY TO DETERMINE THE INTEGRATED TECHNOLOGICAL AIR TRANSPORTATION SYSTEM GROUND REQUIREMENTS OF LIQUID-HYDROGEN-FUELED SUBSONIC, LONG-HAUL CIVIL AIR TRANSPORTS

Preliminary Design Department

Prepared by
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16. Abstract

An exploratory study was conducted to evaluate the feasibility and cost impact of implementing a liquid-hydrogen-fueled (LH_2), air transport support system at Chicago-O'Hare International Airport. The study assumed an available supply of hydrogen to the airport boundary. It also assumed that the present widebody fleet at O'Hare was replaced by 400 passenger, LH_2-fueled aircraft operating on the current frequency schedule and route network. The LH_2 aircraft configurations used in this study were developed during a previous NASA-sponsored study.

A baseline air terminal concept was developed which permitted airlines and the airport to operate JP- or LH_2-fueled aircraft at common terminal gates.The concept included installation of a hydrogen liquefaction and storage facility on airport property, as well as the fuel distribution system. The capital investment and hydrogen-related operating costs to the airlines were estimated.

The study concluded that the system would be technically and operationally feasible at O'Hare, and that economics would be a prime factor in future decisions regarding the use of LH_2 as an air transport fuel. Research and technology recommendations were made to improve component efficiency/reliability. The study also concluded that additional investigation should be conducted on the implementation of a nationwide or worldwide LH_2 air transportation system, to understand fully the operational and economic implications of the total system, before decisions could be made relative to committing to this option.

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FOREWORD

This study was performed by the Preliminary Design Department of The Boeing Commercial Airplane Company. The following Boeing personnel, under the direction of Mr. Glen W. Hanks, Program Manager, made up the study team and were responsible for the subjects noted.

D. G. Andrews	Aircraft Interfaces
O. B. Brende	Safety
E. E. Eckert	Ground Service and Equipment
M. Hamamoto	LH_2 System Analysis
R. H. Kimble	Economic Analysis
R. L. Kreitinger	Requirements and Study Integration
H. J. Miyatake	Maintainability
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R. A. Taylor	LH_2 System Installation and Airport Evaluation

Assistance was provided under subcontract by the following industry organizations.

United Air Lines	Mr. Ralph Cramer, Staff Engineer, Ground Equipment Engineering–Airline Operations Requirements and Evaluation
Air Products & Chemicals, Inc.	Mr. James E. West, Special Projects Manager, Industrial Gas Division–LH_2 Liquefaction and General System Technical Definition and Economics

In addition, the Chicago Department of Aviation, through its appointed coordinator, Mr. A. F. Gedroc, was most cooperative throughout the study and provided detailed information regarding the current and planned facilities and procedures at Chicago-O'Hare International Airport (ORD). This organization was very responsive to contractor requests for advice and critique during the study. Appreciation is also expressed to American Airlines, Continental Air Lines, Delta Air Lines, Northwest Airlines and Trans World Airlines, for providing details regarding their widebody fueling practices at O'Hare airport.

CONTENTS

CONTENTS (Continued)

CONTENTS (Concluded)

FIGURES

FIGURES (Concluded)

TABLES

AN EXPLORATORY STUDY TO DETERMINE THE INTEGRATED TECHNOLOGICAL AIR TRANSPORTATION SYSTEM GROUND REQUIREMENTS OF LIQUID-HYDROGEN-FUELED SUBSONIC, LONG-HAUL CIVIL AIR TRANSPORTS

Preliminary Design Department
Boeing Commercial Airplane Company

1.0 SUMMARY

This exploratory study resulted in (a) the definition of potential liquid hydrogen (LH_2) fueling system concepts that could be installed and operated on existing airports, (b) the technical and economic impact of those systems on airport and airline operations, and (c) identification of the research and technology effort that would be required to ensure that the airport portion of an LH_2 fueled air transport system could be made available, should the United States wish to exercise that option. The existing and planned facilities at the Chicago-O'Hare International Airport (ORD) were used as the focus of the major part of the study. Gross extrapolations were made to other airports and a potential scenario for introduction of LH_2 fuel into the air transportation system was developed and evaluated as affecting ORD. All work was based on the assumption that current JP-fueled widebody transports would be replaced with 400 passenger, 10 186 km (5500 nmi) design range LH_2 transports operating at current frequencies over the existing route network during the 1990-2000 time period. Narrowbody transports were assumed to continue using JP fuel. The following major points represent the considered inputs and judgment of the participants in this study, including the Chicago Department of Aviation and subcontractors United Air Lines and Air Products and Chemicals, Inc.

- A 726 000 kg/day (800 ton/day) liquefaction capacity was found to be adequate to meet the 544 300 kg/day (600 ton/day) aircraft block fuel demands. The liquefaction plant can operate efficiently at 120% rated capacity to accommodate demand variation due to fleet growth or fueling philosophy that might be applied by operating airlines. A storage capacity of 1 452 000 kg (1600 tons) was determined adequate to meet variations in fuel demand and provide a fuel supply in case of normal system interruption. This compares with the current total United States LH_2 production capacity of approximately 98 000 kg/day (108 tons/day) and the largest existing storage facility, 236 000 kg (260 tons), at the NASA/Kennedy Space Center.

- Several LH_2 fuel distribution concepts were considered. Dual fueling (LH_2 or JP) at main terminal gates serving widebody transports was found to be the most desirable: at ORD, competitive airlines rely heavily on quick exchange of passengers and baggage. The installation could be made without major disruption to airport and airline operations. A concept that would isolate the fueling of LH_2 transports from those using JP fuel would cause less airport disruption during installation, but airline operations would be severely impacted.

- A capital investment of \$469 million (1975 dollars) would be required to implement the LH_2 liquefaction, storage and distribution system for the dual fueling concept when supplied with gaseous hydrogen (GH_2). If LH_2 is delivered to the airport storage facility from remote liquefaction facilities, the capital investment for the airport reliquefaction plant would be reduced to \$270 million; however the increased price of LH_2 delivered to the airport (versus GH_2) must be taken into consideration when comparing capital costs of liquefaction and reliquefaction plants. (Electric power costs for hydrogen liquefaction are significant.) Annual costs to the airlines for the LH_2 fuel were determined parametrically to include the effects of hydrogen delivery state (LH_2 or GH_2), fueling concept (dual or separate), airplane fuel tank configuration (internal or external), and type of capital financing (private or public). The study also indicated that depending on the cost of electric power, the cost of GH_2, and the financing method employed LH_2 costs to the airlines would be competitive within the range of JP fuel costs of 19 to 40¢/l (0.72 to 1.50\$/gal). Capital investment and annual costs are detailed in the concept appraisal section.

- A 12-year implementation period would permit adequate planning, installation and checkout using advanced (not fully developed) liquefaction system technology. This time period would also be compatible with transport development through certification providing it is preceded with adequate Research and Technology (R&T), and an economical source of gaseous hydrogen is available. It was determined that over 90% of the widebody operations in the United States could be operated on LH_2 after an additional five years on the assumption that two major airports, offering the LH_2 fuel capability, are implemented each of the five years.

- All potential technical problems identified during the study lend themselves to straight-forward engineering solutions:
  1. Changes to airline operating procedures would be limited to the fueling function (revised fueling equipment and operating procedures, as well as extensive ground crew training) and to the passenger loading provisions necessary to handle the double deck aircraft configuration.
  2. Installation of the LH_2 system at ORD could be accomplished using existing hardware design concepts and construction techniques. Disruption of airport operations could be limited to localized areas around the terminal proper. (This conclusion does not necessarily apply to other airports with real estate limitations for the LH_2 system.)

- Research and technology effort is recommended in the following areas:
  1. Ground to airplane fuel and vent connection concept research
  2. Liquefaction cycle efficiency and control
  3. Vacuum jacketed line failure sensing systems research
  4. System engineering studies of a functional LH_2 airport complex to determine technical and economic characteristics that would affect implementation decisions regarding the adoption of LH_2 on a system-wide basis

2.0 INTRODUCTION

National concern over potential energy shortages has directed attention to a broad spectrum of energy users; toward conserving conventional forms of energy and substituting unconventional forms where feasible. Transportation is a major energy consumer, most of which is derived from petroleum products. Hydrogen is one of several potential alternate fuel candidates for air transportation and several studies have been performed, focusing on the various elements of a hydrogen system. NASA has sponsored industry studies on the production and liquefaction of hydrogen and on liquid hydrogen technology for subsonic aircraft. The present study explores the feasibility and impact on an air terminal of implementing a liquid hydrogen (LH_2) air transportation system. The position this investigation of user facilities and operations occupies in the general approach to the energy problem is shown in figure 1.

2.1 OBJECTIVES

The general objective was to make a preliminary assessment of the impact on air terminals and airline ground operations of the use of LH_2 as a fuel for commercial air transports. This was accomplished, as illustrated in figure 2, by formulating concepts for the air terminal studied, based on the integrated requirements of the operating airlines, the fuel system and the air terminal facility. The concepts thus formulated were appraised for technical and operational feasibility, and economic impact. Finally R&T recommendations were made relative to areas considered to be high risk at current levels of technology.

2.2 SCOPE

The study was based on implementation of an LH_2 air transportation system at O'Hare International Airport, Chicago, Illinois (ORD) in the 1990-1995 time period. The current widebody fleet operating from ORD was assumed to be replaced by 400-passenger 10 186 km (5500 nmi) design range, LH_2 aircraft operating over the current route network at today's widebody frequencies. Two airplane configurations developed during a previous study (ref. 1) were used. Principal characteristics of those configurations are shown in figure 3.

The contract statement of work stipulated that a fuel supply was to be assumed available at the airport boundary, delivered either as a gas by pipeline, or as a liquid by tank truck or rail tank car. The study did not address the production of hydrogen nor its transmission to the airport boundary.

2.3 APPROACH

A team approach was utilized in order to properly analyze and integrate the design, installation and operational aspects of the study. The team included two subcontractors who interfaced with Contractor team members in their areas of expertise. Air Products and Chemicals, Inc., well-known in the field of hydrogen cryogenics, contributed to the design and costing of the fuel system. United Air Lines, the largest operator of widebody aircraft at ORD, contributed to the design of ground operational equipment

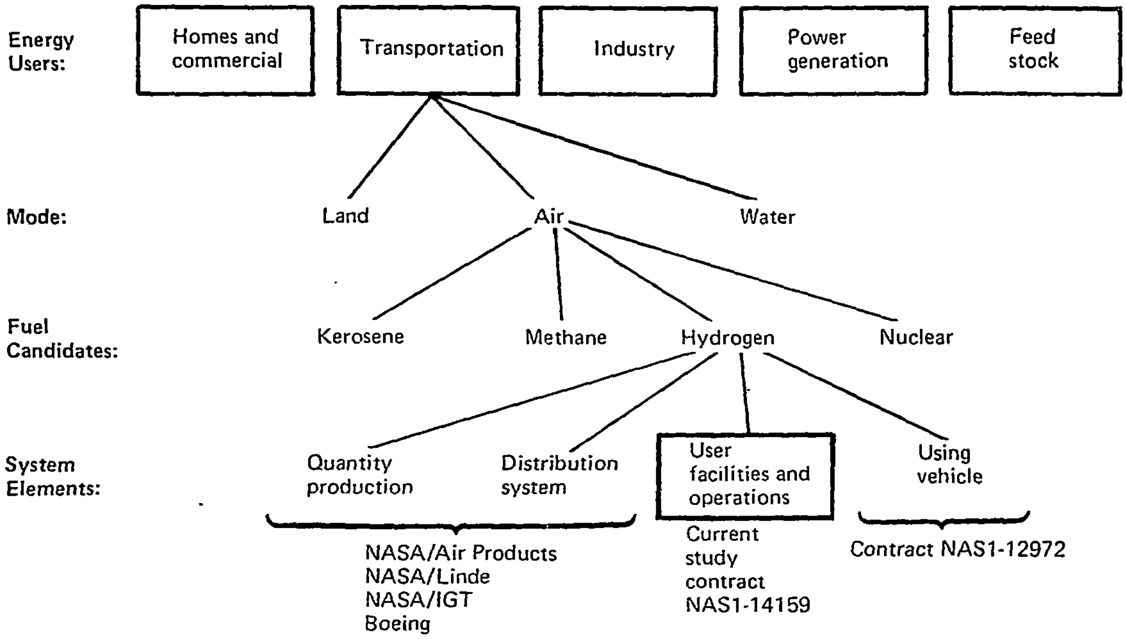


Figure 1.—Approach to the Energy Problem

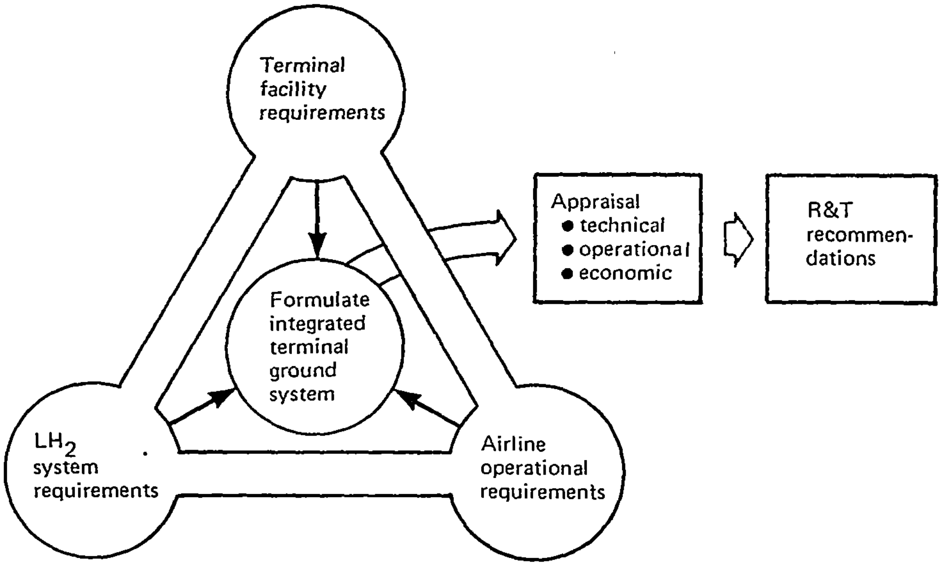


Figure 2.—Study Objectives

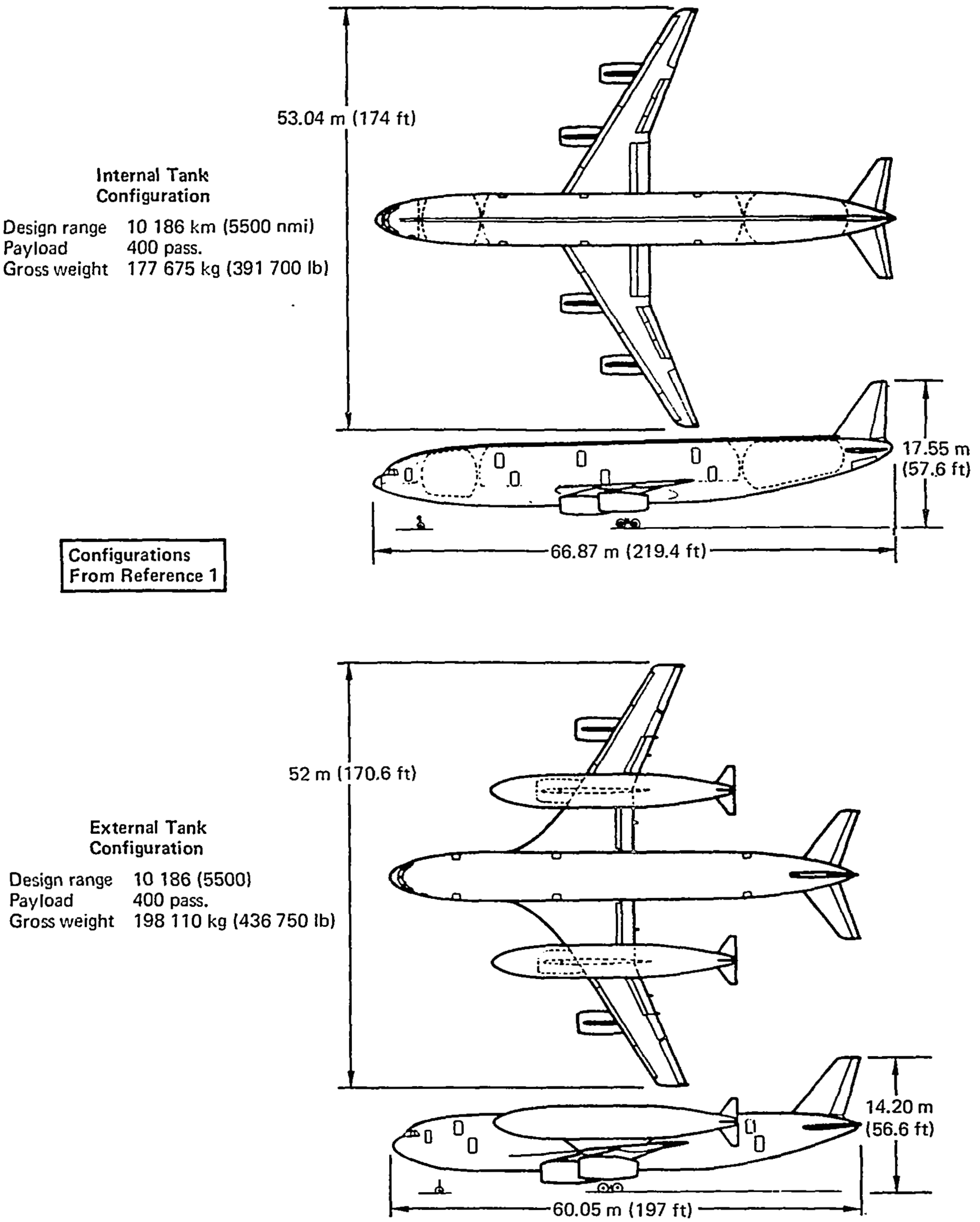


Figure 3. —Study Configurations

and the evaluation of ground operations. The Chicago Department of Aviation (not under contract) provided information on the management and operation of O'Hare, planning data, and a critique of conceptual arrangements developed during the study.

2.3.1 STUDY FRAMEWORK

The study was conducted as shown in figure 4. Fifteen domestic airports were identified as candidates for study from considerable data developed on widebody operations, traffic characteristics and other factors relating to their operating environments. The NASA designated ORD as the airport to be studied. The airport configuration, as shown in figure 5, was based on Composite Utility Drawings furnished by the Chicago Department of Aviation. Existing facilities are shown solid, with planned additions to runways and taxiways as dashed lines.

Basic ground rules were established from considerations of safety and airline operating objectives. These strongly influenced the requirements upon which the air terminal concepts were formulated. They are listed and discussed in section 2.3.2.

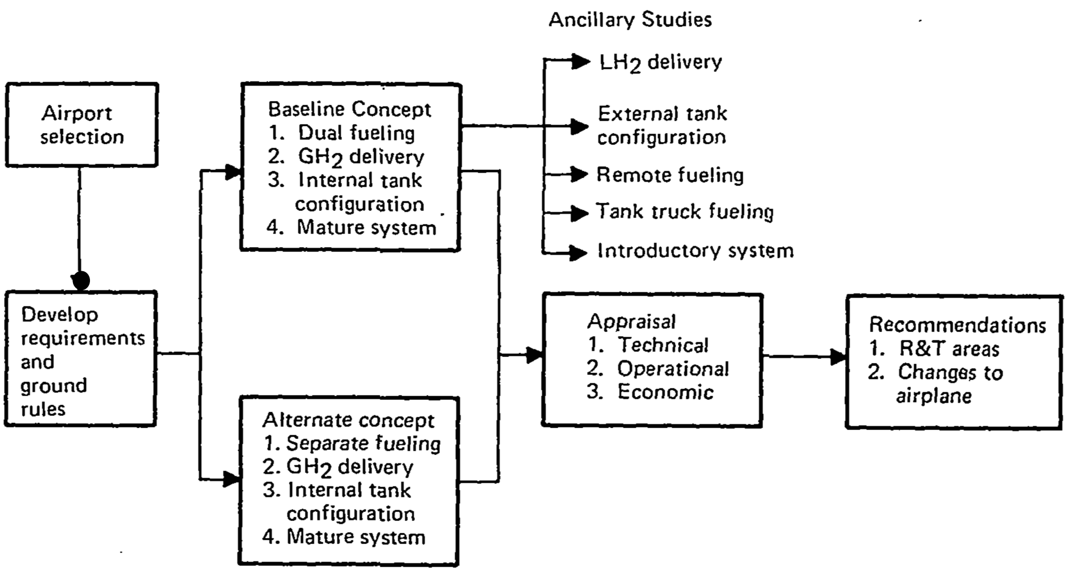


Figure 4.—Principal Study Work Elements

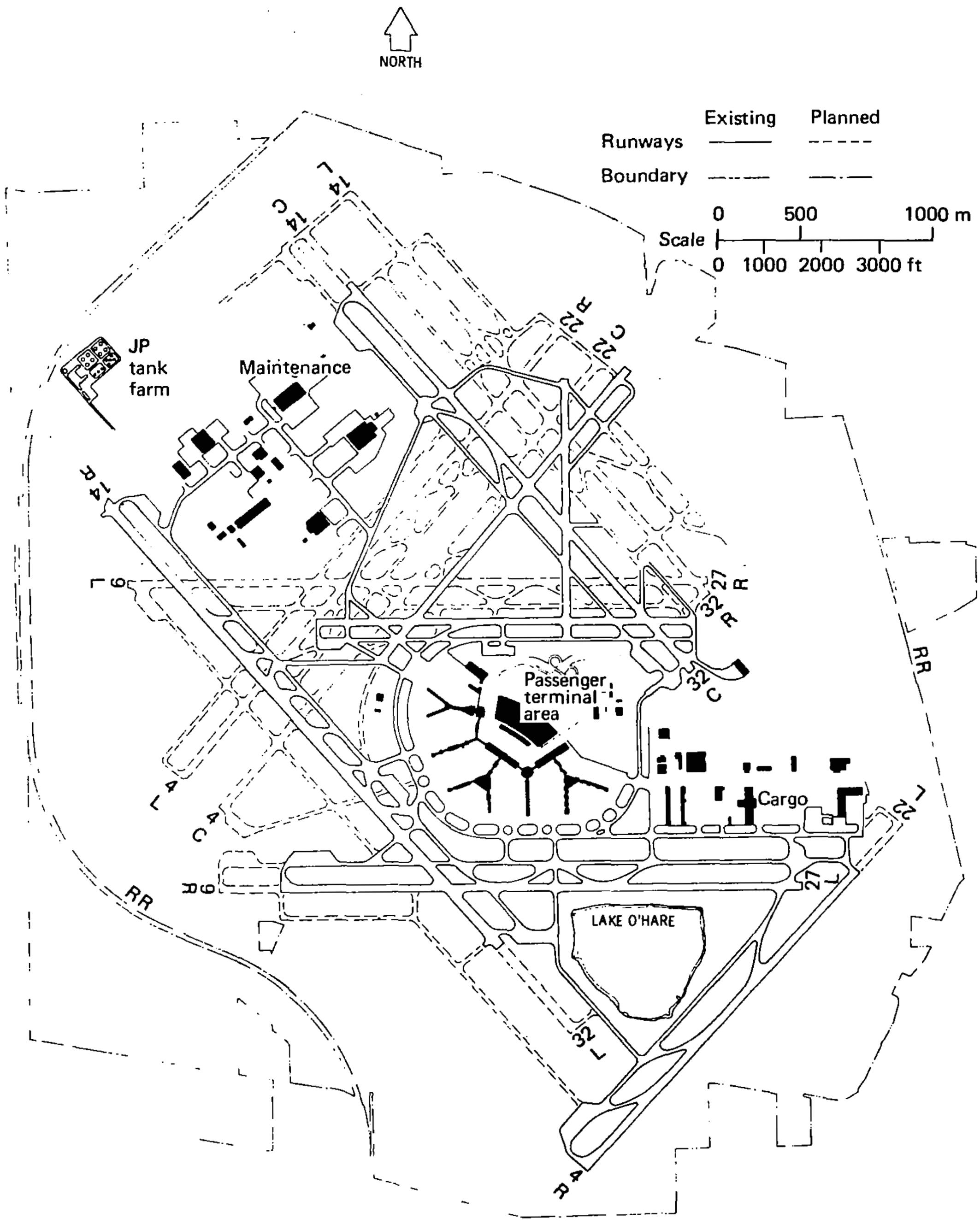


Figure 5.—O'Hare International Airport

After establishing ground rules and requirements, a baseline air terminal concept was developed which utilized existing terminal facilities at ORD for both LH_2-fueled airplanes and narrow body, JP-fueled aircraft. This concept, which was investigated in depth, retained normal airline flexibility of operations. It was based on gaseous hydrogen delivery to the airport, a fleet of internal tank LH_2 airplanes, and the route structure and fueling characteristics of a mature system.

An alternate concept, based on separation of JP and LH_2 fueling gates, was developed to evaluate the impact of that constraint on facilities and operations. The two concepts were carried through technical, operational and economic appraisals, and recommendations were made for further research and technology efforts. The recommendations included those desired to make the LH_2 airplanes more compatible with the air terminal concepts.

Several ancillary studies were conducted to determine the impact of changes to major input factors on the baseline concept. These included liquid hydrogen delivery to the airport rather than GH_2 delivery, external tank transport configuration in place of the internal tank configuration, and two variations in fueling philosophy. The final ancillary study postulated a pattern of LH_2 air transportation network growth and some gross estimates of capital investment impact on major domestic air terminals.

Technical, operational and economic appraisals were made of the baseline and the alternate concept. From these appraisals, recommendations for changes to the internal-tank airplane configuration were identified to make it more compatible with the air terminal concepts. Also, areas were identified from these appraisals, which would benefit from further study, or in which special research and technology is necessary to ensure acceptable standards of safety, reliability and/or operational flexibility.

This document is structured to follow the study flow as depicted in figure 4. The characteristics of ORD facilities, operations and traffic are discussed in section 4. Development of the baseline and alternate concepts is contained in sections 5 and 6, respectively. Ancillary studies are covered in section 7. Appraisal results are provided in section 8, with recommendations for changes to the internal tank airplane configuration in section 9. Recommendations for further study and/or development are contained in section 10.

2.3.2 BASIC STUDY GROUND RULES

Ground rules, adopted from considerations of safety and airline operating practices, had a major impact on all aspects of the study.

Safety Considerations

General safety considerations are discussed below; however, specific applications of these principles are to be found throughout this document.

The properties of hydrogen that make it markedly different from kerosene are its low boiling point 20.3° K (-423° F) and the low energy required to ignite hydrogen/air mixtures (below visibility level of a spark). The low boiling point makes contamination control and pressure relief provisions major goals in the design of safe hydrogen systems. The low ignition energy dictates particular care in insuring that hydrogen can be vented or leaked only to controlled areas.

At the extremely low energies for hydrogen-air ignition (approximately 0.02 millijoules as compared to 0.2 millijoules for kerosene), it must be assumed that the potential for igniting a hydrogen leak is always present. The elimination of ignition sources is not practical, therefore a hydrogen system must be designed such that the potential for a leak in a critical area is minimized, and fires from small leaks do not jeopardize equipment or personnel safety. This design requirement has been successfully met by the chemical industry and in the surface transportation of hydrogen. There is no technical reason why the requirement cannot be met in the design and operation of aircraft and associated ground systems.

Both burning and detonation can be initiated over a wide range of hydrogen-air mixture ratios. The flammability range is 4 to 75 mole (volume) percent hydrogen in air; the detonation limit is 17 to 60 mole percent hydrogen in air. Experience shows that hydrogen-air mixtures confined in a closed area can be detonated; however unconfined hydrogen-air mixtures are likely to burn rapidly. The design of hydrogen systems must insure that hydrogen-air mixtures cannot be formed or remain undetected in a closed area.

The flame produced by hydrogen burning in air is relatively nonluminous and its low density and high liquid volatility results in a rapid dissipation of hydrogen spills. These properties lower the damage potential of a major liquid spill such as that resulting from an airplane crash. Hydrogen tank rupture experience obtained during development of the Saturn Launch Vehicle indicates that damage from a tank rupture is considerably less than that resulting from accidents with equivalent quantities of conventional fuels. Danger to personnel outside a hydrogen spill footprint is low because of the low radiative heat transfer from the fire.

When liquid hydrogen is contained in a closed system, the system pressure will rise due to vaporization of the liquid, followed by super heating of the vapor. This pressure rise is limited only by the pressure-volume-temperature (PVT) characteristics of hydrogen, the ambient temperature, and/or the strength or safety relief capability of the system. Excessive pressure buildup in any part of a hydrogen system is an extreme safety hazard to personnel and equipment. This condition is avoided by the use of pressure relief devices at all points where liquid or cold hydrogen can be trapped between closures.

The primary hazards of fire, explosion and cryogenic temperatures must be minimized by incorporating in the air terminal fuel system the proven and effective design features developed during the highly successful space programs. Lessons learned from those programs are particularly applicable to the liquefaction plant and to much of the distribution system considered in this study. Continuous daily airport LH_2 operations, however, will involve situations that did not occur in the infrequent, highly-controlled space program operations. Particular attention must be placed on safety in those areas where the airplane and LH_2 system interface. Of these, the most critical is airplane fueling which is conducted in an environment of ground vehicles and personnel performing many diverse functions. Operating procedures and training programs must be tailored to personnel who, in most cases, have a very limited technical and experience background in cryogenics.

During design of the LH_2 facility and distribution system the following safety considerations must receive special attention:

- Separation of the LH_2 facilities from roads, buildings, runways, etc
- Adequate ventilation for enclosed areas to eliminate the probability of accumulation of combustible mixtures
- Automated malfunction sensing and system shutdown controls with manual control backup
- Ignition sources
- Provisions to confine/control large LH_2 spills in critical areas

An acceptable level of safety in operation of the airport liquid hydrogen fuel system can be achieved by applying space program experience, practical safety standards to system design, and to the development of rigid operating procedures.

Airline Operations

The following considerations are important to efficient airline operations at ORD:

- Operating procedures at ORD which degrade airline economics or cause undue passenger inconvenience are unacceptable. Ground time is unproductive to an operating airline and must be held to a minimum. This is especially critical at ORD, where widebodies fly relatively short stage lengths and are part of a complex scheduling network.
- The consolidation of an airline's operations at an air terminal is important. Dispersed operations result in inefficient use of ground personnel and equipment, and tend to decrease that airline's interconnect traffic. A large majority of the ORD passenger traffic is made up of the "through passenger" type. Many of those passengers change flights at ORD. The major trunk carriers tailor their service individually to ensure that passengers will continue on their airline. Any major physical separation of portions of their fleet would disrupt this competitive situation.

- During peak passenger/transport traffic periods, gate space at ORD is at a premium, and no major expansion has been agreed upon. The makeup of the parked fleet varies considerably during the day. This has forced the airlines to equip a majority of their gates to handle nearly every model in their fleet. Allocation of gates to specific models would disrupt their ability to follow this concept.

To attract the interest of airlines that operate widebody-type aircraft, the operating features of new concepts such as LH_2 fuel, must be responsive to the above three characteristics. They basically dictate that the LH_2 fuel concept should permit operations at a majority of existing gates available to each affected airline and should serve both LH_2- and JP-fueled aircraft.

In addition, while there is less penalty in an LH_2 airplane, as compared to a JP-fueled airplane, to operate with excess fuel aboard, it would be quite unlikely that any airline would adopt LH_2 based on operations from only one airport. Rather the airline (or several airlines) would adopt LH_2 for a significant portion of their fleet and operate from several airports whose traffic adapts to the capacity of the particular airport design. The LH_2 system at any airport such as ORD, should therefore be applicable to mature system type operations.

The above considerations resulted in two basic ground rules that had a significant effect on the course of the study. Those were:

- Prime consideration to be given to a concept that permits both JP- and LH_2-fueled aircraft to operate from the same gates.

- LH_2 system provisions at ORD to be based on a mature system wherein the current route structure and frequencies are assumed and with a similar fueling philosophy, i.e., fuel to be loaded as needed for the specific mission (An investigation of fuel requirements at ORD during system introduction and growth is discussed in section 7.5.)

3.0 ABBREVIATIONS AND SYMBOLS

ANC	Anchorage International Airport, Anchorage, Alaska
APU	auxiliary power unit
AR	aspect ratio
ASM	available seat miles
ATA	Air Transport Association
ATC	air traffic control
ATL	The William B. Hartsfield International Airport, Atlanta, Georgia
A_{wet}	airplane wetted area
b	wing span
BPR	bypass ratio
BTU	British Thermal Unit
cfm	cubic feet per minute
$\bar{c}$	mean aerodynamic wing chord
C_D	drag coefficient
C_L	lift coefficient
CRES	corrosion resistant steel
C_w	mean aerodynamic wing chord
DEN	Stapleton International Airport, Denver, Colorado
DFW	Dallas/Fort Worth International Airport, Dallas/Ft. Worth, Texas
DOC	direct operating cost
DOT	Department of Transportation
ECS	environmental control system
FAR	Federal Aviation Regulation
ft	foot, feet

F_n	net thrust
GH_2	gaseous hydrogen
GN_2	gaseous nitrogen
H_2	hydrogen
HNL	John Rodgers/Honolulu International Airport, Honolulu, Hawaii
hp	horsepower
HX	heat exchanger
IAD	John Foster Dulles International Airport, Washington, D.C.
IATA	International Air Transport Association
ID	inside diameter
J	joules
JFK	John F. Kennedy International Airport, New York, New York
JP	jet fuel
k	kilo (10^3)
K	Kelvin
kg	kilogram
km	kilometer
kw	kilowatt
l	liters
LAX	Los Angeles International Airport, Los Angeles, Calif.
LD GR	landing gear
LF	passenger load factor
LH_2	liquid hydrogen
L/D	lift to drag ratio; ratio of engine inlet length to compressor diameter; ratio of heat exchanger length to diameter
lb	pound

M	Mach number
M	mega (10^6)
m	meter
MAX	maximum
M_{CR}	cruise Mach number
MIA	Miami International Airport, Miami, Florida
MLG	main landing gear
NAS	National Aerospace Standard
nmi	nautical mile
NPV	net present value
OD	outside diameter
OEW	operational empty weight
ORD	O'Hare International Airport, Chicago, Illinois
Pa	pascals
PL	payload
ppm	parts per million
R	Rankine
R&T	research and technology
ROI	return on investment
S_w	wing area
SEA	Seattle-Tacoma International Airport, Seattle, Wash.
sec	second
SFC	specific fuel consumption
SFO	San Francisco, California

SOB	side of body
SPS	secondary power system
TOFL	takeoff field length
TOGW	takeoff gross weight
TPHP	typical peak hour passenger
v	velocity
V-J	vacuum jacketed
WTD	weighted
W/S	airplane wing loading
ΔP	pressure loss
Λ	wing sweep

4.0 O'HARE INTERNATIONAL AIRPORT

With the introduction of the jet age in 1959, Midway Airport would no longer suffice and development of ORD began in earnest. By 1963 all airline traffic had been moved to ORD, located 35 km (22 miles) northwest of the Chicago Loop.

The airport is owned by the City of Chicago and is operated by its Department of Aviation. The Department is headed by the Commissioner of Aviation who reports directly to the Mayor. The airport, including passenger terminals and customs facilities, is available for use 24 hours a day, every day of the year. Aircraft operations, controlled by the world's busiest FAA Control Tower, grew from 510 000 in 1965 to 613 000 in 1975; passengers (arriving plus departing) increased from 21 million to 37 million in the same period.

4.1 EXISTING FACILITY

Starting with the 1200-acre area of Douglas-Orchard Airport, the city has continued acquiring adjacent properties. The present field boundaries, (fig. 6) extend about 6.5 km (4.0 miles) north-south by 5.3 km (3.3 miles) east-west and enclose an area of about 28 329 000 m^2 (7000 acres). This is considerably larger than other "large hub" domestic airports such as New York's Kennedy Airport at 21 044 400 m^2 (5200 acres) and Los Angeles International Airport at 12 950 400 m^2 (3200 acres). The airport area is virtually surrounded by trunk line railroads and is the focus of a well developed highway network.

The ORD runway system includes three pairs of widely-spaced parallel runways, as shown in figure 6. According to reference 2, these runways are adequate for an air traffic activity of 500 000 operations per year. The 1975 traffic count was 613 000 operations and landing delays at ORD are frequent.

As shown in figure 7, passenger accommodations include three terminal buildings and a circular restaurant building from which concourses lead to the airplane loading positions. Terminal no. 1 on the west side, leading to Concourse B-C, accommodates all international passenger traffic. Terminals no. 2 and 3 and Concourses D, E-F, G, and H-K support the domestic traffic. The international and domestic concourses provide 70 loading gates which are exclusively leased by the airlines. Most of the gates are fitted with passenger loading bridges. A 1967 study (ref. 3) found this terminal "over-utilized" with a calculated space factor of 19.7 m^2 (212 ft^2) per peak-hour passenger. These facilities handled 37 000 000 passengers (arriving and departing) in 1975.

An area for airplane maintenance is on airport property about 1.6 km (1 mile) northwest of the passenger terminal. Hangars for widebody aircraft are provided by United (two 747's), American (one 747), Delta (one L-1011), Eastern (one L-1011), and Trans World Airlines (L-1011 nose only).

An area of about 607 050 m^2 (150 acres) serves the air cargo traffic at ORD, which in 1972 handled almost 600 000 000 kg (660 000 tons). United, Flying Tiger, Trans World, Continental and American Airlines maintain individual cargo terminals. Smaller lines lease space in the two consolidated cargo buildings. Air freight forwarders such as Emery, REA, Airborne, WTC, and Shulman are also represented here.

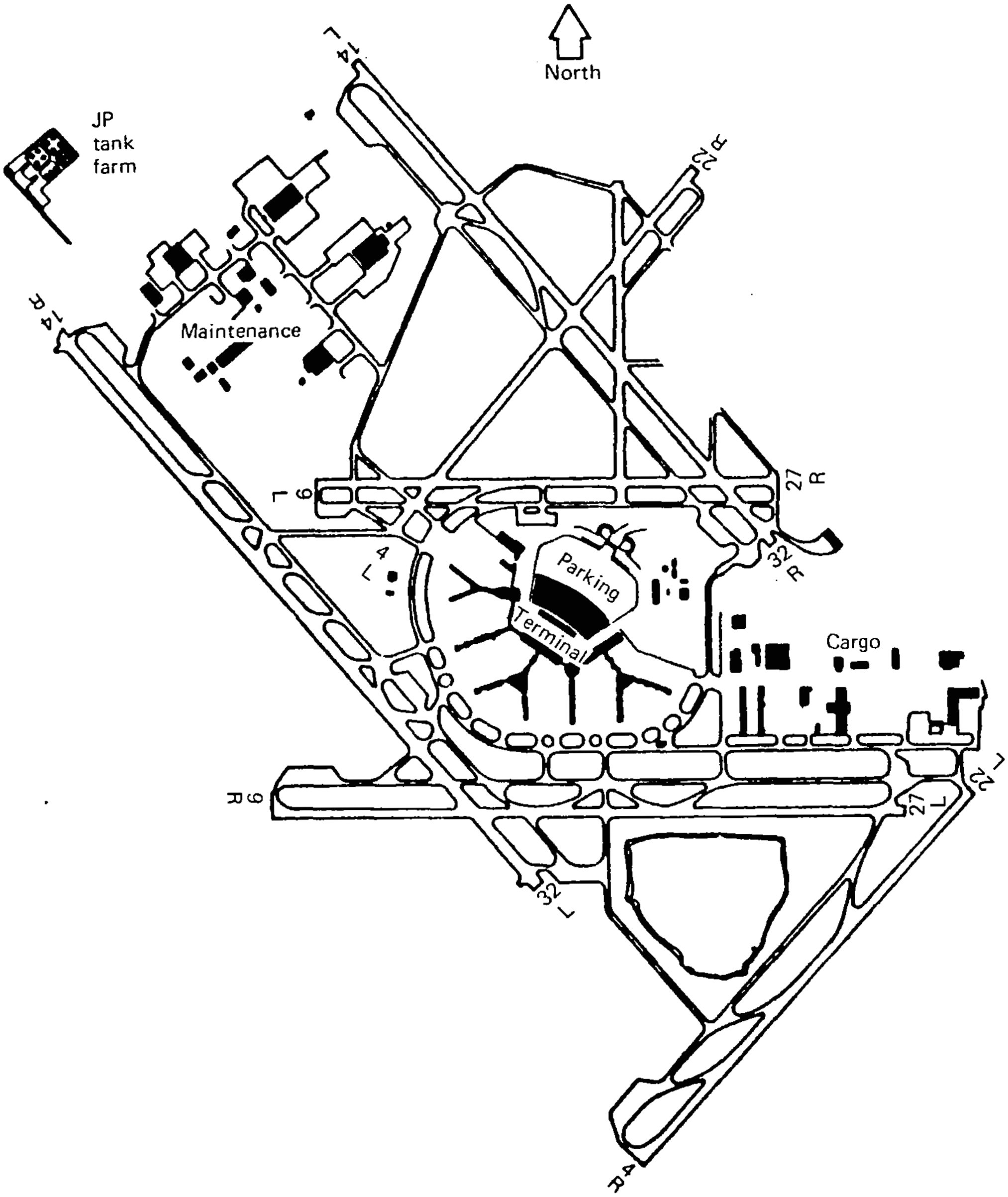


Figure 6. —Current O'Hare Facilities

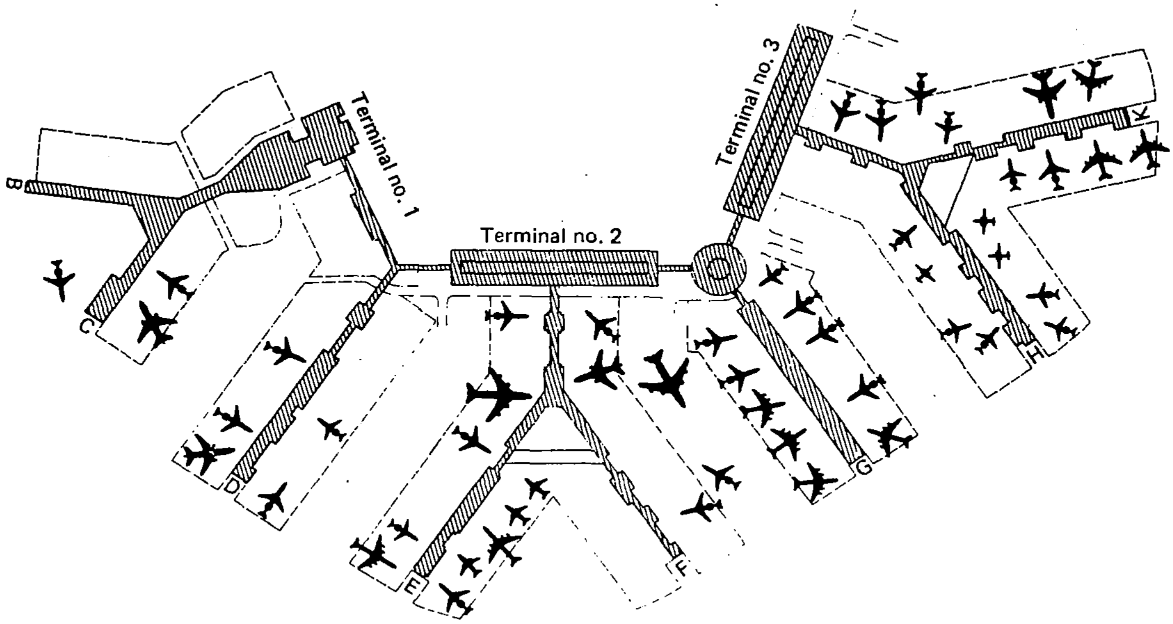


Figure 7.—Existing Passenger Terminal

A fuel tank farm, designed to provide a 3 day supply, is located about one km NW of the maintenance area. An additional 1 day supply is provided in underground satellite tanks adjacent to the passenger loading aprons. A fuel distribution system of underground piping serves all but a few passenger gates and the Flying Tiger cargo terminal. The remaining passenger gates, cargo terminals, and maintenance area are served by tank trucks. The entire fueling system is operated by a private contractor on behalf of the using airlines.

4.2 PLANNED DEVELOPMENT

Plans for improvement to the runway system are shown in figure 5. They include lengthening four runways: 4R-22L, 9R-27L, 14R-32L and 14L-32R; replacing two runways which presently crowd the existing passenger terminal: 4L-22R and 9L-27R; and adding two close parallel runways to be designated 4L-22R and 14L-32R (the runways currently bearing those designations will become "C" for center runways). These improvements will more adequately serve the changing fleet mix (growth in size of airplane) as well as marginally increase the airport operations capacity.

Future plans call for alleviating congestion at the terminal gates. The problem will be attacked on two fronts: move the international traffic out of Terminal 1 (Concourse B-C) to some other location (not firmly selected); then rebuild the existing terminal to provide a significant increase in the number of gates available for domestic passenger traffic (perhaps up to 110).

The existing cargo terminal area is insufficient to serve the forecast growth in air cargo. Two additional areas within the airport boundaries, south and west of the passenger terminal, have been designated for cargo terminal expansion. Together, these expansion areas total over 2 832 900 m^2 (700 acres).

Maintenance area requirements have been forecast to increase by 50% during the planning period. The area at the far north end of the airport, lying between runway ends 14L and 22R, is presently allocated to fulfill this future need.

4.3 O'HARE WIDEBODY TRAFFIC AND REFUELING CHARACTERISTICS

The characteristics of current widebody traffic at ORD were analyzed to provide a baseline from which liquid hydrogen fuel requirements could be estimated. The number of daily flights, the time-of-day variation in departures and the average fuel loaded per flight were important factors in determining the size of the hydrogen liquefaction plant, storage vessels and distribution lines.

The following paragraphs present the analysis method and results obtained in terms of JP fuel requirements for the current widebody fleet at ORD. Section 4.5 converts these data into LH_2 fuel requirements for an equal sized fleet of 400 passengers, 10 186 km (5500 nmi), hydrogen-fueled airplanes operating over the same route network and at the same flight frequencies.

4.3.1 WIDEBODY TRAFFIC

Widebody (747, DC-10, L-1011) flights through ORD (ref. 4) are tabulated in appendix A. These data include airplane type, airline, origin and destination airports, flight numbers, and arrival and departure times. The flights, which represent the total widebody passenger transport traffic, are shown graphically in figure 8. They are identified by incoming and departing flight numbers and by airline. Length of the line denotes ground time. Other than those that overnight at ORD, a majority of the airplanes are on the ground one hour or less, indicating the efforts by airlines to maintain high utilization by keeping ground times to a minimum. There are 22 daily 747 flights, 17 L-1011 flights and 73 DC-10 flights. (NOTE: A few flights, which are scheduled less than daily, are considered as daily flights to represent the "busiest day" of the week.)

The numbers of widebody aircraft on the ground at ORD during any hour of the day are shown in figure 9. A general high level of gate occupancy exists between 0500-2100 hours, with moderate peaking during early morning and late afternoon hours. This pattern of traffic is not typical of major coastal airports, with a large percentage of widebody flights devoted to transcontinental and intercontinental traffic. Maximum gate demand at ORD occurs between 4-6 PM, when 20 widebody aircraft belonging to 12 different airlines are at the airport.

4.3.2 FUELING CHARACTERISTICS

Hourly hydrant demand, based on each of the 112 aircraft of figure 8 requiring fuel, is shown in figure 10, with details provided in appendix A. It was assumed that fueling

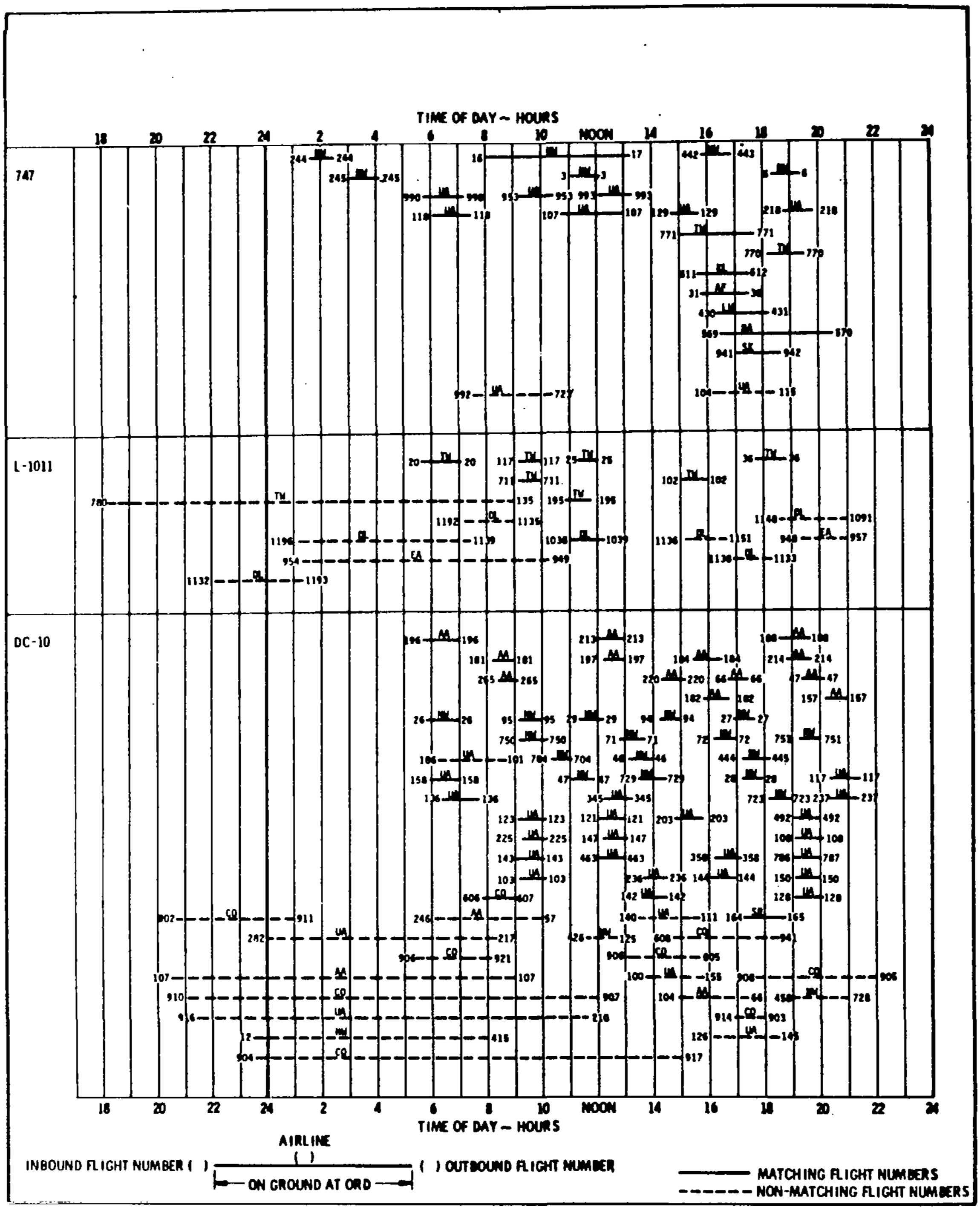


Figure 8.—ORD Widebody Operations

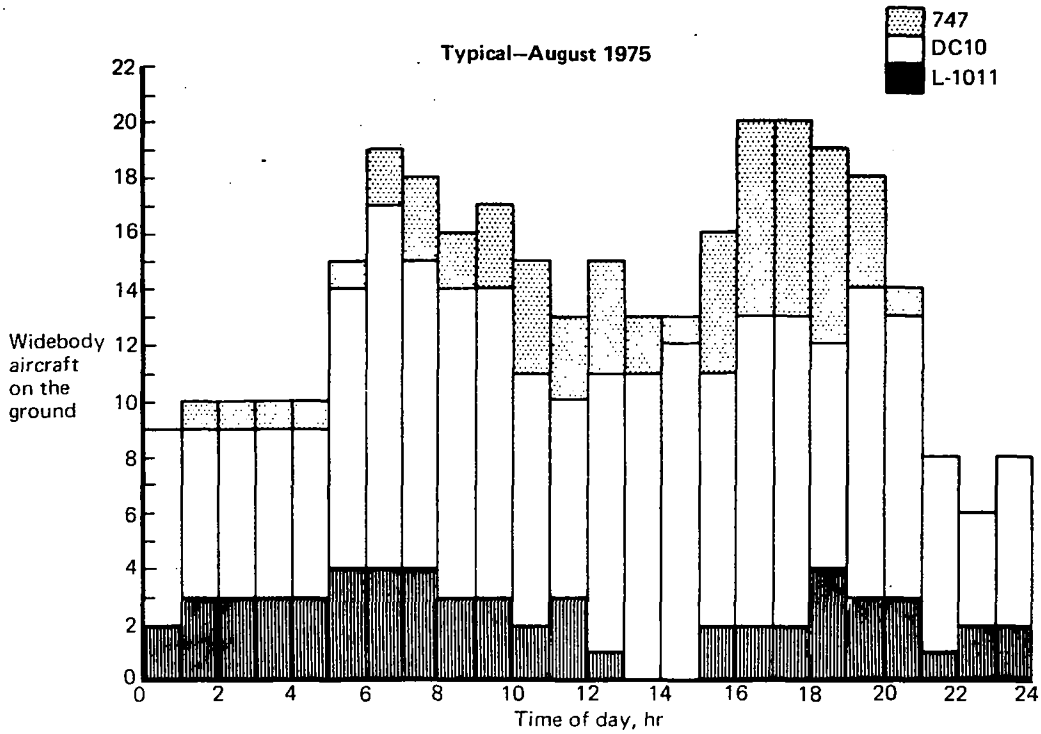
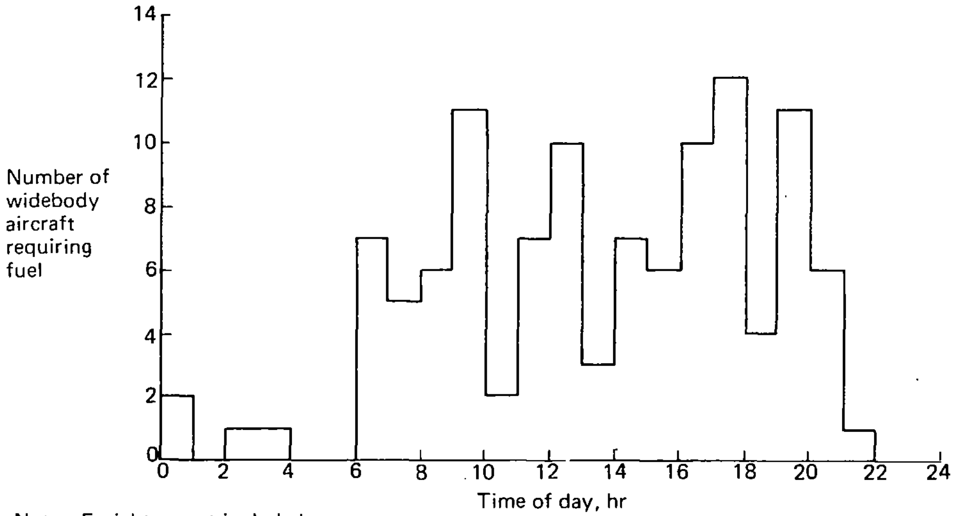


Figure 9.—Hourly Widebody Aircraft at ORD



Note: Freighters not included

Figure 10.—Hourly Widebody Hydrant Demand at ORD

would be accomplished reasonably close to takeoff to minimize fuel depletion due to boiloff. Aircraft on the ground for several hours were assumed to be refueled during the last full hour; aircraft with short ground time (approximately 1 hour) spanning 2 clock hours were assigned a refueling hydrant during the earlier of the 2 clock hours. The resulting hydrant demand peaks between 5-6 PM, with a requirement for simultaneous fueling of 12 aircraft. Other high demand times occur at 9-10 AM, 4-5 PM and 7-8 PM.

Normal airline fueling practice is to carry only enough fuel for a flight, plus reserves. The penalties for carrying excess fuel are shown in figure 11 for JP fueled and LH_2 fueled 10 186 km (5500 nmi) design range airplanes. For example, a 1000 nmi mission flown with full tanks results in a 40% fuel-burned penalty for the JP airplane and about an 18% penalty for the LH_2 airplane. These penalties have a significant impact on operating economics and are avoided except when tempered by large differences in local fuel prices, or fuel availability. It was assumed that the LH_2 airplanes in this study were operating in a mature transportation system, and that fuel loadings were proportional to length of flight. (The "Full tank" operating philosophy is used in section 7.5, Air Transport System Impact, during the introduction and early period in system growth.)

To determine current normal fueling practices at ORD, fueling data were obtained from six major airlines operating widebodies through ORD. The data, shown in appendix A, were received in varying degrees of detail, and represented about 83% of the total ORD widebody passenger flights. Fuel loadings for specific flight numbers, obtained from CO, TW and UA, accounted for all but eight flights operated by those airlines as listed in reference 4. It was assumed that those eight flights did not take on fuel at ORD.

These data were extrapolated to estimate fuel loadings of the other 17% of widebody operations out of ORD. Overall results are summarized in figure 12 which shows the range of fuel loadings and averages for the three types of aircraft. A weighted composite fleet average loading is also shown. Maximum loadings of 113 550 l (30 000 gal) for the 747 are for Chicago-Honolulu (HNL) flights, the maximum segment length of any widebody flight out of ORD. The "63% max–international" label in figure 12 applies to the HNL flights, which require more fuel than other truly international flights, such as ORD-FRA, ORD-LHR, etc. As would be expected, the mid-continent, hub-type operations at ORD resulted in average fuel loadings that were relatively low–23% of capacity for the composite fleet.

During August 1975 there was an average of only two widebody freighter flights per day from ORD. These were not included in the above data because they would not have a measurable impact on fuel requirements, (i.e. departures at off-peak hours, short-flight segments, fueled at the separate cargo facility.)

Delay data (appendix A) for ORD operations–1972 and 1973–were received from the CAB. Average inflight delays during that period were 12.4 min. Ground taxi delays averaged 9.8 min. The effects of these factors on fuel demand were taken into consideration in sizing the LH_2 system.

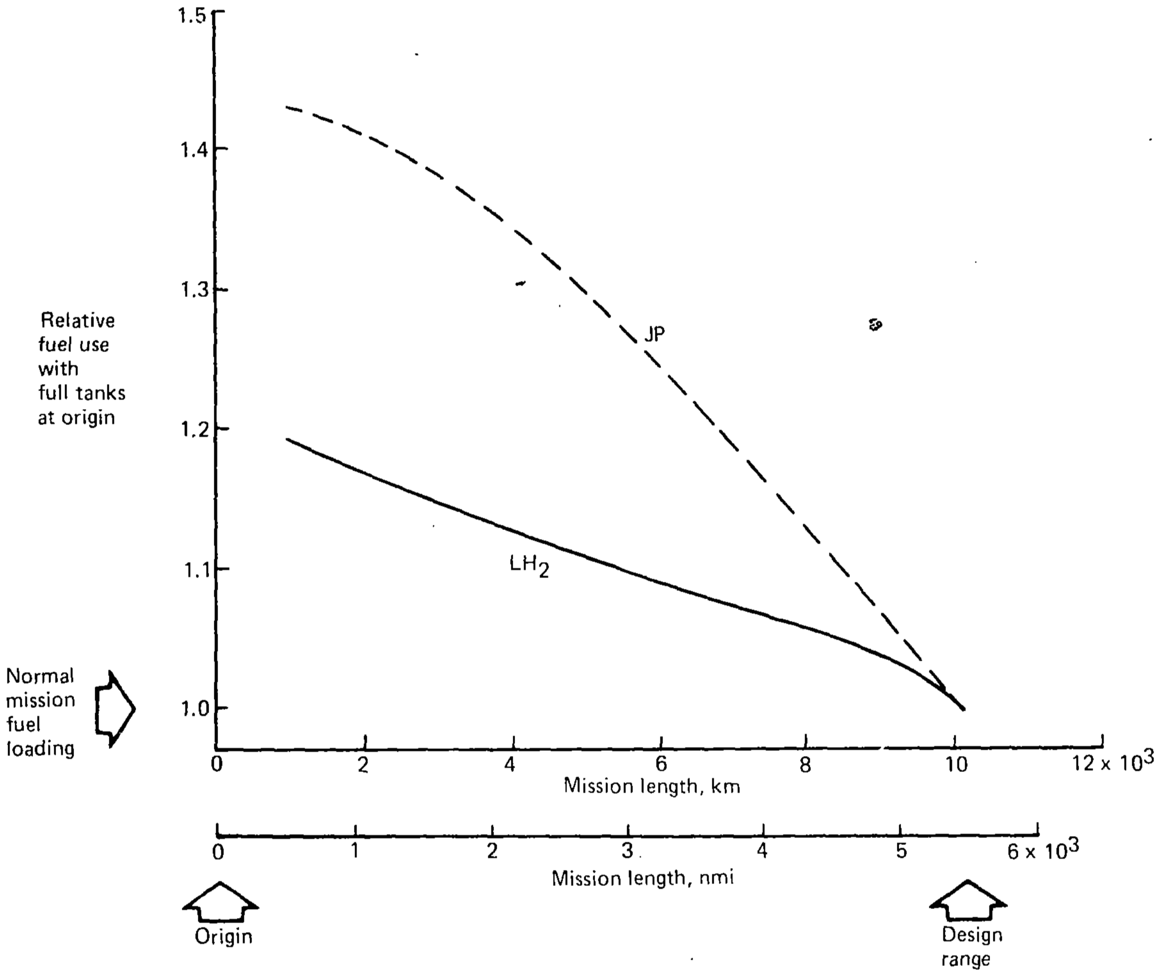


Figure 11.—Fuel Use—Normal Versus Full-Capacity Operation

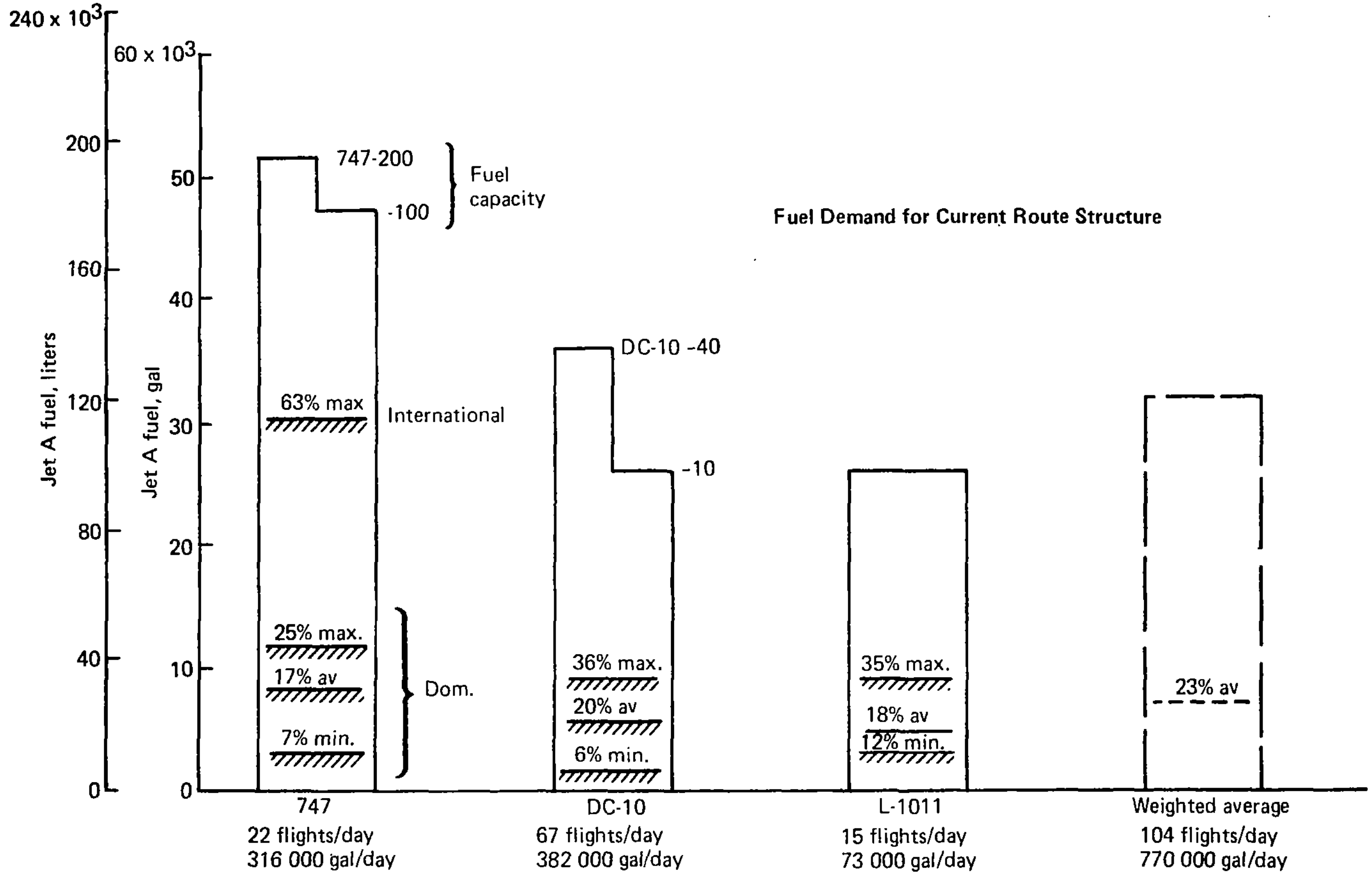


Figure 12.—Widebody Fueling Characteristics—ORD

Note: Fuel loadings based on UA, CO, and TW data (50% flights)

In summary, Chicago-O'Hare is the world's busiest airport. It averages 840 scheduled airline departures per day, of which only 112 (13%) are widebody aircraft. This ratio is typical of inland hub airports, which also serve relatively short route structures and do not experience as severe peaking periods during the day as major coastal airports. The route system served by ORD requires an average JP fuel onload of only 23% of widebody airplane capacity, which translates into 2 914 450 l (770 000 gal) per day for that portion of the total traffic. There are only 20 of these aircraft at the airport during the peak period of 4- 6 PM, of which 12 require simultaneous fueling between 5-6 PM.

4.4 BASELINE AIRPLANE CHARACTERISTICS

The configuration selected to be the baseline study airplane was the 400-passenger, Mach 0.85, internal tank configuration of reference 1. A general arrangement (figure 55 of ref. 1) is reproduced as figure 13. This configuration has a design maximum gross weight of 177 675 kg (391 700 lb), a maximum payload of 39 917 kg (88 000 lb) and a design range of 10 186 km (5500 nmi). The operating empty weight is 109 817 kg (242 100 lb) and has a fuel capacity of 27 942 kg (61 600 lb). The general size is similar to a current 747; however, a double-deck passenger compartment is contained between large liquid hydrogen tanks in the fore and aft fuselage.

Fuel consumption calculations to estimate the fleet fuel requirements of section 4.5 were based on the aerodynamic data and fuel consumption rates in appendix D of reference 1. To accurately calculate boiloff on the ground and in the air, the heat transfer rate through the insulation and the LH_2 wetted area is required, as a function of fuel remaining in the tank. Neither fuel tank characteristic was included in reference 1, hence both were calculated.

4.4.1 FUEL TANK CHARACTERISTICS

Reference 1 specified the insulation used in the baseline (internal tank) LH_2 airplane as 0.15 m (six inches) of ROHACELL 415 foam. This variety of insulation has a specified conduction rate of 3.1 x 10^{-4} watts/cm-°K (0.018 Btu/hr-ft-°F) which is equal to 54.8 w/m^2 (17.4 Btu/hr-ft^2) assuming standard day temperature and 6 inches of foam. A forward tank boiloff rate of 1.0 kg/minute (2.2 lb/minute) at full capacity is further assumed. Using a calculated LH_2 wetted area of 131 m^2 (1410 ft^2) the conduction rate is:

$$Q = \frac{1.0 \text{ kg/min } (2.2 \text{ lb/min}) \text{x} (60 \text{ min/hr}) \text{x} 221 \text{ watt-hrs/kg } (190 \text{ Btu/lb})}{131 \text{ m}^2 \ (1410 \text{ ft}^2)}$$

$$= 56.1 \text{ w/m}^2 \ (17.8 \text{ Btu/hr-ft}^2)$$

which is an excellent correlation. A heat transfer coefficient of 55.5 w/m^2 (17.5 Btu/hr-ft^2) was used in all boiloff calculations.

The variation of liquid wetted area with the amount of fuel remaining in the tank was computed using tank dimensions measured from drawings in reference 1, and integration of the volumes and wetted areas for each tank. Example curves of wetted area versus volume are shown in figure 14.

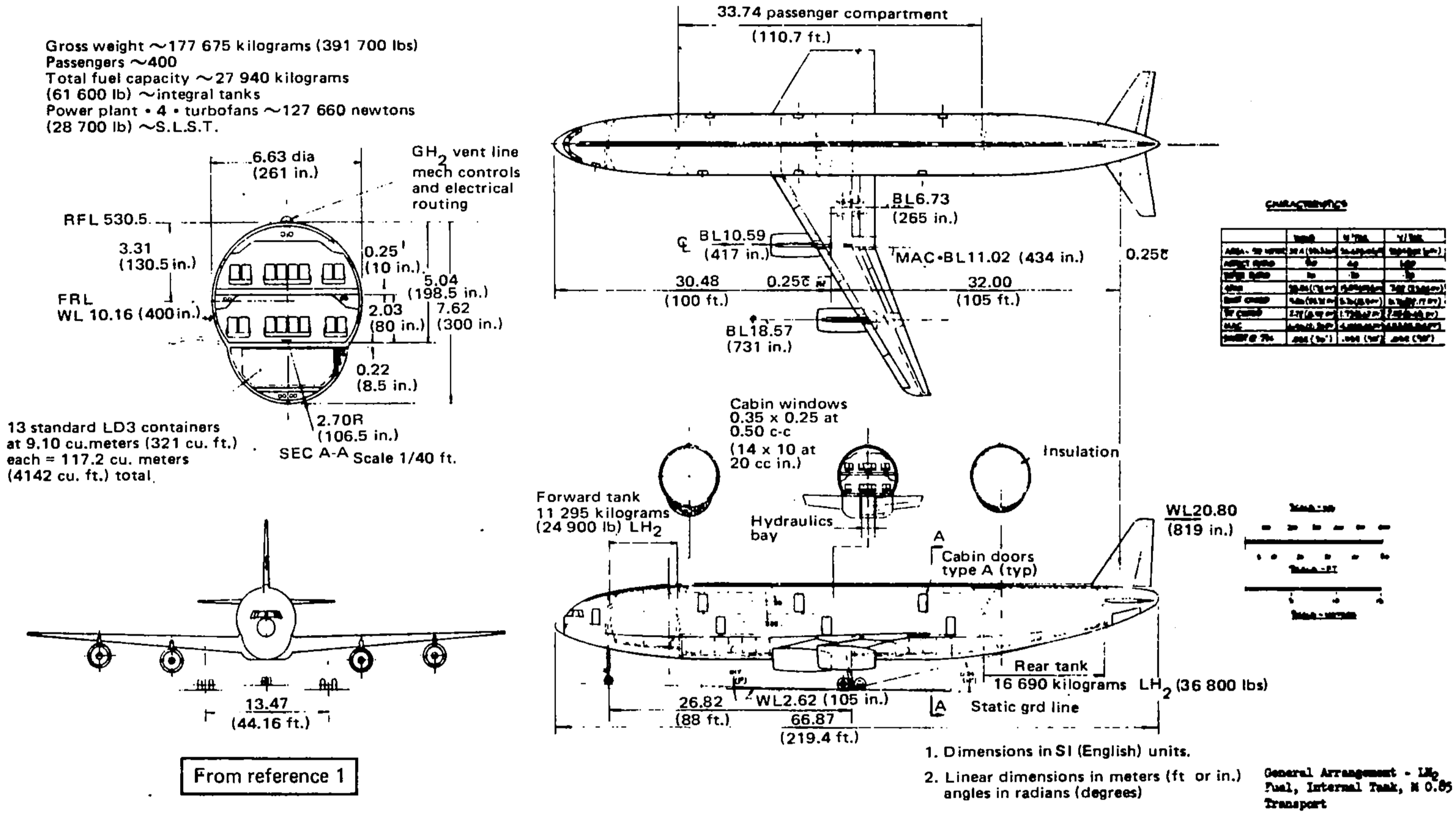


Figure 13.—Internal Tank Configuration

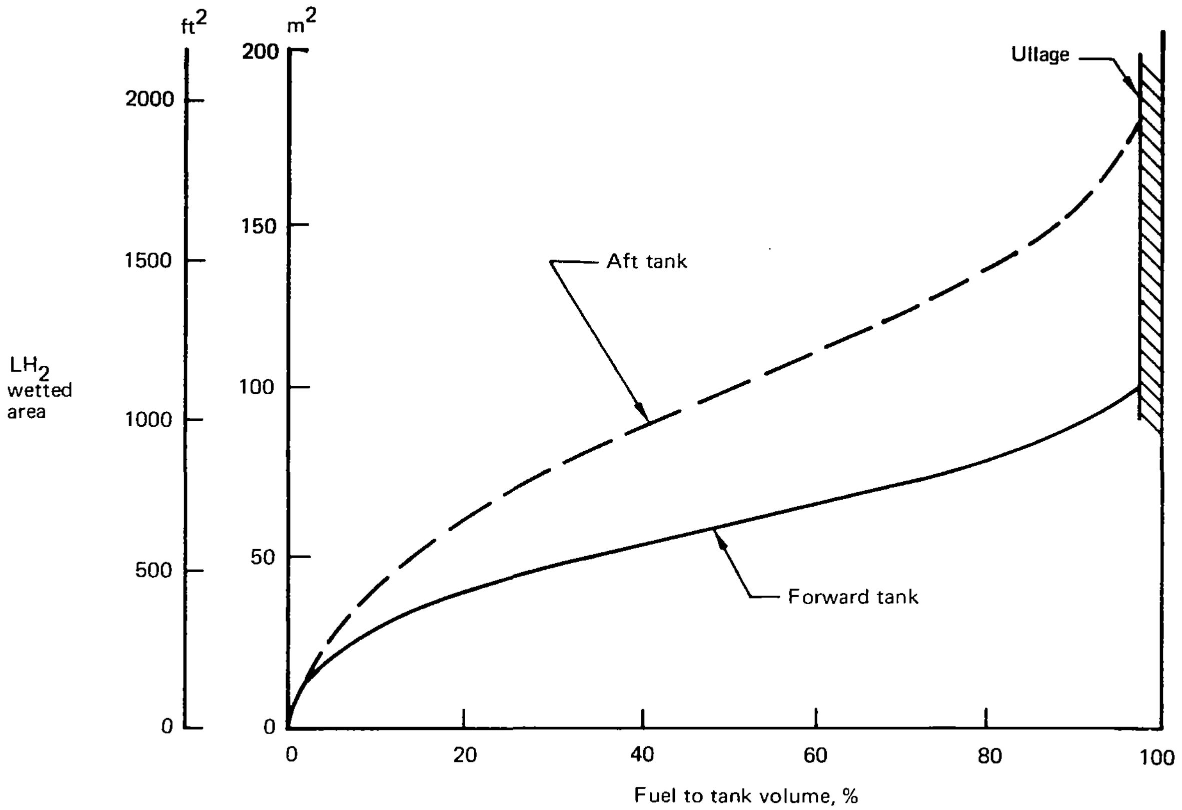


Figure 14.—LH_2 Wetted Areas—Baseline Airplane

4.4.2 AIRCRAFT INSULATION EFFECTS

Baseline aircraft insulation requirements were also developed for a balanced condition maintained between LH_2 vaporization rate and fuel flow to the aircraft engines. This would apply in case tank venting during flight was unacceptable.

As shown in figure 15, the tank heat leak, hence insulation requirement, for the forward tank would be approximately 31.5 w/m^2 (10 Btu/hr ft^2). The aft tank would have a heat leak requirement of 30.0 w/m^2 (9 Btu/hr ft^2). This reduction in aircraft heat leak results in a 23 216 kg/day (30 ton/day) reduction in LH_2 requirements for the widebody fleet. Although these reduced tank heat leak values were not used in the present study, they should be evaluated against the corresponding weight and volume penalties in future studies.

An aircraft tank heat leak of 55.2 w/m^2 (17.5 Btu/hr ft^2) was used for all subsequent analyses in this study.

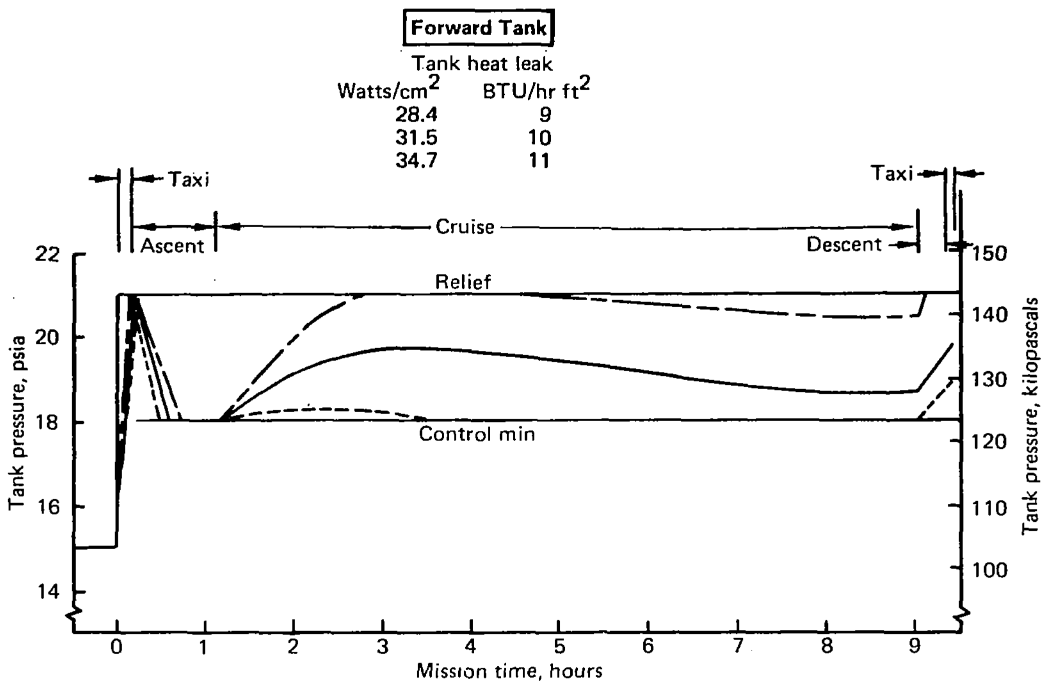


Figure 15.—Pressure History—Internal Tank Configuration

4.5 LH_2 FLEET FUEL REQUIREMENTS

To determine the block fuel required and the amount of GH_2 vented into the airport liquefaction system, each of the 112 airplanes per day was assigned a simulated mission, as shown in figure 16, based on the various stage lengths in the current widebody route network. The amount of fuel burned and free-vented was obtained for two cases: Case 1, wherein just enough fuel to complete the mission, plus reserves, was loaded; and Case 2, wherein the tanks were topped off at ORD. The block fuel required for each simulated mission was obtained using performance data from Appendix D, reference 1. The fuel consumed and vented during each flight was determined, as was the fuel remaining at the end of each mission.

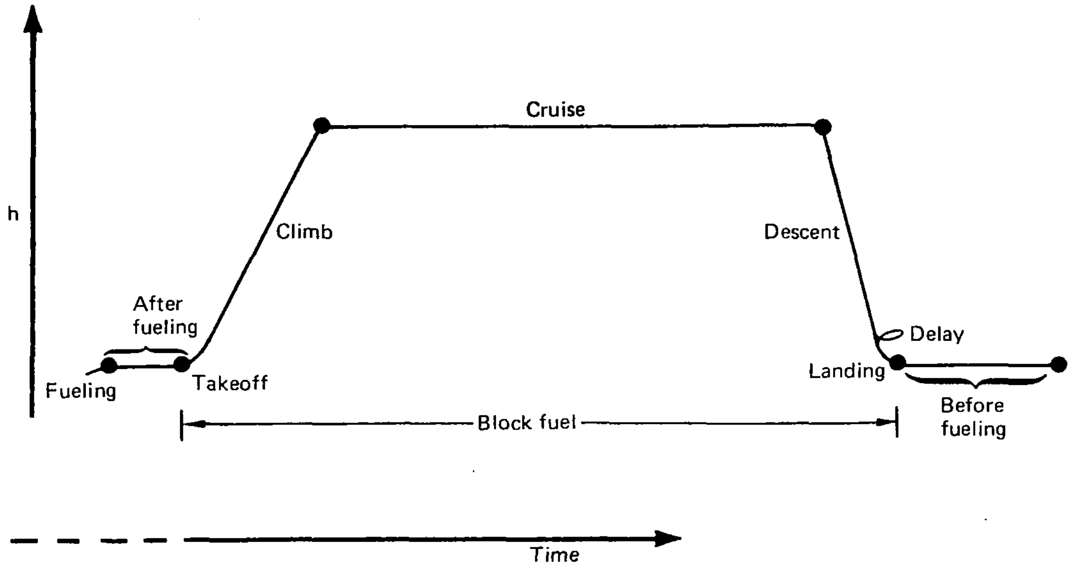


Figure 16.—LH_2 Mission Simulation

A detailed discussion of total LH_2 system requirements, that is, airplane block fuel, airplane ground boiloff losses and airport LH_2 system losses, is contained in section 5.1. The airplane total block fuel for the 112 simulation missions was found to be:

LH_2 BASELINE AIRPLANE BLOCK FUEL–ORD

Case 1.	Minimum LH_2 loaded for each mission - kg/day (tons/day)	545 000 (600)
Case 2.	Tanks topped off for each mission - kg/day (tons/day)	590 000 (650)

Case 1 was used to approximate the fuel required for a mature system type operation. Case 2 was used in calculating fuel requirements during system introduction and growth, which is discussed in section 7.5.

5.0 BASELINE CONCEPT

The baseline concept assumes delivery of gaseous hydrogen (GH_2) via a pipeline to a liquefaction plant at the airport and assumes the internal tank aircraft configuration. Development of the baseline was directed toward a system that would have the least impact on air terminal facilities and airline operations. A key item toward minimizing the impact resulting from the introduction of LH_2 into airline operations that also included JP is co-location of the two fuels and associated aircraft. Therefore, the baseline concept assumes that LH_2 and Jet-A are compatible and the fuels, aircraft, and associated facilities can be co-located. Figure 17 is a simplified schematic of the baseline concept.

Two key fuel-system related objectives were established for the development of the baseline which also were used in the development of the alternate concept. These are:

1. Airport LH_2 requirements must be satisfied after:
   a. A single failure in the liquefaction, storage, and/or distribution systems
   b. Airport downtime due to weather, strikes, etc.
   c. Aircraft accident or disability

2. No uncontrolled venting of hydrogen at the airport

These objectives were pursued through evaluation of several approaches to the storage, distribution, and venting of hydrogen. These approaches are outlined in figure 18 and discussed in section 5.2.

5.1 LH_2 SYSTEM REQUIREMENTS

Analyses of widebody traffic show that the LH_2 distribution system must be capable of simultaneously fueling 12 airplanes during the peak traffic period at ORD. Therefore, to satisfy current widebody aircraft schedules, the main distribution system must be capable of handling an LH_2 flow of 226 796 kg (500 000 lb) per hour. A limiting design condition for handling the GH_2 vented from the aircraft was not obvious, however, it is desirable to limit tank blowdown to approximately 4 min. to maintain current through-stop airplane ground time. Assuming that the tanks of 12 widebody aircraft are simultaneously depressurized, the vent flow would be approximately 56 699 kg (125 000 lb) per hour. Approaches to handling aircraft and ground system vent gases are discussed in section 5.2.1.

The ORD Airport and fleet fuel requirements data presented in section 4.5 were used to size the liquefaction, storage, and distribution systems. An analysis of aircraft requirements and ground system losses resulted in a hydrogen liquefaction requirement of 725 748 kg (800 tons) per day. The allocation of this hydrogen is shown in table 1. These data were developed as described in sections 5.1.1, 5.1.2, and 5.1.3.

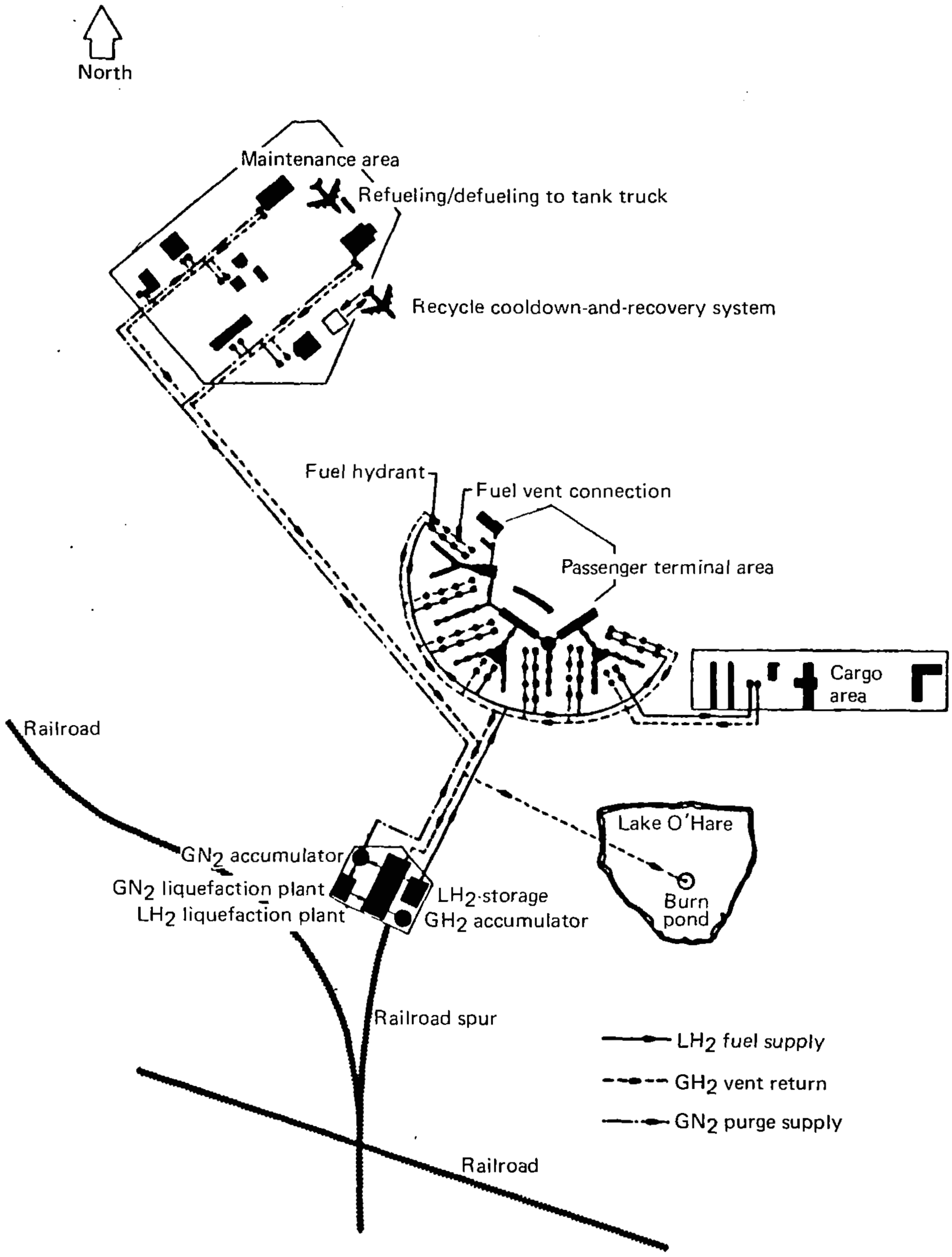


Figure 17.—Baseline LH_2 Fuel System Concept

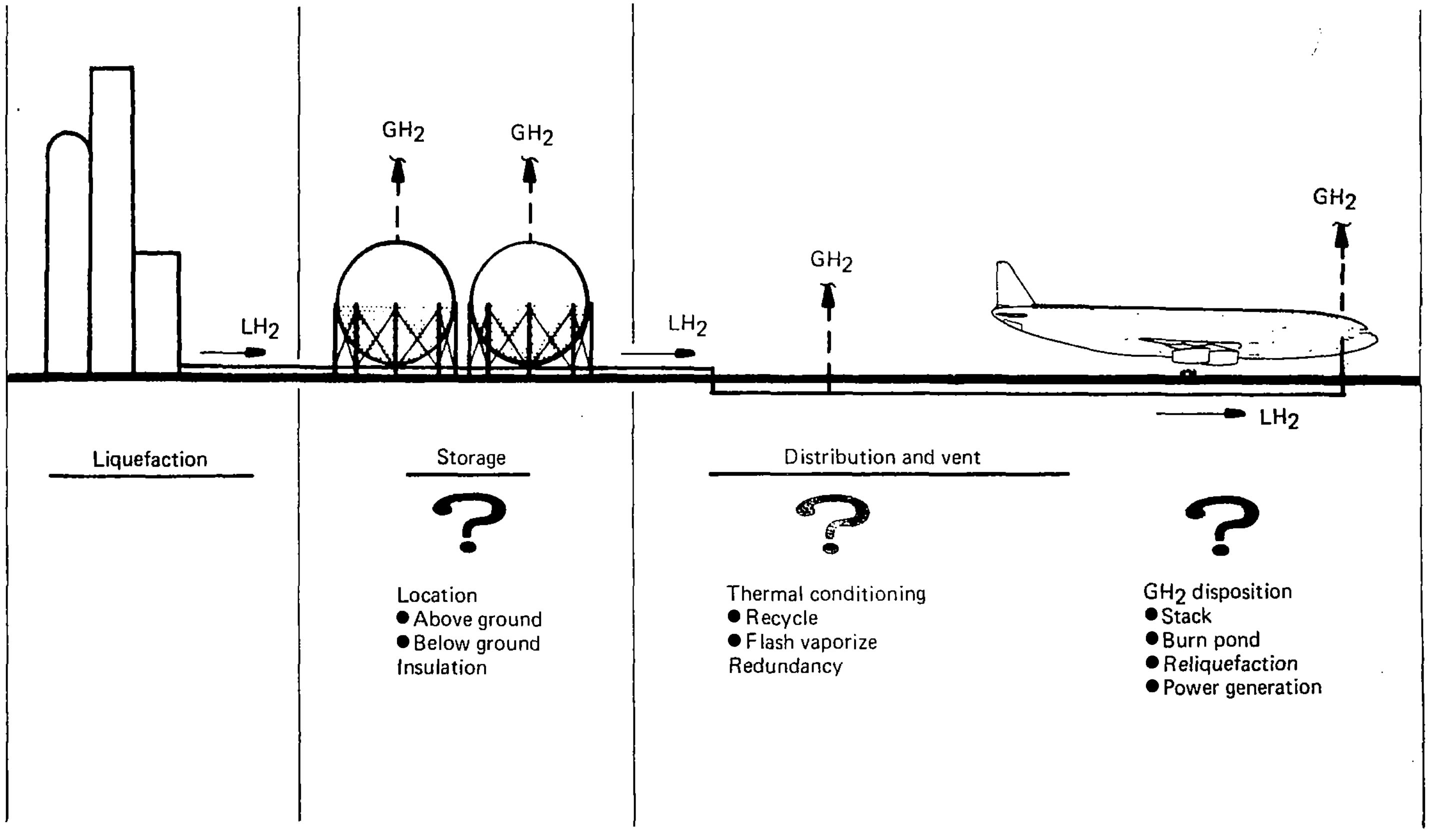


Figure 18.—Concept Development Considerations

Table 1.—LH_2 Ground System—H_2 Allocation

	kg/day (tons/day) sub-totals	kg/day (tons/day) total
Loaded on aircraft		
Block fuel	544 311 (600)	
Blowdown reserve	34 473 (38)	
Vent-loss make-up	28 123 (31)	
Ullage make-up	12 701 (14)	
Tank cooldown (incl. maint.)	5 442 (6)	625 050 (689)
Ground system losses		
Cooldown—connect	2 722 (3)	
Delivery lines	9 072 (10)	
Storage farm	7 257 (8)	19 051 (21)
Demand variations		
Operation peaks	81 647 (90)	81 647 (90)
Total LH_2		725 748 (800)

5.1.1 LH_2 LOADED ON AIRCRAFT

The LH_2 that must be loaded on the aircraft includes the LH_2 vaporized during liquid expulsion, tank cooldown and tank loading, in addition to the block fuel. The allocations of hydrogen (table 1) were developed as follows:

Block Fuel

Block fuel includes all the hydrogen used by the aircraft from the time it leaves the gate to its arrival at its destination or its next refueling stop, as determined from current operations. This amounts to 544 311 kg (600 tons) per day for the ORD fleet, as described in section 4.5.

Blowdown Reserve

Blowdown reserve includes the GH_2 displaced during aircraft loading plus the LH_2 vaporized during resaturation of the LH_2 to the loading system back pressure. Both these items are part of the aircraft unusable fuel and must be replaced each time LH_2 is loaded on the aircraft.

The blowdown reserve was calculated assuming the LH_2 remaining in the tanks was equal to flight reserves plus unusable fuel and the pressure in the tanks is reduced from 144.8 kPa (21 psia) to 104.8 kPa (15.2 psia) prior to loading. The LH_2 vaporized during the resaturation process is approximately 18 144 kg (20 tons) per day; the GH_2 displaced during loading is approximately 16 329 kg (18 tons) per day. These values are based on the study aircraft with a tank heat leak of 55.2 w/m^2 (17.5 Btu/hr ft^2). These losses could be reduced by improving the aircraft tank insulation and/or using a lower tank vent setting as described in section 4.4.

Vent-Loss Make-Up

The vent-loss make-up is the ground boiloff from the aircraft tanks prior to refueling. This was calculated using the airport and aircraft data presented in section 4.3. Aircraft tank boiloff was assumed to be a direct function of wetted tank surface area, as shown in figure 19. This is representative of large, continuously venting, lightly insulated tanks of the type used in the study aircraft.

Ullage Make-up

Ullage make-up is the gas required to repressurize the tank volume vacated by the liquid during expulsion and represents unusable LH_2 in the aircraft tanks. This was calculated using the aircraft data presented in section 4.5.

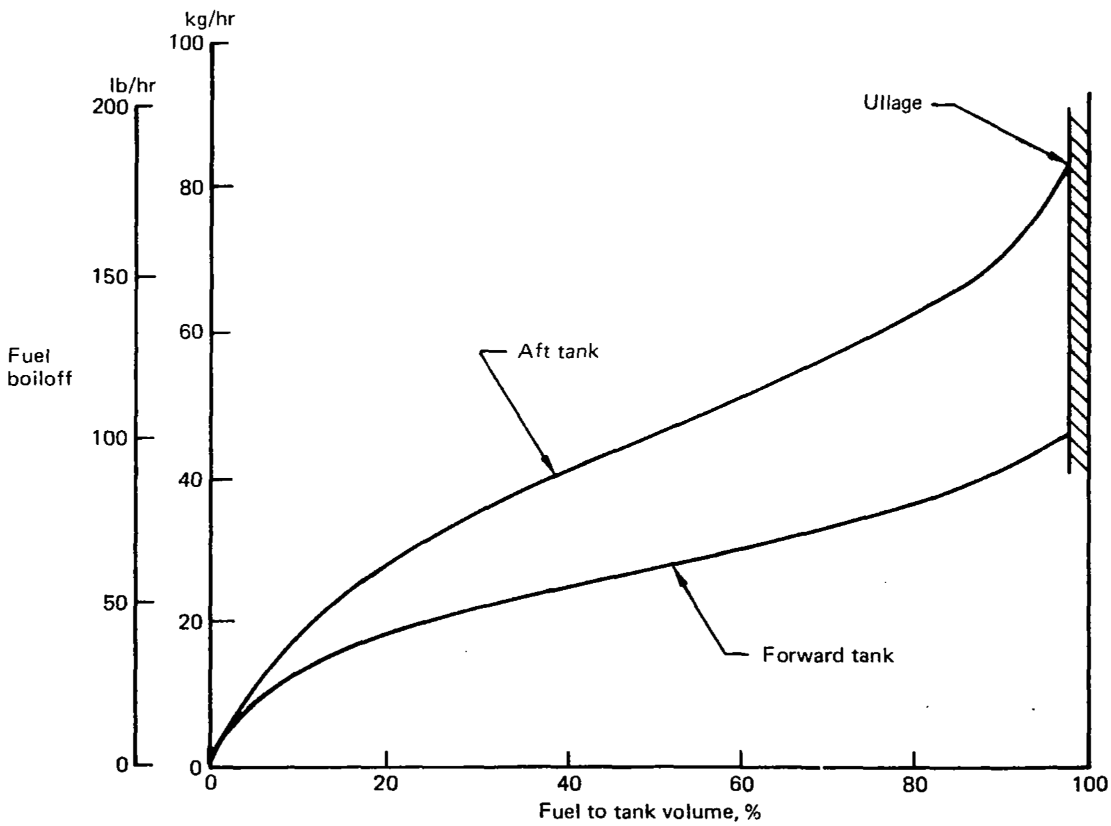


Figure 19.—LH_2 Boiloff Rate—Baseline Airplane

Tank Cooldown

Tank cooldown accounts for losses from active aircraft during LH_2 loading and losses from aircraft returning from major maintenance. It was assumed that prior to refueling, aircraft tanks would be vented to a back pressure of approximately 104.8 kPa (15.2 psia). This venting to a low back pressure does not allow a significant temperature increase in the aircraft tank walls or insulation (less than 1.2 K (2.2°R)) as long as some liquid remains in the tank. Therefore, cooldown losses from active aircraft are relatively small (less than 907 kg/day (1 ton/day)). The balance of the cooldown losses, 4536 kg/day (5 tons/day) is based on two aircraft per week returning from maintenance that requires tank inerting.

5.1.2 GROUND SYSTEM LOSSES

The LH_2 vaporized in the ground system is reliquefied, hence it must be accounted for in the liquefaction plant load requirements. The allocations of this hydrogen were developed/obtained as follows.

Cooldown Connect

Cooldown and connect losses include cooldown and venting of the lines between hydrants and aircraft. This was estimated assuming a transfer line section with a holding capacity of 13.6 kg (30 lb).

Delivery Lines

Delivery line losses include all losses in the distribution system from the hydrogen liquefaction plant to the LH_2 hydrants. These losses were estimated using data obtained from Air Products and Chemicals.

Storage Farm

Storage farm losses were calculated using data provided by Air Products and Chemicals from similar tanks.

5.1.3 DEMAND VARIATIONS

Demand variations include increases in LH_2 requirements resulting from seasonal and other changes in airport traffic. The nominal requirements were derived from data contained in the ORD 1975 operations report. Approximately two days of LH_2 storage capacity is available to handle short term LH_2 demand variations resulting from weather or short term (less than 1 day) interruptions or increases in service. The operation of the liquefaction plant will be adjusted plus or minus 20% for refilling storage tanks and to handle long term seasonal or strike-related changes in demand.

5.2 CONCEPT DEVELOPMENT CONSIDERATIONS

There were four primary areas that required selection of an approach in the development of the baseline system. These are outlined in figure 18 and involve:

1. Disposition of the vent gas from aircraft and ground system
2. Limiting thermal losses and thermally conditioning the LH_2 in the distribution system
3. Limiting the impact of distribution system failures on airport operations
4. LH_2 storage techniques

5.2.1 VENT GAS DISPOSITION

A basic objective in the development of the baseline concept was to avoid uncontrolled venting of hydrogen at the airport. This ground rule was established to minimize the possibility of entrapment or ingestion of GH_2 in enclosed volumes, such as aircraft wheel wells, terminal air conditioner inlets, etc. The four vent gas handling techniques shown in figure 20 satisfied this objective and they were evaluated in terms of operational feasibility and cost effectiveness. These techniques involve:

1. Utilization of an on-board burn stack for GH_2 from the aircraft tanks along with stacks or a burn pond for GH_2 vented from the storage and distribution system

2. Utilization of burn stacks or a burn pond for all vented GH_2

3. Recovery and reliquefaction of all GH_2

4. Utilization of GH_2 as a powerplant fuel

The design of an aircraft on-board vent gas disposal system that must handle a GH_2 flow ranging from 90.7 kg/hr (200 lb/hr) to 4309 kg/hr (9500 lb/hr) – inactive to blowdown – would not be difficult, but would add to aircraft fuel subsystem complexity, weight, and cost. The design of a ground stack system that could handle the nominal boil-off from a single aircraft, as well as 12 simultaneous aircraft blowdowns is possible, but difficult, and the stack system could not be located in the terminal area for safety reasons. The same would apply for a burn pond except, in this case, variable load bubble caps could be used to adjust the system for a wide range of flow conditions. However, recovering and reliquefying all the GH_2 also reduces the duty cycle variation impact by allowing the introduction of GH_2 vent gas into the primary GH_2 supply to the liquefaction plant; a flow of 30 239 kg/hr (66 667 lbs/hr). This technique also allows the saving of GH_2 and, with insulated lines, the saving of refrigeration (energy). These savings are reduced by the cost and maintenance of the vent gas return system. As shown in figure 21, the cost return from the GH_2 saved plus the refrigeration power exceeds the cost of a vacuum jacketed vent return system. This is true even at \$0.29/kg (\$0.13/lb) which is an extremely optimistic cost estimate for GH_2.

Utilization of hydrogen as a fuel to satisfy ORD electric power requirements was also evaluated. The current ORD requirement is 35 megawatts. The baseline hydrogen

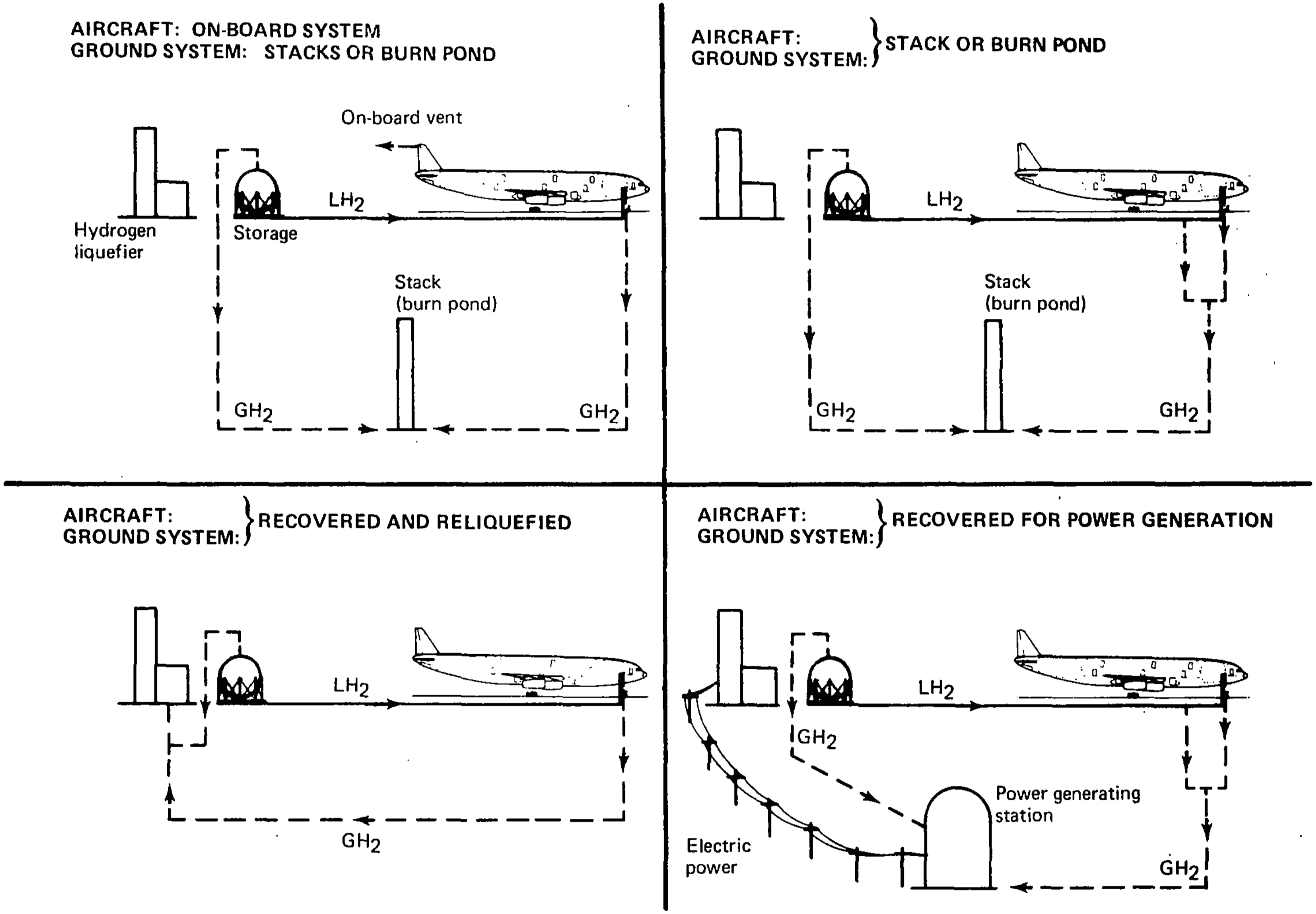


Figure 20.—Vent Gas Control Techniques

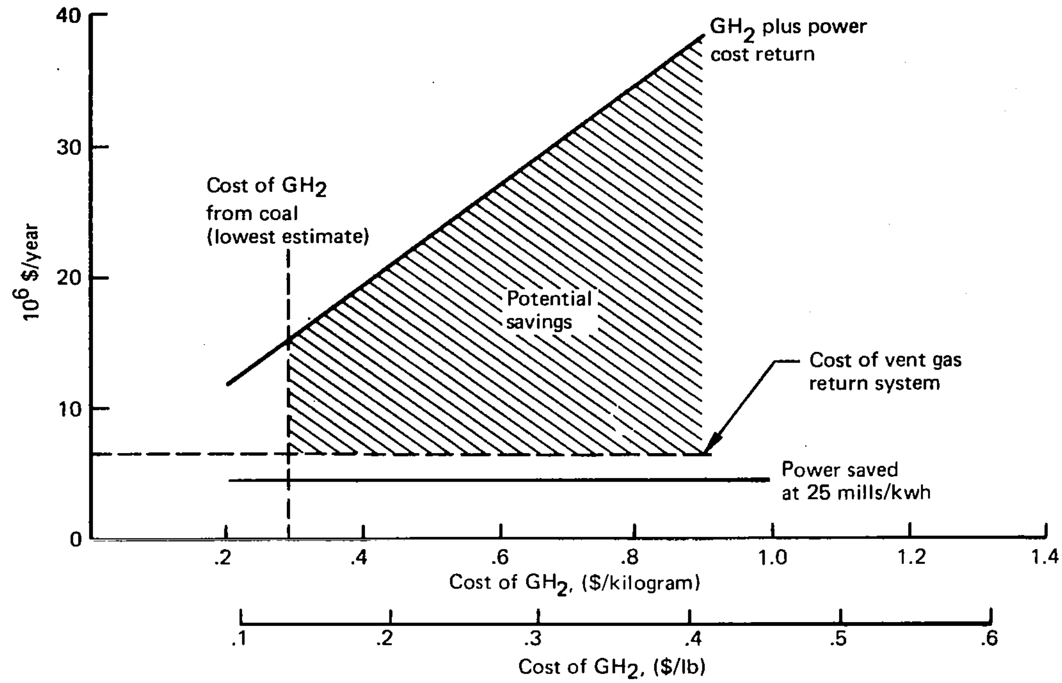


Figure 21.—Vent Gas Recovery—Cost Trade

liquefaction and distribution system requires approximately 350 mw. This translates into a hydrogen requirement of 694 000 kg/day (765 tons/day) assuming a 40% hydrogen to electric power conversion efficiency. This quantity of hydrogen is almost seven times the quantity of vent gas recovered at the airport. This imbalance between supply and requirements, along with the loss of refrigeration, does not favor the utilization of vent gas for electric power generation. A second possibility would be to utilize gaseous hydrogen piped to the airport for power generation. This would not result in a refrigeration loss and would offer an environmentally acceptable alternative to fossil fuel or nuclear power generation. However, to be cost competitive with the 25 mils/kwh (1975 dollars) power cost projected for Illinois, the cost of GH_2 must be less than \$0.22/kg (\$0.10 /lb). The ability to supply 385 mw to ORD was checked with Commonwealth Edison of Illinois. They indicated this power requirement is well within their current reserves and should be no problem in the 1990 - 2000 time period. In the development of the baseline system, it was assumed that Commonwealth Edison would provide power at a cost of 25 mils/kwh.

A vent gas recovery system was chosen for the baseline concept because:

1. It allowed a simple solution to vent gas duty cycle matching

2. It was cost effective

3. Vent gas supply and electric power demand did not match

5.2.2 LH_2 DISTRIBUTION AND CONDITIONING

A primary objective of the baseline concept was to limit the impact of H_2 on the air terminal facilities and airline operations. This requirement essentially dictated delivery of LH_2 to the widebody gates as they currently exist and a provision for redundancy in case of a distribution system failure.

The simplest distribution system from a hardware and architectural standpoint is fueling aircraft by tank truck. This concept was rejected by the airport authority because it would not be physically possible to provide room for tank trucks in the terminal ramp area. It was also noted that fueling the aircraft outside the gate area would require increased turn-around times for the aircraft, an objectionable restraint to the airlines. These alternate fueling methods are discussed in more detail in sections 7.3 and 7.4. The remaining distribution system option was to deliver LH_2 to the gates via insulated pipe. Ignoring cost, the primary problem with this technique is that heat transferred to the LH_2 in the distribution lines would result in an increased bulk liquid temperature. This increased temperature could result in LH_2 flash vaporization during aircraft loading. The problem would be particularly severe during low traffic periods, such as from 9:00 p.m. to 5:00 a.m. at O'Hare. Two methods were considered for eliminating this problem. These were:

1. Recirculating LH_2 back to the storage farm. This prevents a significant LH_2 bulk temperature increase by decreasing liquid residence time and allows conditioning of the liquid to a saturation temperature approaching 101 kg (1 atmosphere) in the storage tank.

2. Flash vaporizing the liquid immediately up-stream of the ground-to-aircraft connect. This allows the liquid temperature to rise in the pipeline, then reconditions the liquid by flash vaporization on a demand basis. A possible configuration for the flash vaporizer is shown in figure 22.

Operating characteristics for the two distribution system techniques are shown in table 2. The flash vaporization system was chosen for the baseline because:

1. It required the least quantity of line

2. It required the lowest delivery pressure for a given line size

3. It resulted in the lowest overall losses

Limiting the delivery pressure was considered mandatory to prevent any condition that would allow the aircraft tank pressure from exceeding its relief setting of 248 kPa (36 psia). A pressure of approximately 345 kPa (50 psia) should satisfy this concern, considering the connect system pressure drops.

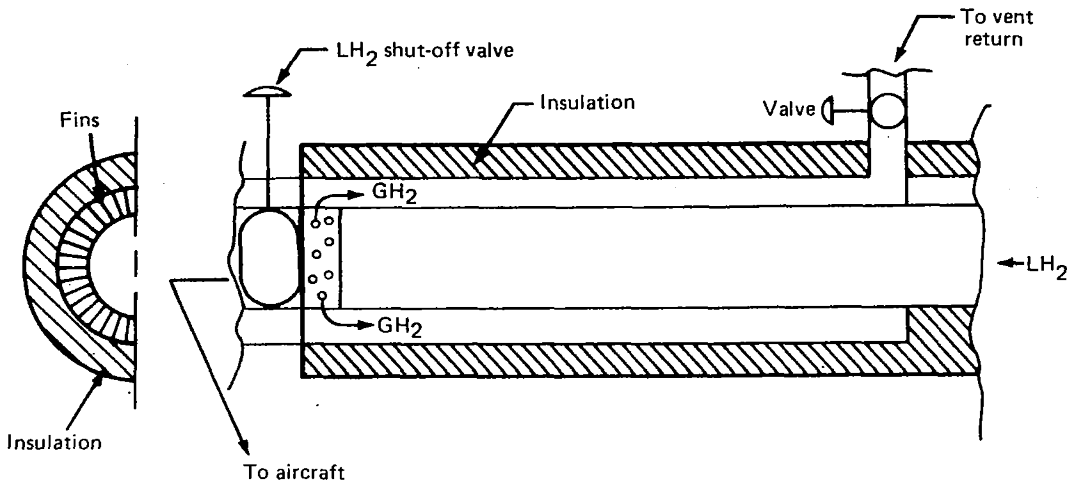


Figure 22.—LH_2 Flash Vaporizer

Table 2.—LH_2 Distribution and Conditioning System Comparison

Item	Technique: Flash vaporization	Technique: Recirculation	
Line ID — m	0.41	0.41	0.51
(in.)	(16)	(16)	(20)
Delivery pressure — kPa	345	276-1034	193-441
(psia)	(50)	(40-150)	(28-64)
Aircraft connect pressure — kPa	145	145-924	145-393
(psia)	(21)	(21-134)	(21-57)
Boiloff — kg/day	3629	6623	8437
(tons/day)	(4)	(7.3)	(9.3)
LH_2 line length — m	6,706	13 411	13 411
(ft)	(22 000)	(44 000)	(44 000)

5.2.3 DISTRIBUTION SYSTEM FAILURE IMPACT

To accept LH_2 as an aircraft fuel, the airlines must be satisfied that system failures and/or maintenance requirements will not result in major disruption in their schedules. The impact of failures in the hydrogen liquefaction facility and the storage tank farm can be limited using classic redundancy techniques. Redundancy can also be applied to limit the impact of failures in the distribution system. The application of redundancy in the distribution system, however, requires more than a simple doubling of components because:

1. The use of two lines filled with LH_2 increases losses and requires a large unusable liquid inventory

2. The use of an empty standby liquid line leads to a significant airport down time for cooling the line to operating conditions

As discussed earlier, it was determined that recovery and reliquefaction of hydrogen vent gas and associated refrigeration was desirable. It was also determined that the vent gas return line size requirement was approximately equal to the liquid delivery line size. This allowed consideration of both four- and three-line systems that would satisfy redundancy requirements. Table 3 shows the options and associated advantages and disadvantages. A three-line system with one normally filled with liquid and two used for venting was selected for the baseline. The second vent line also can be used as a substitute LH_2 supply line. This option has a potential for requiring an airport shutdown period of greater than 1 hour for cooldown, except during peak operating hours, when the vent gas flow is sufficient to maintain adequate line precolling for the rapid introduction of LH_2.

5.2.4 LH_2 STORAGE TECHNIQUES

The development of a storage technique for LH_2 involved limiting losses (insulation), satisfying delivery requirements (expulsion), and safety (location). Table 4 shows the

Table 3.—LH_2 System Considerations

Consideration/Option	Advantages	Disadvantages
Distribution system redundancy		
• Total (2 vent/2 liquid)	• Minimizes airport down time • Accommodates airport growth	• High cost • Large unusable liquid inventory
• Partial (2 liquid/1 vent)	• Lowers cost • Low airport down time (no precool)	• Large unusable liquid inventory • Liquid line must be emptied if vent line fails
• Partial (selected) (1 liquid/2 vent)	• Lowers cost • Minimizes unusable liquid inventory	• One hour or greater airport down time possible

Table 4.—LH_2 Storage Characteristics

Consideration/Option	Advantages	Disadvantages
<u>Insulation</u> ● Non-evacuated ● Foam ● Laminar ● Frozen earth	● Configuration flexibility ● Not size limited ● Simple field fabrication ● Apparent adaptability to underground installation	● High maintenance ● Redundancy requirement limits size advantage ● Unproven for LH_2 (poor results with LNG) ● Variable thermal performance
● Evacuated (selected)	● Low maintenance (proven in LH_2 service) ● Required size within state-of-art ● Low and predictable heat leak	● Difficult to use in underground installation ● Configuration limited ● Requires skilled labor for field installation
<u>Expulsion</u> ● Pressurized	● Low cost ● Low maintenance	● Relatively high tank pressure ● Variable LH_2 saturation temperature ● Difficult duty cycle match
● Pump (selected)	● LH_2 saturation temp. controlled ● Simple duty cycle match ● Low tank pressure	● High maintenance
<u>Location</u> ● Underground	● Directed detonation ● Limited spill potential	● Maintenance difficult ● Increased detonation potential
● Above ground (selected)	● Limited detonation potential ● Easy access for maintenance	● Difficult spill control ● High visibility

options and associated advantages and disadvantages in each of these areas. Proven in service, evacuated insulation was chosen for the baseline because of its low and predictable heat leak. A satisfactory alternate technique has not been developed. Pumped expulsion of LH_2 was chosen for the baseline concept to satisfy a distribution system requirement for an approximately 101 kPa (1 atmosphere) pressure saturation temperature. This condition is difficult if not impossible to meet using pressurized expulsion and the requirements of the ORD liquid delivery duty cycle. The low storage tank pressure was also a safety consideration in the selection of pumped LH_2 delivery. At first glance underground storage of LH_2 appeared desirable from a safety standpoint. However, space provisions for maintenance on underground tanks increased the danger of creating trapped volumes of GH_2. These trapped volumes increased the possibility for detonation, hence decreased the safety advantage for underground storage. These considerations, and the fact that a low storage pressure would be utilized, led to the selection of above ground LH_2 storage for the baseline concept.

5.3 SELECTED CONCEPT DESCRIPTION

Details of the selected concept were developed based on analyses of requirements and considerations presented in sections 5.1 and 5.2. These details include the sizes and operating characteristics of major system elements and associated components. The major elements of the concept and their location on the airport are shown in figure 17. Figure 23 is a schematic showing the liquefaction, storage, and distribution elements of the system.

Installation of the system and its impact on the airport are presented in section 5.5; the impact on airline ground operations is presented in section 5.6.

5.3.1 LIQUEFACTION FACILITY

Gaseous hydrogen is delivered to the airport in two 0.36-m (14-in.) diameter (ID) pipes at a pressure of 4480 kPa (650 psia) and at ambient temperature. Each supply line has sufficient capacity to meet the demand of the liquefaction plant. The supply hydrogen is stored in an underground accumulator before it is piped into the liquefaction plant. Pressure in the accumulator is kept at 4480 kPa (650 psia). The accumulator volume is approximately 7510 m^3 (265 000 ft^3). This allows smoothing of the flow to the liquefier and adequate standby hydrogen for a switch from dual to single line GH_2 delivery.

Impurity levels of gaseous hydrogen delivered from the hydrogen gasification plant are in the order of one ppm total content of nonhydrogen species, except it is assumed to be saturated with moisture. Moisture is removed at the liquefaction plant.

The hydrogen liquefier is designed for a nominal output of 726 x 10^3 kg/day (800 tons/day). This output can be varied ±20% to meet fluctuations in fuel usage and in storage tank levels. The liquefier is designed to produce essentially all para hydrogen. This represents a higher energy cost than that obtained by direct liquefaction of the delivered gaseous hydrogen (approximately 75% ortho hydrogen). However, the stability of para hydrogen is required to insure predictable aircraft fuel loads.

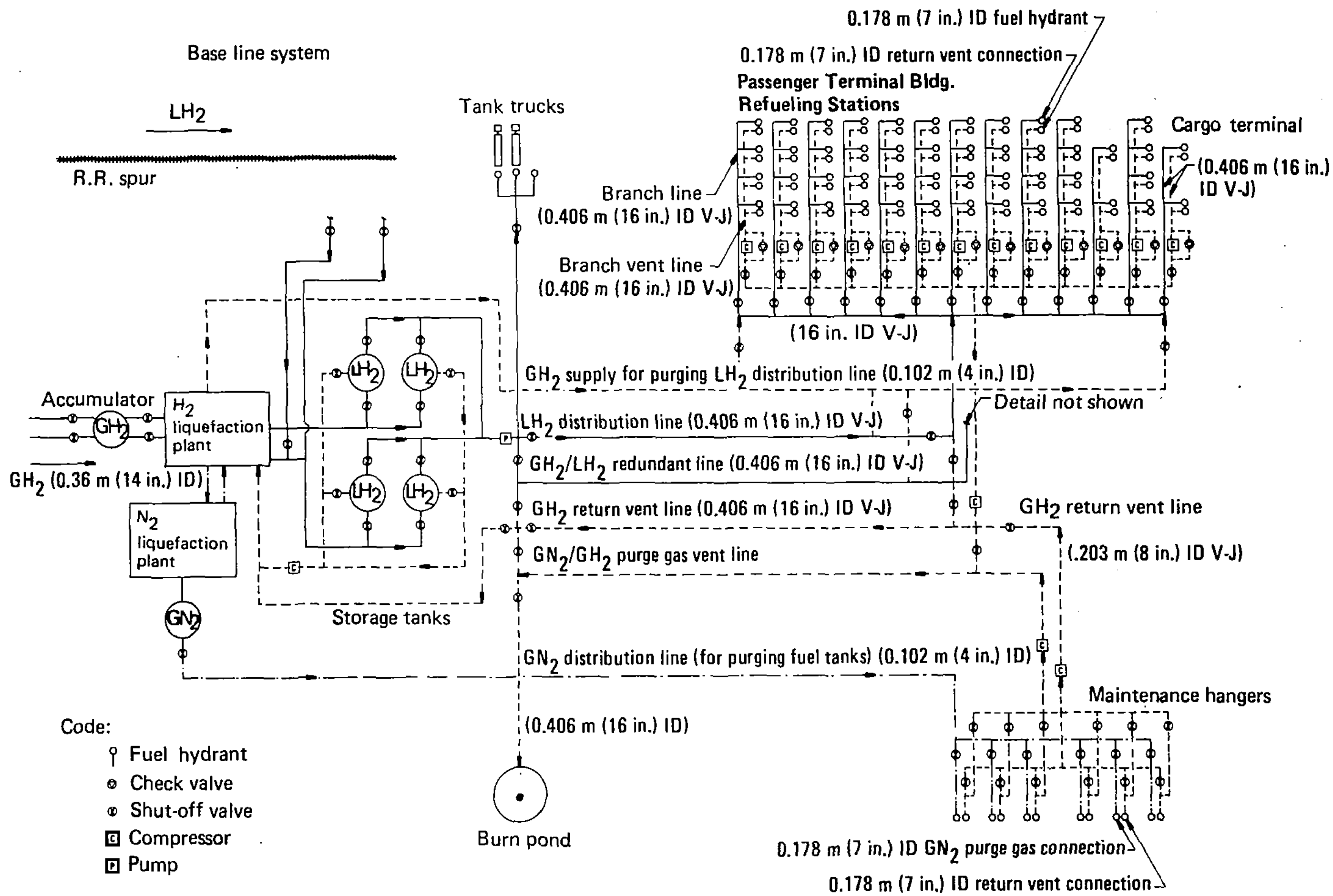


Figure 23.—Fuel System Distribution Line Schematic—Baseline Concept

The hydrogen liquefaction plant, shown in figure 24, consists of three modules, each having approximately 243 080 kg/day (268 tons/day) capacity. Each module consists of one H_2 liquefier, six H_2 recycle compressors and two feed gas driers. Heat exchangers within the H_2 liquefier are multiple units installed in parallel. In addition, each module includes a nitrogen liquefier and a purifier to remove impurities from return vent gas. Liquid nitrogen is used to precool high pressure hydrogen feed gas in the hydrogen liquefier process.

A building containing an office, maintenance station, and central control station is located at the site of the liquefaction plant. The functions of the central control station are to monitor and control liquefaction process, storage and distribution of LH_2, pumping of GH_2 return, to detect leakage and vacuum break of pipe line, and to keep records of fuel delivered.

Nitrogen is produced and used as a refrigerant in the hydrogen liquefaction process. A portion of this nitrogen is stored in an accumulator for use in purging airplane fuel tanks. The accumulator pressure varies from 550 to 1030 kPa (80 to 150 psia).

5.3.2 STORAGE FACILITY

Liquid hydrogen is stored in four spherical tanks located adjacent to the hydrogen liquefaction plant. Total capacity of these tanks is equivalent to 2 days of LH_2 production (1.45×10^6 kg (1600 tons)). Two of the tanks are maintained in a full condition to provide back-up for major short-term failures, such as liquefaction plant power loss. The other two tanks are used as active storage to handle the peaks and valleys in daily liquid demand. One of these tanks also acts as reserve storage when a storage tank must be emptied for maintenance.

Hydrogen from the liquefaction plant is piped into active storage before distribution to the refueling stations. A rail spur is provided for transportation of LH_2 in tank cars to the storage tanks as a backup system to the liquefaction plant. Approximately 37 500 m^2 (8.8 acres) of clear land is required for the storage facility.

The storage tanks are located above ground. An aggregate of stones enclosed in a concrete retaining wall is placed underneath the storage tanks to serve as a heat sink in the event of tank rupture. This accelerates vaporization of LH_2. The storage tank is of double-wall construction with a 23.2 m (76 ft) diameter stainless steel inner sphere. The annular space is evacuated and filled with perlite powder insulation. Figure 25 presents a schematic of a storage tank. The boiloff rate from the storage tanks is less than 1% of the daily liquefaction rate (7.26×10^3 kg/day (8 tons/day)). This boiloff is collected, compressed, and piped back to the liquefaction plant. The nominal storage pressure is 110 kPa (16 psia). Pressure in an active storage tank is allowed to reach 138 kPa (20 psia).

5.3.3 DISTRIBUTION SYSTEM

The LH_2 delivery and vent gas return lines are shown in figure 23. The system consists of LH_2 supply, GH_2 vent gas return lines and also a redundant 16 in. ID line extending

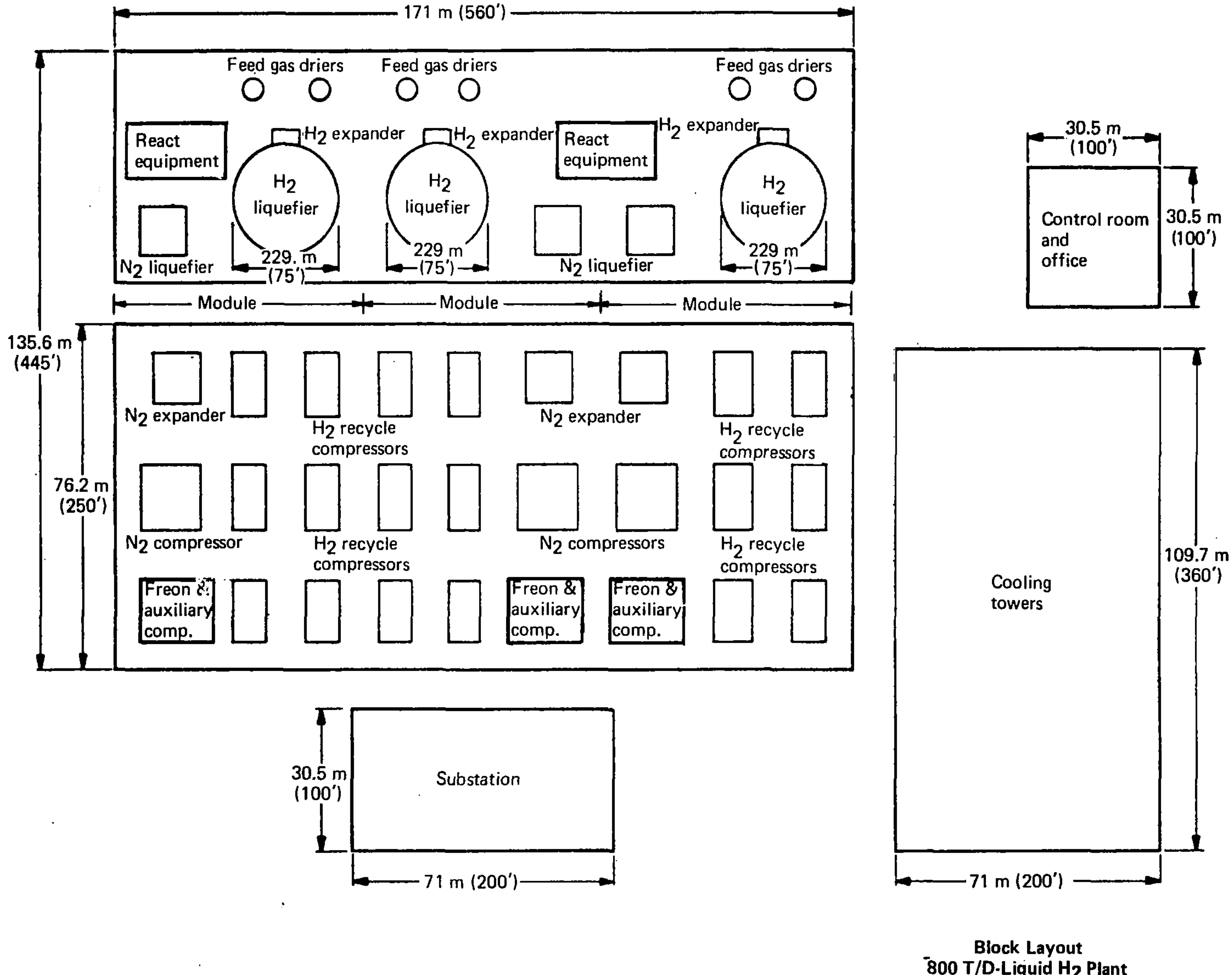


Figure 24.—725,680 kg/day (800 ton/day) LH_2 Plant.

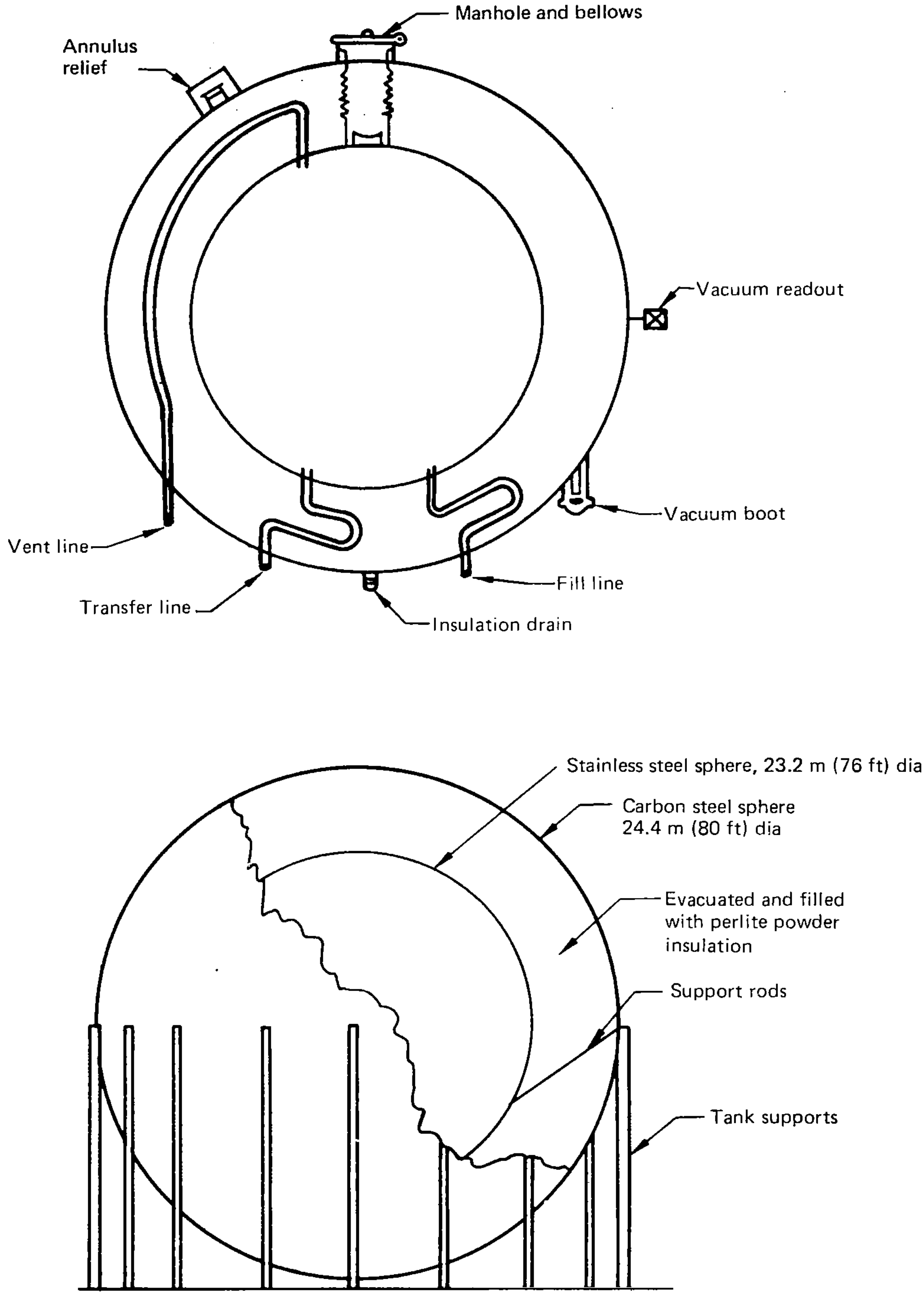


Figure 25.—LH_2 Storage Sphere Fitting Schematic

from the LH_2 pumping station to the junction where the lines branch out to the passenger terminal building. This redundant line is normally used as a GH_2 return vent line, but can be used in the event the main LH_2 supply line must be shut down for maintenance work. Any sections of the LH_2 supply and GH_2 vent gas return lines that can be isolated with shut-off valves are equipped with pressure relief valves. Gaseous hydrogen discharged from the relief valves is routed to the burn pond through 0.102 m (4 in.) ID lines.

Supply Lines

The main supply line has a capacity of 226 750 kg/hr (500 000 lb/hr) at 345 kPa (50 psia). Each branch line is capable of supplying four hydrants at full airplane refueling rate. The design flow rate of each hydrant and airplane connection is 56 688 kg/hr (125 000 lb/hr) which is equivalent to loading the average ORD LH_2 airplane in 10 min., or loading a full tank of fuel in 1/2 hour.

The main supply lines and the branch lines to each terminal finger are approximately 0.406 m (16 in.) ID. Four 0.178 m (7 in.) ID fuel hydrants are provided in each terminal branch line. A variable capacity pump installed in the main supply line pumps liquid hydrogen to a maximum pressure of 345 kPa (50 psia) for airplane refueling. Airplanes are refueled with a tank-back pressure above ambient, but not above 145 kPa (21 psia). The LH_2 fuel distribution line pressures at the design condition are shown in table 5 and figure 26. The system pressure drop characteristics as a function of airplane refueling rate are shown in figure 27.

Redundant pumps are placed in the LH_2 trunk line. Each pump has a capacity of delivering the design flow rate of 226 750 kg/hr (500 000 lb/hr) at 345 kPa (50 psia), therefore a pump failure would not cause a fueling delay. Constant pump output pressure of 345 kPa (50 psia) is maintained by varying the pumping rate according to demand. The fuel supply pressure varies at the airplane connection, depending on the number of simultaneous airplane fueling connections made. A fuel flow control on the airplane fuel connection regulates the airplane fuel supply pressure to a maximum of 145 kPa (21 psia) during normal refueling.

Heat leaks through the LH_2 distribution lines cause approximately 9070 kg (10 tons) per day of LH_2 boiloff. Heat leak is estimated to be approximately 4510 kg (5 tons) per day through super-insulated V-J lines and the remaining 4510 kg (5 tons) per day through pumps, shutoff valves, pressure relief valves, hydrants, etc. Heat leak through superinsulated vacuum jacketed lines was estimated from heat leak factors provided by Air Products and Chemicals, Inc.

Return Vent Line

All aircraft are connected to a vent gas return during their entire ground stay. Vent gas return lines are provided at maintenance areas, as well as at the gates. Airplane fuel-tank vent gas and boiloff are normally routed back to the liquefaction plant; however, a burn pond is provided as a back-up system for disposing of gaseous hydrogen.

Table 5.—LH_2 Fuel Distribution System Characteristics

Maximum fuel distribution rate = 226 750 kg/hr (500 000 lb/hr)		
LH_2 fuel distribution pump:		
Inlet pressure	=	101 kPa (14.7 psia)
Outlet pressure	=	345 kPa (50 psia)
Pump power requirement	=	298 kw (400 HP)
Distribution line pressure drop:		
Pump out pressure	=	345 kPa (50 psia)
Main supply line pressure drop (16 in. ID)	=	145 kPa (21 psig)
Branch line pressure drop (16 in. ID)	=	28 kPa (4 psig)
Aircraft connection pressure drop (7 in. ID)	=	28 kPa (4 psig)
Aircraft fuel tank pressure	=	145 kPa (21 psia)

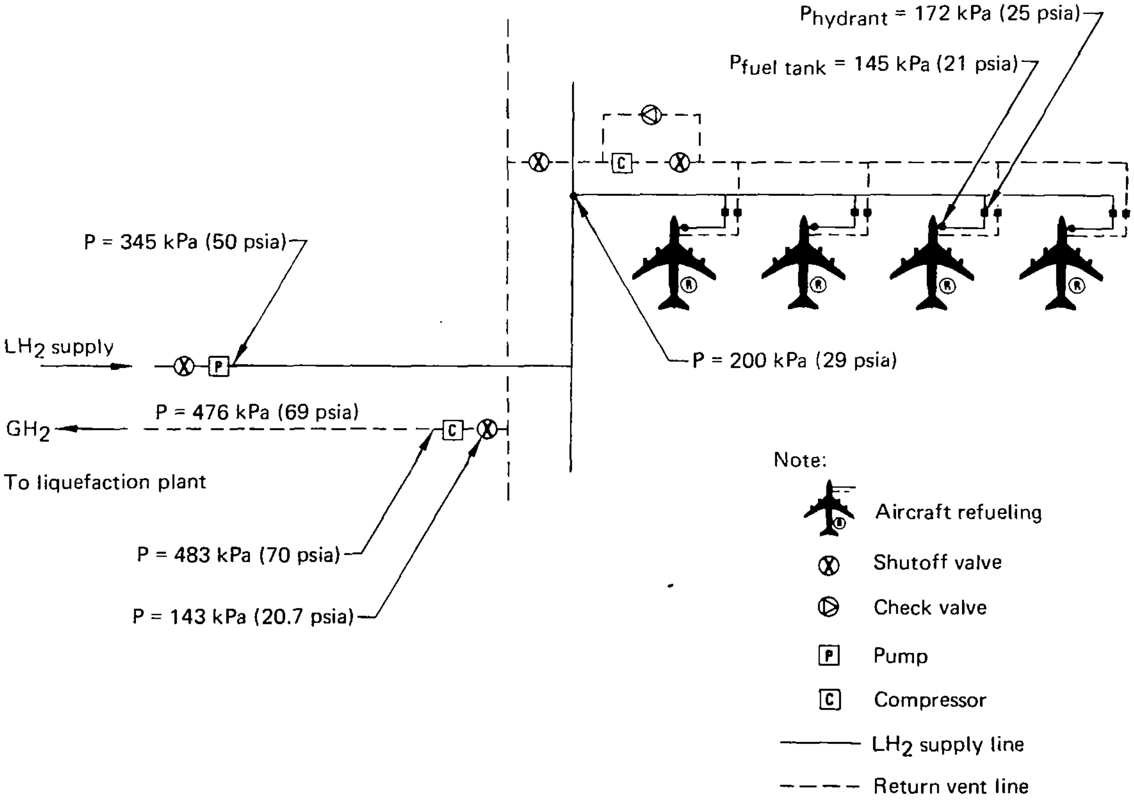


Figure 26.—LH_2 Branch Line Design Condition

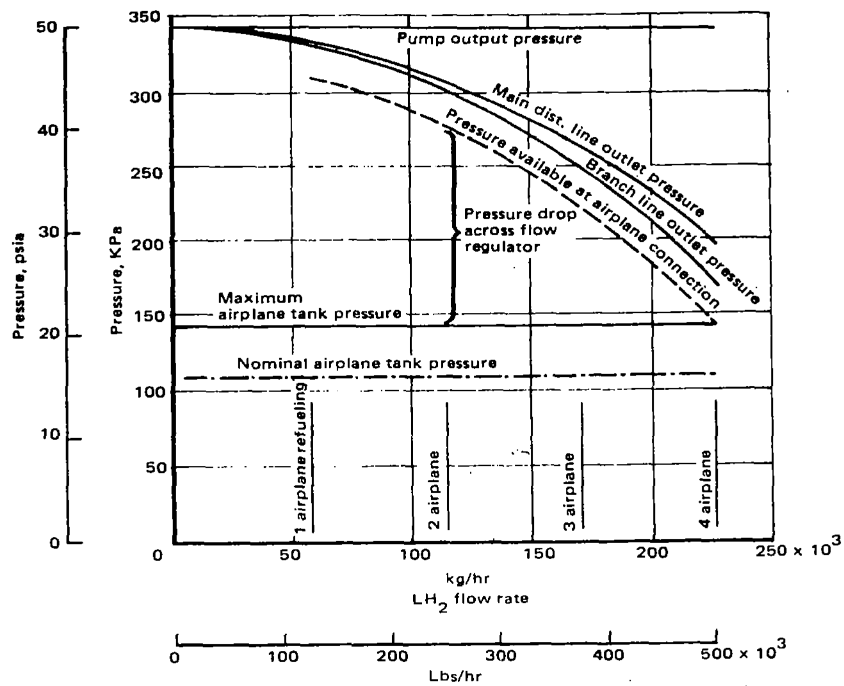


Figure 27.—LH_2 Distribution Line Pressure Drop

Pressure distribution at the design condition in the GH_2 return vent line is shown in table 6. The design condition assumes the tanks of 12 widebody aircraft are simultaneously depressurized. This also allows refueling three widebody airplanes in addition to cooling down fuel tanks of four widebody airplanes, as shown in figure 28.

The airplane LH_2 fuel flow rate is kept below 14 285 kg (31 500 lb) per hour, or one-fourth the design refueling rate during fuel tank cooldown. This is to keep the airplane fuel vent system and vent return connection below 0.178 m (7 in.) ID. Also, airplane fuel tank pressure during cooldown is allowed to increase to 172 kPa (25 psia).

Vent gas from each LH_2 aircraft gate is collected and manifolded into two 0.406 m (16 inch) ID branch lines. Four 0.178 m (7 in.) ID vent line connectors are provided on each branch line. A small compressor is designed to handle boiloff during cooldown of two aircraft at a total flow rate of 28 344 kg/hr (62 500 lb/hr) and used to keep GH_2 pressure in the vent line from dropping below ambient. The compressors in the branch lines are bypassed during normal refueling conditions.

The main return line is designed to handle 56 699 kg/hr (125 000 lb/hr) of boiloff. Three compressors placed parallel in the main return line boost vent gas pressure to 393 kPa (57 psia). This is to ensure return vent line pressure of not less than 207 kPa (30 psia) at the liquefaction plant. Flow rate in the compressors is varied according to the amount of vent gas to be evacuated. Any two of the compressors are able to handle the design flow requirement.

Table 6.—GH_2 Vent Return System Characteristics

LH_2 boiloff rate	= 56 688 kg/hr (125 000 lb/hr)
Pressure drop from branch line to main compressor inlet	= 62 kPa (9 psig)
Main compressor inlet pressure	= 117 kPa (17 psia)
Compressor outlet pressure	= 400 kPa (58 psia)
Compressor outlet temperature	= 53 K (96°R)
Compressor power requirement	= 3500 kw (4700 HP)
Line pressure drop from main compressor to storage tank	= 190 kPa (27.5 psig)
Storage tank inlet pressure	= 207 kPa (30 psia)
Storage tank inlet temperature	= 53 K (96°R)

Distribution and Vent Line Design

A schematic of the superinsulated vacuum jacketed line used in the LH_2 distribution and vent gas return system is shown in figure 29. The inner pipe is wrapped with thermal radiation shielding, such as aluminized mylar, and encased in a vacuum jacket. These inner pipes are welded in the field to one continuous piece, and provided with bellows at each valve, where there is a significant line direction change, and where there is a hard point restraint. Pressure relief devices are provided in each section of line that can be isolated by valves.

The vacuum jacket is made up of 152-m (500-ft) sections. The vacuum breaks have evacuated joints as shown in figure 29, to minimize heat leakage.

Maintenance

Vacuum gauges and transducers are provided for central control station monitoring of the vacuum level in pipes and components. If hydrogen leakage or loss of vacuum are detected in the distribution lines, the liquid is drained and the line warmed and purged with nitrogen before repair work is initiated.

Upon completion of repairs, air is purged from the transfer line before LH_2 is introduced. The line is purged with nitrogen gas and then with warm hydrogen gas. The nitrogen gas concentration must be at a very low level before cold hydrogen gas is introduced or it will solidify and could prevent the valves from closing and block instrumentation lines.

Shutoff valves are installed in the main supply line to isolate sections for maintenance work in the event of vacuum jacket failure. The main supply line is installed with a downward slope of approximately 1:1000 toward the LH_2 plant, so that liquid hydrogen can be returned to storage prior to pipe maintenance. Isolation valves are provided on each branch supply line and branch return vent line for easy maintenance of fuel hydrants and return vent connectors.

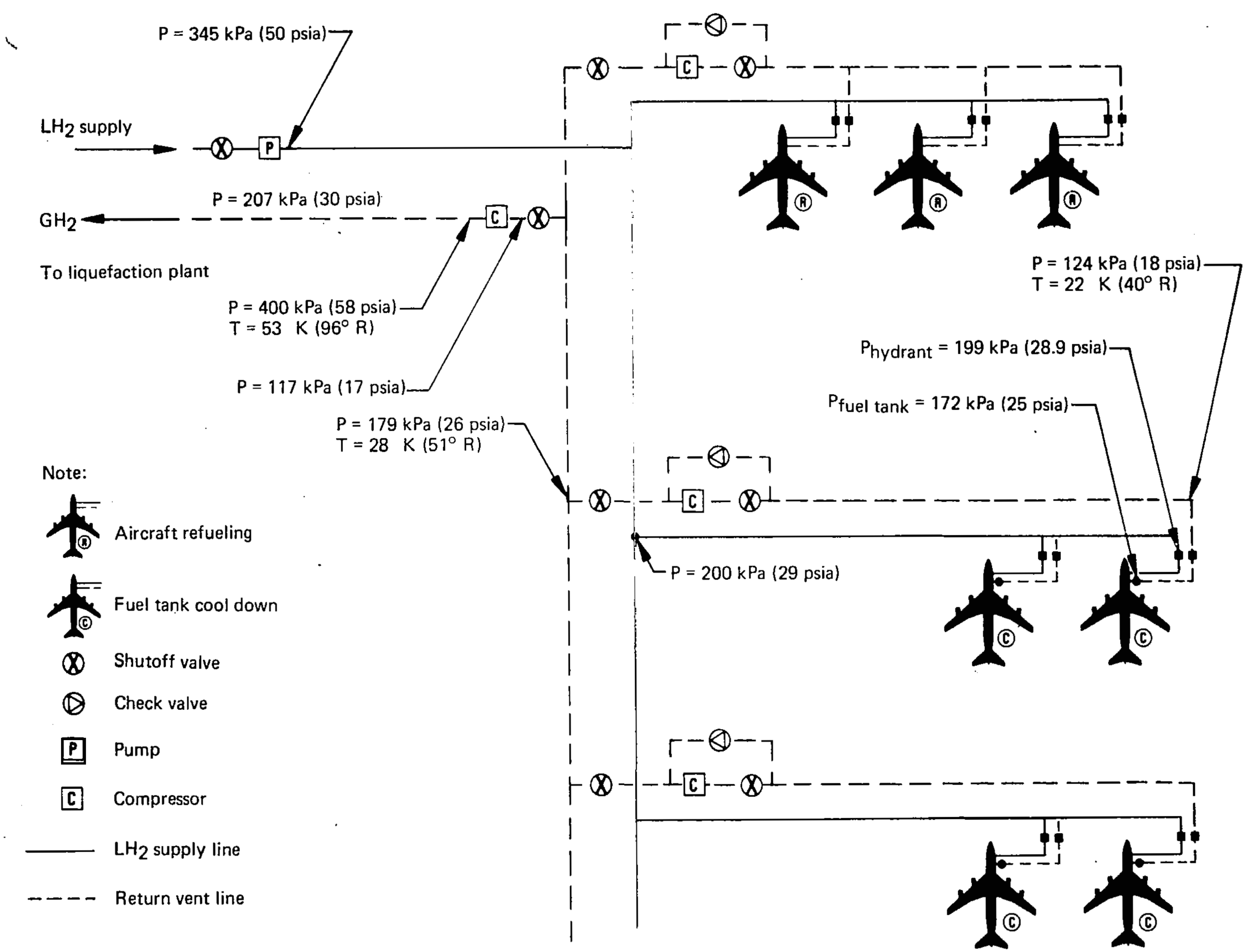


Figure 28.—GH_2 Return Vent Line Design Condition

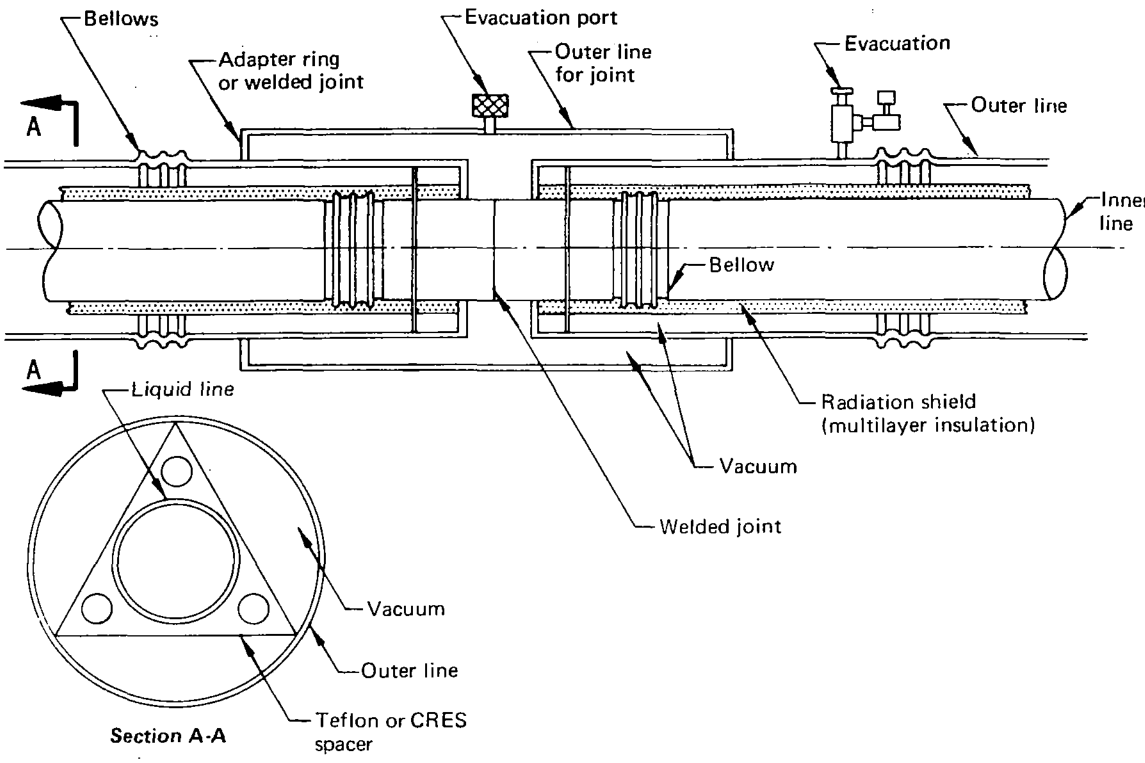


Figure 29.—Super Insulated Vacuum-Jacketed Pipe

Operation

Airplanes are normally refueled at the passenger gates and cargo air terminals. However, warm airplane fuel tanks are cooled using hydrogen routed through a truck-mounted hydrogen recycle cooldown and recovery system. This cooldown is conducted away from the terminal area, principally in the maintenance area. The use of a recycle cooldown and recovery system is expected to be more economical than direct cooling with LH_2, and maintains availability of LH_2 hydrants during the extended time periods required for cooling.

Except under emergency situations, defueling of airplanes for fuel tank maintenance is conducted in the maintenance area. The fuel is offloaded into refueling trucks and transferred to the LH_2 storage tanks.

Upon defueling, airplane fuel tanks are warmed and purged of gaseous hydrogen, with gaseous nitrogen piped to the maintenance hangars from the nitrogen generation plant. Before refueling with LH_2 upon completion of maintenance work, the fuel tanks are purged with nitrogen gas to ensure that they are free of oxygen.

Winter weather conditions at O'Hare field would cause considerable inconvenience if maintenance operations not requiring aircraft defueling were conducted outdoors. Therefore, maintenance hangars are provided with aircraft vent connections to the GH_2 collection system and high volume ventilation systems. The rate of ventilation is controlled by hydrogen detectors mounted near the vent connections and at hangar high points. The maintenance area is also provided with a gaseous nitrogen supply for purging warm hydrogen tanks.

5.4 SYSTEM SAFETY FACTORS

Safety requirements established by the National Fire Protection Association are incorporated in the design of the airport LH_2 and GH_2 facilities. Methods of hydrogen hazard control and safety recommendations suggested by major hydrogen producers and major users such as NASA, Atomic Energy Commissions, etc., are used in areas/designs where applicable. In general, these safety recommendations are concerned with exposure of the personnel and facilities to hazards of hydrogen. However, in this study, the safety of the hydrogen system from the various hazards associated with a major airport operation is given equal emphasis.

5.4.1 LIQUEFACTION PLANT AND LH_2 STORAGE

Location of these facilities on the airport has been established, in part, by potential hazards associated with aircraft operations. Distance from the LH_2 facility to active runways is such that an aircraft, crashing during takeoff or landing, will probably not impact and burn (kerosene fire) close enough to the hydrogen facilities to cause damage or ignition of hydrogen. Studies of jet transport accident data indicate a distance of 305 m (1000 ft) from an active runway centerline to the hydrogen facility is adequate spacing. These historical data are shown in figure 30.

Liquefaction plant and storage sphere spacing is established to provide protection from a hydrogen fire. This spacing is such that a fire resulting from a massive liquid hydrogen spill will not damage adjacent tanks or equipment. Each storage sphere

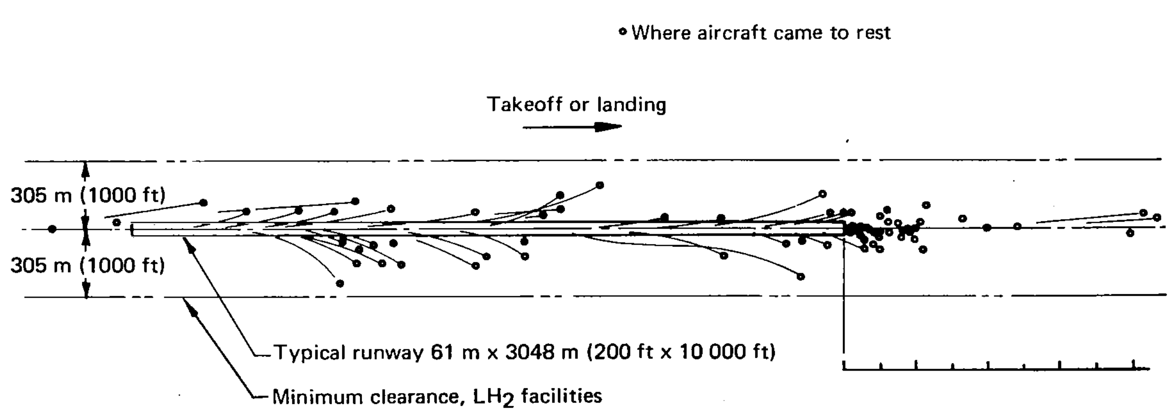


Figure 30.—Runway Clearance Criterion

installation includes a dike enclosure capable of containing the entire contents of the sphere. The minimum distance from the edge of a dike to the surface of an adjacent storage sphere or to an adjacent facility is 62 m (205 ft). A minimum distance of 107 m (350 ft) from the edge of the dike to adjacent inhabited buildings is maintained.

A policy of nonconfinement is applied to the design to minimize the possibility of an explosion if a hydrogen leak/spill occurs. Safety relief devices and controls are protected from physical damage and readily accessible for emergency shut down. Control systems are automated fail-safe designs such that incapacitations or personnel error will not damage the system, cause a hazardous situation, or result in injury to personnel. The system design considers protecting the system and facility from the operators, as well as the operators from the hydrogen system. Major components of the facility (system) are separated, isolated, or protected such that a failure of one will not likely result in failure to another, i.e., a cascading effect.

5.4.2 LH_2 DISTRIBUTION AND GH_2 COLLECTION SYSTEM

All piping (vacuum-jacketed) from the storage area, to the terminal refueling areas is located in an underground tunnel to minimize the possibility of damage from vehicular and aircraft movement and from other airport activity. Adequate ventilation is provided in these enclosures to assure that a combustible mixture of hydrogen and air will not accumulate in event of a leak. Hydrogen detectors, vacuum loss detectors and heat sensors are installed to warn of system leakage and fire in enclosed areas.

Terminal area branch lines are located on top of the terminal buildings. They are installed in open channels to catch LH_2 in event of a massive leak. Gaseous hydrogen is prevented from entering and accummulating in terminal buildings by the positive internal air (ventilation) pressure. Hydrogen leakage in the area of a ventilation module on top of the building is prevented from entering the building, via the module air inlet by stopping the air inlet fan and closing an inlet door. This is accomplished automatically by hydrogen leak detectors.

To avoid over-stressing the distribution and collection piping, the system is designed with frequent expansion bellows to accommodate a temperature range of about 278°C (500°F). To prevent excessive pressure buildup, the design provides dual pressure relief protection (relief valves and blow-out plugs) in each section of piping that can be blocked by valves. The relief gas is vented into a relief line which routes it to the burn pond. Leakage in a section of piping is controlled by isolating that section with shut-off valves controlled automatically by hydrogen detectors, temperature sensors, and/or line pressure drop.

5.4.3 AIRCRAFT FUELING SYSTEM

The primary hazard associated with the LH_2 hydrant refueling system and with the LH_2 truck refueling is leakage (and fire) at the airplane receptacle, or a fuel line rupture (and fire) adjacent to the aircraft. The hazard in either event is minimized by rapid (automatic) shut down of the fueling operation. The LH_2 supply line is supported in a position to the side of the aircraft so that in event of a line rupture, the LH_2 will not flow on the fuselage or puddle under the aircraft.

Fire protection in the refueling area is provided by a water spray directed at the aircraft, passenger loading ramp, and terminal building wall to cool materials below the ignition point. The water spray is a fixed installation with automatic rapid response operation.

5.4.4 AIRCRAFT MAINTENANCE AND HANGAR AREAS

Hangar facilities presently in use are modified to accommodate LH_2-fueled aircraft. Existing and new buildings meet the requirements established by the National Fire Protection Association for explosion venting and explosion control.

LH_2-fueled aircraft are to be drained and purged prior to being placed in a hangar, if an extended period of maintenance is programmed. Fueled aircraft may be hangared for short periods of maintenance, during which hydrogen bleed-off from tanks is captured and returned to the airport GH_2 vent system. The aircraft should not be left unattended while in the hangar in a fueled condition.

Hangars are equipped with hydrogen detection equipment, which is located in areas where H_2 can be trapped and accumulate. The system has rapid response and will signal an alarm and automatically initiate high-rate ventilation before a combustible mixture can accumulate. Special attention is placed on control of ignition sources inside the hangars. This includes lighting and electrical powered equipment, grounding of aircraft and maintenance stands, use of non-sparking tools, and control of humidity to reduce static charges.

5.4.5 PERSONNEL AND TRAINING

Training must be a continuing function for all personnel involved in operation and maintenance of the LH_2 system and in the servicing, maintenance and operation of LH_2-fueled aircraft. Adequate/proper maintenance, coupled with a systematic inspection program, will enhance the safety of the LH_2 operations–only trained personnel should be allowed to work in these areas.

The type and extent of training must be tailored to individual jobs or assignments. All personnel, however, must be indoctrinated on the characteristics of hydrogen, the potential hazards, how to recognize unsafe situations, and on the contingency procedures provided in the emergency plan. Specific training should include the following:

- Liquefaction plant and distribution system personnel must have an understanding of the airport operations and procedures. They must have a high degree of competence in the LH_2 system operation and must learn to recognize system failures or malfunctions and how to react to emergency situations.

- Aircraft fueling personnel must have a general understanding of the LH_2 distribution system and of the LH_2 aircraft fuel system. Training must include both the standard and emergency operating procedure for the refueling operation.

Danger to the aircraft, passengers, and terminal building in the event of a massive LH_2 spill must be recognized and contingency training practiced periodically. This must include fire fighting and heat control procedures.

- Aircraft maintenance personnel must have a thorough understanding of the airplane fuel system and of the procedures for defueling, purging, and re-activating all or part of the system. Hazards associated with hydrogen leakage from an airplane in an enclosed hangar must be understood and the related emergency procedures must be practiced periodically.

- Airport security and fire fighting personnel must understand the potential hazards to the airport and the public that can result from massive LH_2 spills; this would include fire, immense gaseous hydrogen clouds, explosive mixtures, cryogenic temperatures, and asphyxiation. Training in controlling these hazards must include coordination of the emergency with the hydrogen system personnel. Emergency training must include the proper-response/procedures relating to an LH_2-fueled aircraft accident. Rupture of the aircraft fuel tanks would result in a large LH_2 spill.

5.5 SELECTED SYSTEM INSTALLATION

The hydrogen system includes facilities required to liquefy and store the liquid hydrogen, and the distribution network. Both parts of the installation are required to comply with the safety criteria as well as the requirements of reference 5.

5.5.1 *LIQUEFACTION* AND STORAGE FACILITIES

The liquefaction facility arrangement, as shown in figure 24, requires an area of approximately 42 700 m^2 (10.6 acres).

The storage facility for liquid hydrogen consists of four spherical tanks, each 25 m (80 ft) in diameter and containing 5300 m^2 (1 400 000 gal.) of liquid. When arranged in a square, the tanks and their impoundment reservoirs require an area of approximately 35 700 m^2 (8.8 acres).

Reference 5 requires that an object 25 m (80 ft) tall (above the plane of the runway surface) should be not less than 323 m (1060 ft) from the runway centerline, which is greater than the 305 m (1000 ft) separation required by the safety criteria for hydrogen storage tanks. No part of the liquefaction or storage facilities will exceed 25 m (80 ft) in height.

To minimize construction, operation and maintenance costs, the storage facility is close to the location of greatest usage. Most of the fuel will be dispensed at the existing passenger terminal. Therefore, an area of approximately 120 000 m^2 (30 acres) in that vicinity was selected, as shown in figure 31.

The selected site is located almost directly south of the center of the passenger terminal, across the intersection of Runway 14R-32L and 9R-27L. It is an open area, designated

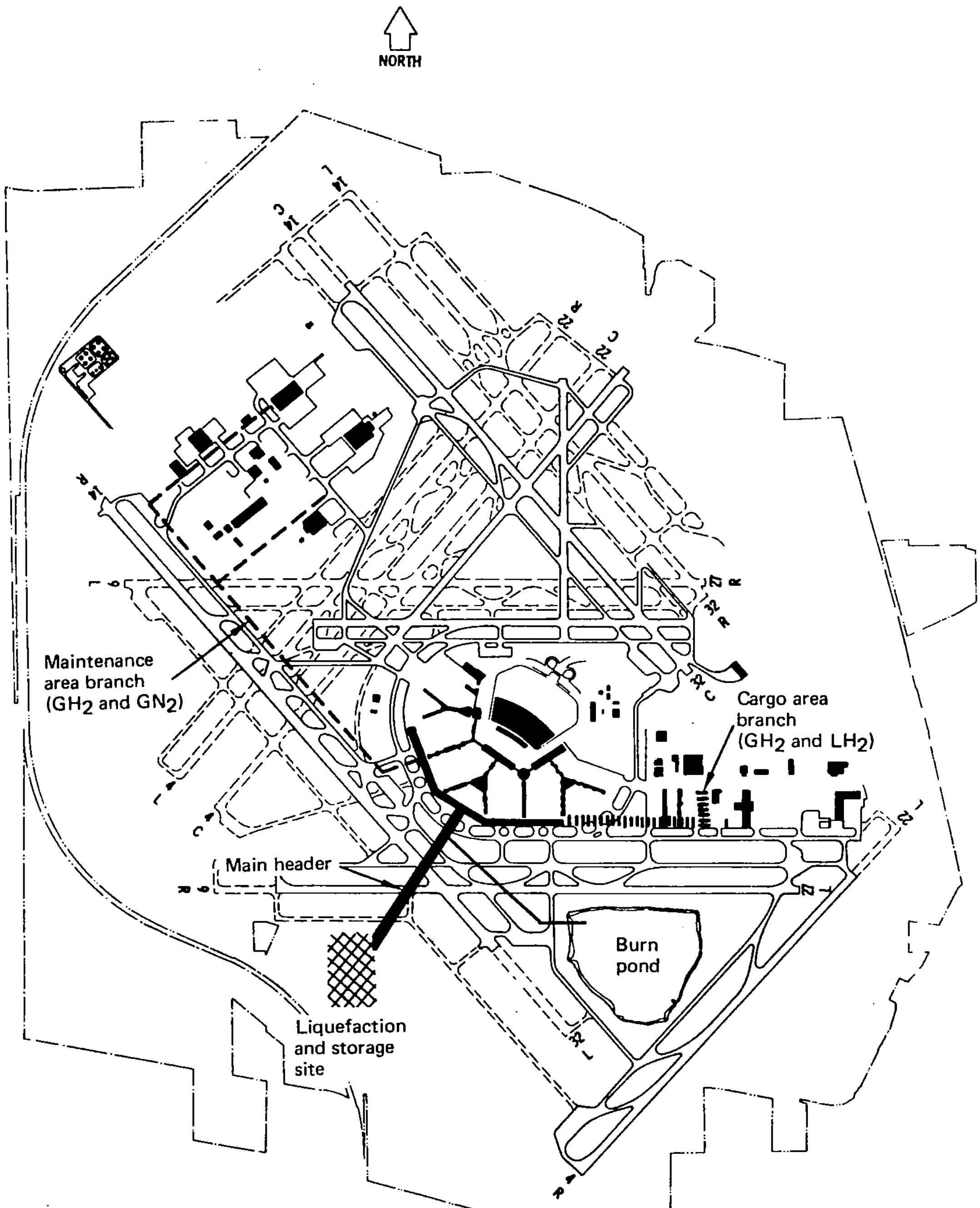


Figure 31.—Hydrogen Fuel Distribution System

for future air cargo development. Subject to future development, there is ample area available, with a railroad available for surface delivery of liquid hydrogen (backup). The Chicago Division of Aviation Planning concurred in the selection of this site for study purposes.

5.5.2 DISTRIBUTION SYSTEM

The fuel system also includes GH_2 and GN_2 lines, valves, hydrants, compressors, fans, and monitoring equipment. The approximate routing of the lines is shown on figures 31 and 32 and the size and number of the various parallel lines are given in table 7.

Several considerations were involved in selecting a practical configuration for the distribution system installations, as illustrated in figure 33. These considerations developed into the requirements shown in table 8 which yielded the installation provisions of table 9.

The requirements ruled out installation of the lines by direct burial or above ground on pedestals. Differences in estimated cost of tunnel versus gallery construction, as shown in figure 34, are of insufficient magnitude to establish a clear preference. Both methods are technically feasible. The tunnel concept shown in figure 35 was used for evaluation of the installation.

They are constructed by a tunneling technique rather than by open-cut trenching, to avoid disruption of aircraft operations. The steel liner plates are installed incrementally as the tunnel excavation progresses, followed by an injection of concrete grout around the periphery to fill voids.

Various arrangements of the lines within the gallery or tunnel, as shown in figure 36, were considered. A straight-forward arrangement of lines on the same horizontal plane (Configuration no. 4, no. 8, or no. 10) was selected.

Figure 37 illustrates a method of removing a section of line from the tunnel. This operation would require a battery-powered hydraulic-actuated cherry picker. A hinged outrigger swinging under the line provides stability during the eccentric lift.

Figures 38 and 39 show a configuration for the required structures and for ventilation provisions in the tunnel.

At the outer end of each concourse the hydrogen lines leave the tunnel and are installed on the roof for distribution to the airplane fueling booms located thereon. Figure 40 shows the routing of the hydrogen lines on the roof of Concourse E-F, the United Air Lines Concourse. The location is complicated by the large ventilator penthouses above the roof. Details of the container for the lines are shown in figure 41. This installation also is typical for the other concourses.

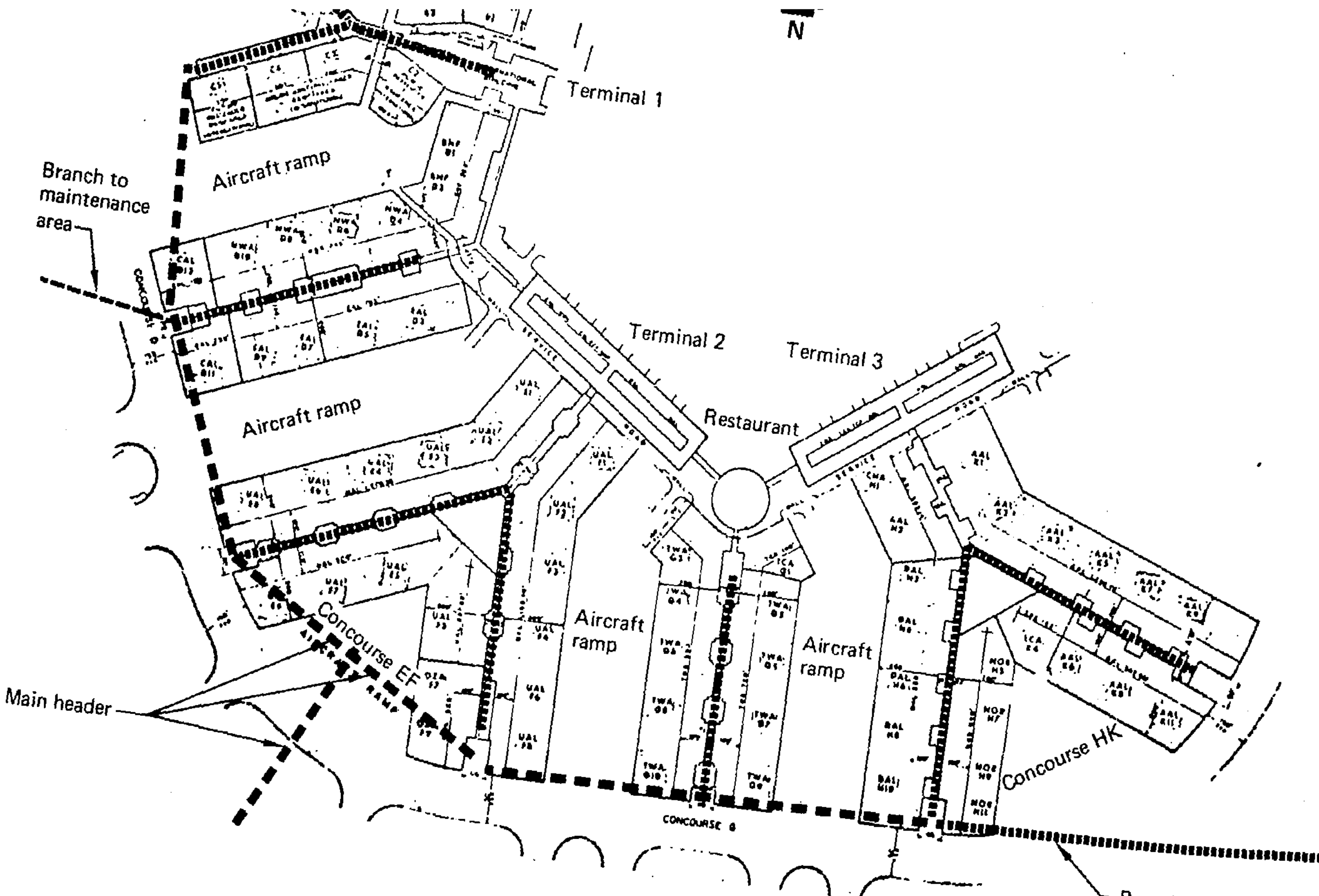


Figure 32.—Distribution System—Passenger Terminal Area

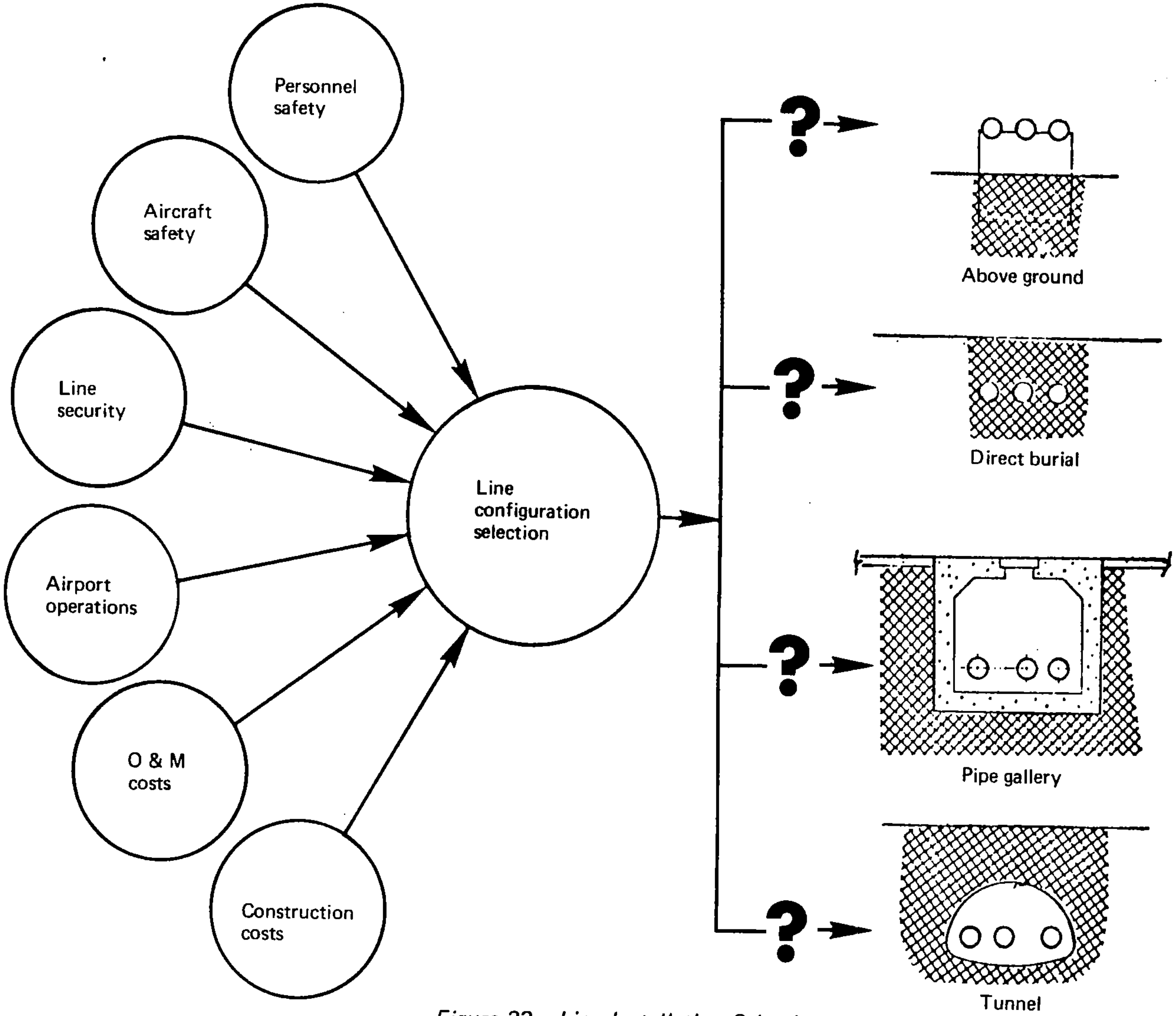


Figure 33.—Line Installation Selection

Table 7.—Hydrogen System Line Elements

	Type	Quant.	Diameter—m ID	Diameter—m OD	Diameter—inches ID	Diameter—inches OD
Main header	GH_2 (V-J)	2	0.41	0.61	16	24
	LH_2 (V-J)	1	0.41	0.61	16	24
	GN_2*	1	0.10	0.11	4	4.5
	Waste gas	1	0.10	0.11	4	4.5
Branches to passenger gates	GH_2 (V-J)	1	0.41	0.61	16	24
	LH_2 (V-J)	1	0.41	0.61	16	24
	Waste gas	1	0.10	0.11	4	4.5
Branch to cargo area	GH_2 (V-J)	1	0.41	0.61	16	24
	LH_2 (V-J)	1	0.41	0.61	16	24
	Waste gas	1	0.10	0.11	4	4.5
Branch to maintenance area	GH_2 (V-J)	2	0.20	0.36	8	14
	GN_2	1	0.10	0.11	4	4.5
	Waste gas	1	0.10	0.11	4	4.5
Branch to burn pond	GH_2	1	0.41	0.43	16	17

*To maintenance area

Table 8.—Line Installation Requirements

- Comply with FAR part 77, objects affecting navigable airspace
- Comply with National Fire Protection Association codes
- Maintain traffic on active runways at all times
- Minimize disruption to taxiways, aprons, hangars, terminal buildings
- Prevent accumulations of hydrogen—air mixtures
- Provide for continuous monitoring of jacket vacuum
- Assure rapid detection of hydrogen or refrigeration losses
- Provide for removal of liquid hydrogen from faulty pipeline
- Provide for maintenance

Table 9.—Line Installation Provisions

- No hydrogen line will be buried directly in the ground
- Lines crossing beneath airport primary surfaces, taxiways, aprons or roadways will be installed in tunnel or pipe gallery
- Hydrogen lines located close together will be installed in the same tunnel or pipe gallery
- Minimum clearance around line will be 0.45 m (18 in.) to facilitate welding, visual inspection, and other maintenance functions.
- Line valves, compressors, and other appurtenances will be installed in structures sufficient to permit inspection and maintenance of all parts.
- All tunnels, galleries and other structures will be positively ventilated to continuously remove gaseous hydrogen
- Flame from leak in one hydrogen line shall not impinge on another line
- Liquid hydrogen lines will be installed on a uniform slope of 1 to 1000 down from the aircraft fueling locations to the hydrogen storage area
- Clearance will be provided in tunnels and pipe galleries for removal and replacement of line sections

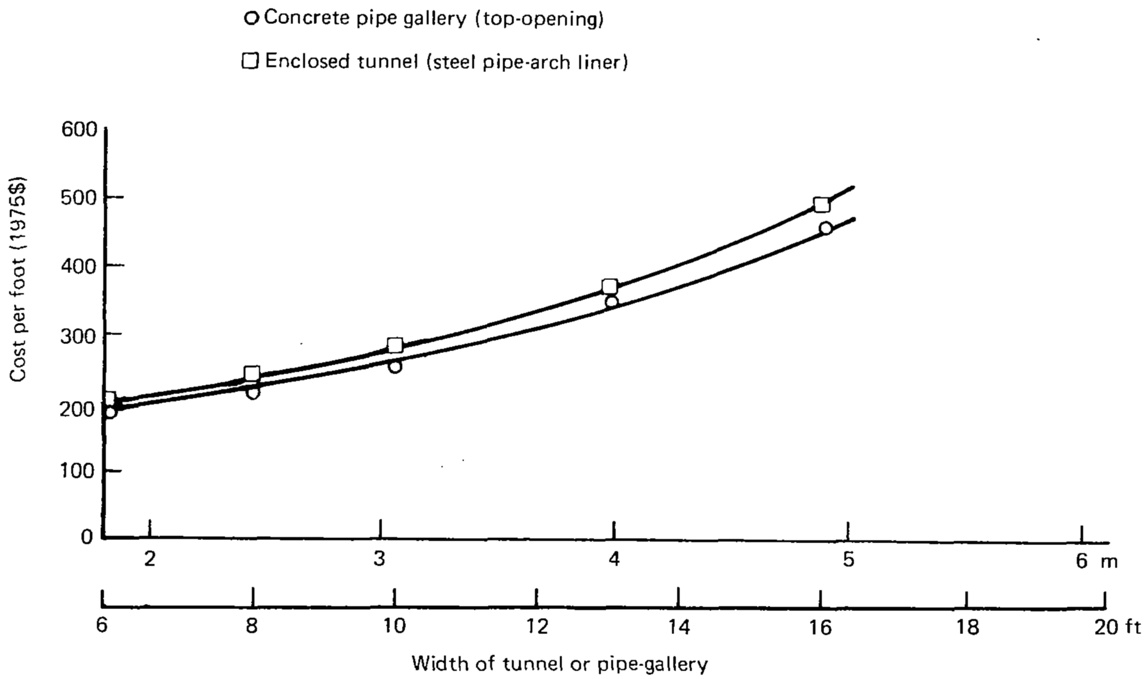
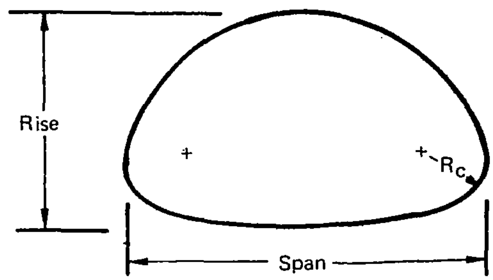


Figure 34.—Tunnel Access

Corner radius (R_C) 0.457 m (1.5 ft)
Corrugations 0.15 x 0.05 m (6 x 2 in.)
seams bolted



Span		Rise		Area		No. of plates
m	in.	m	in.	m^2	ft^2	
1.85	73	1.40	55	2.04	22	5
2.69	106	1.85	73	3.99	43	7
3.33	131	2.16	85	5.67	61	7
3.81	150	2.41	95	7.25	78	8
4.24	167	2.62	103	8.64	93	9
4.72	186	2.87	113	10.50	113	10
5.05	199	3.07	121	12.17	131	10

From: Reference 6, table 1-21

Figure 35.—Structural Steel Pipe-Arches

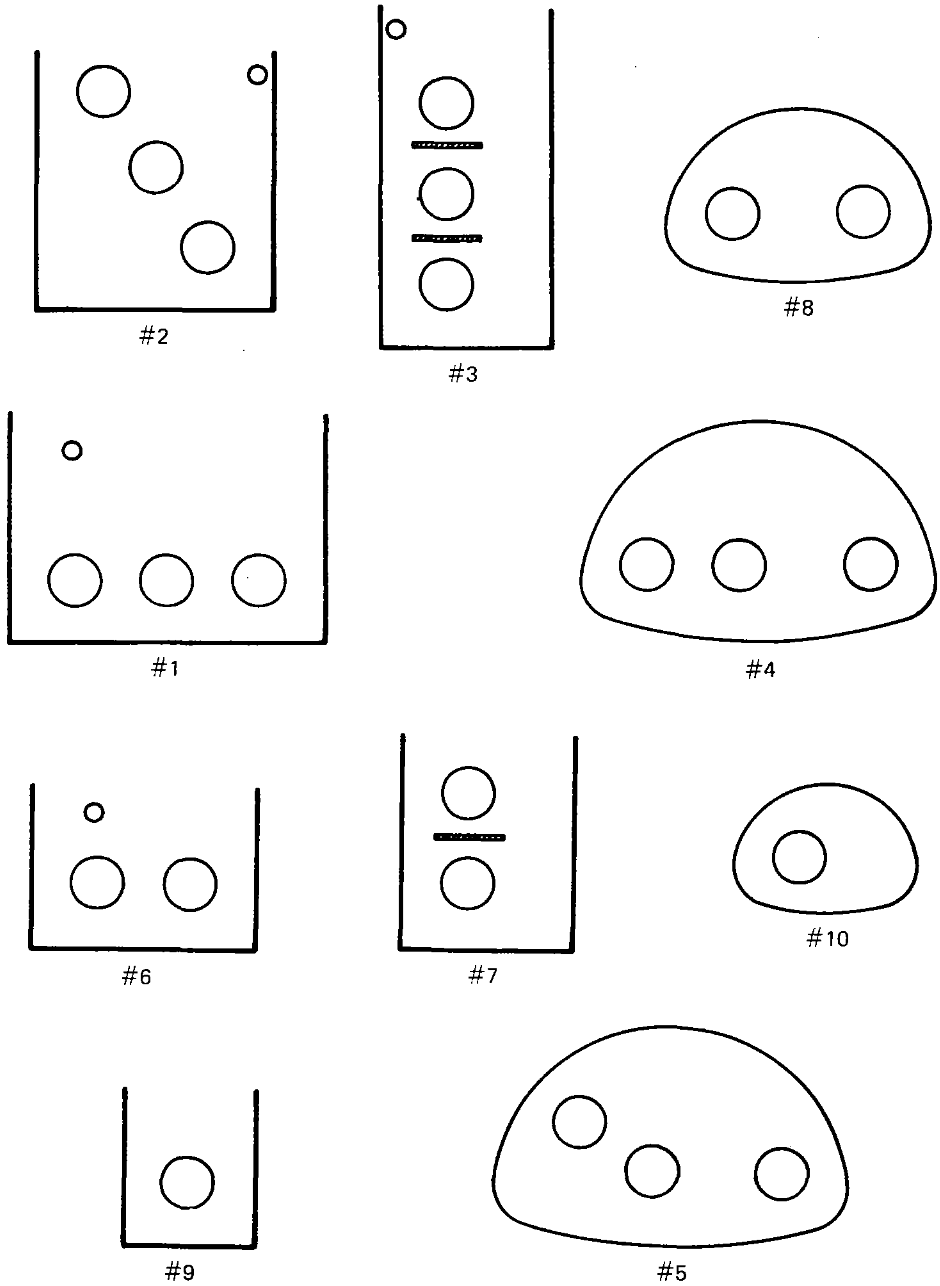


Figure 36.—Line Installation Configurations

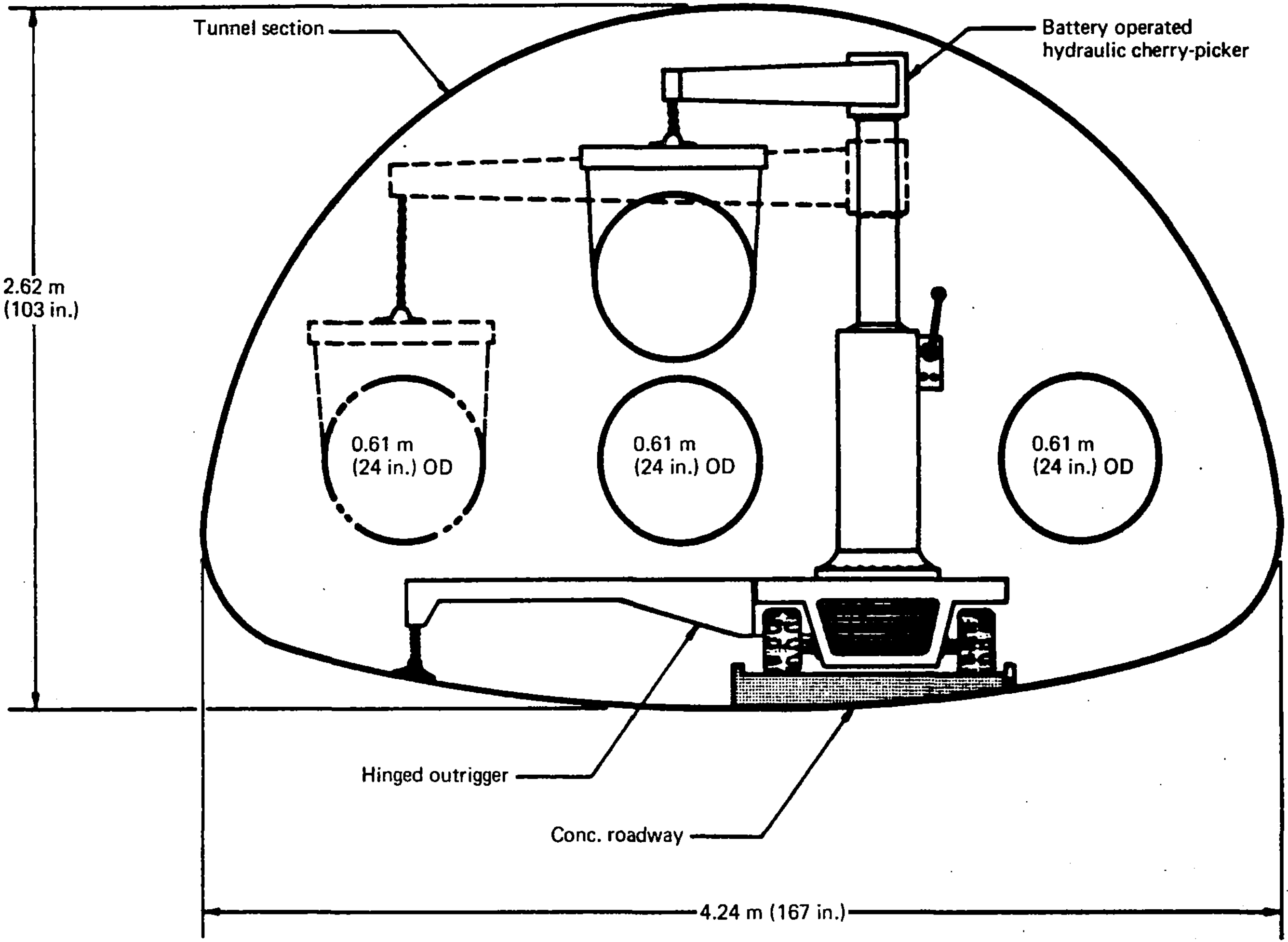
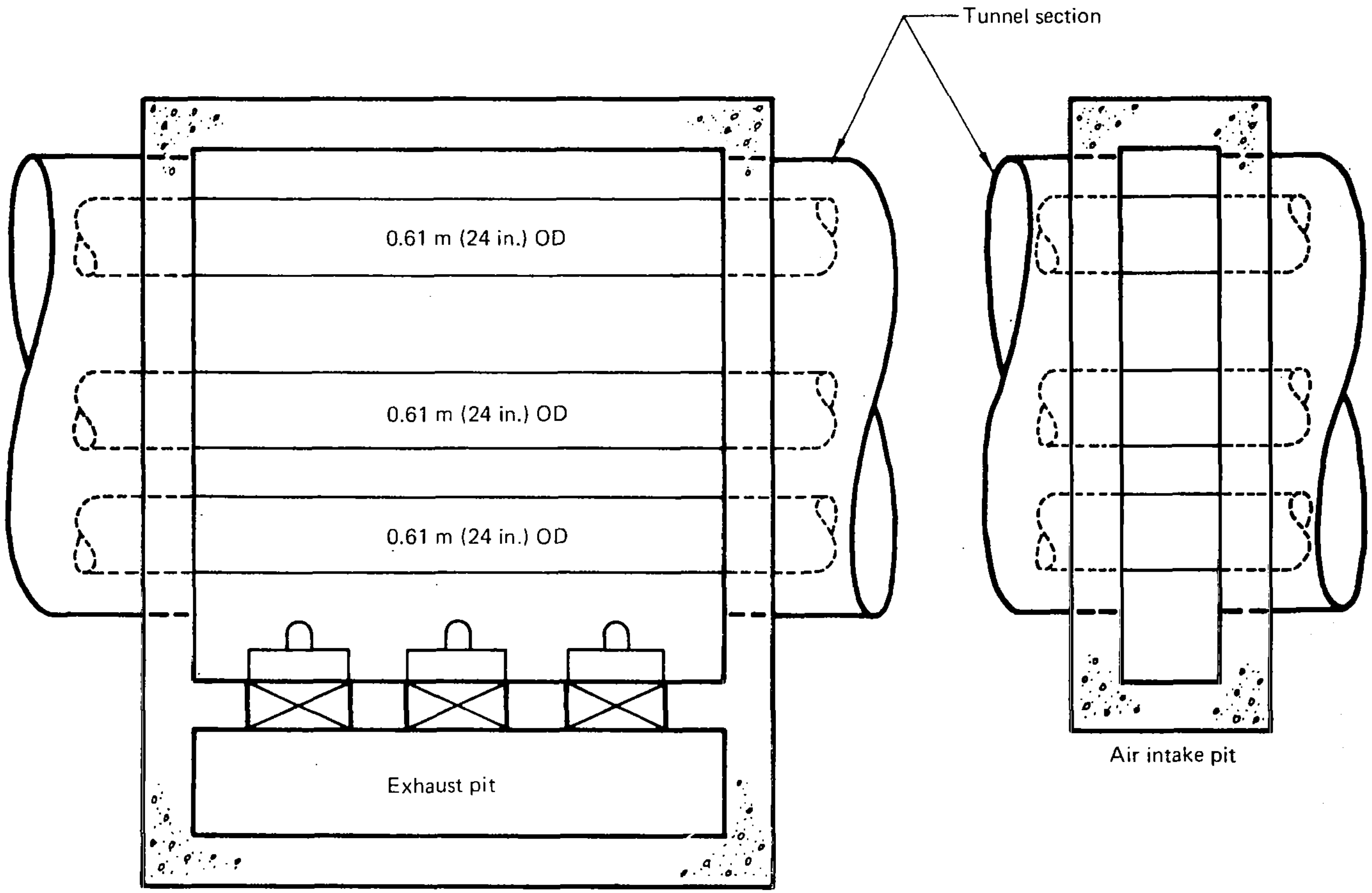


Figure 37.—Line Repair Equipment



Plan View

Figure 38.—Tunnel Access and Ventilation Structure

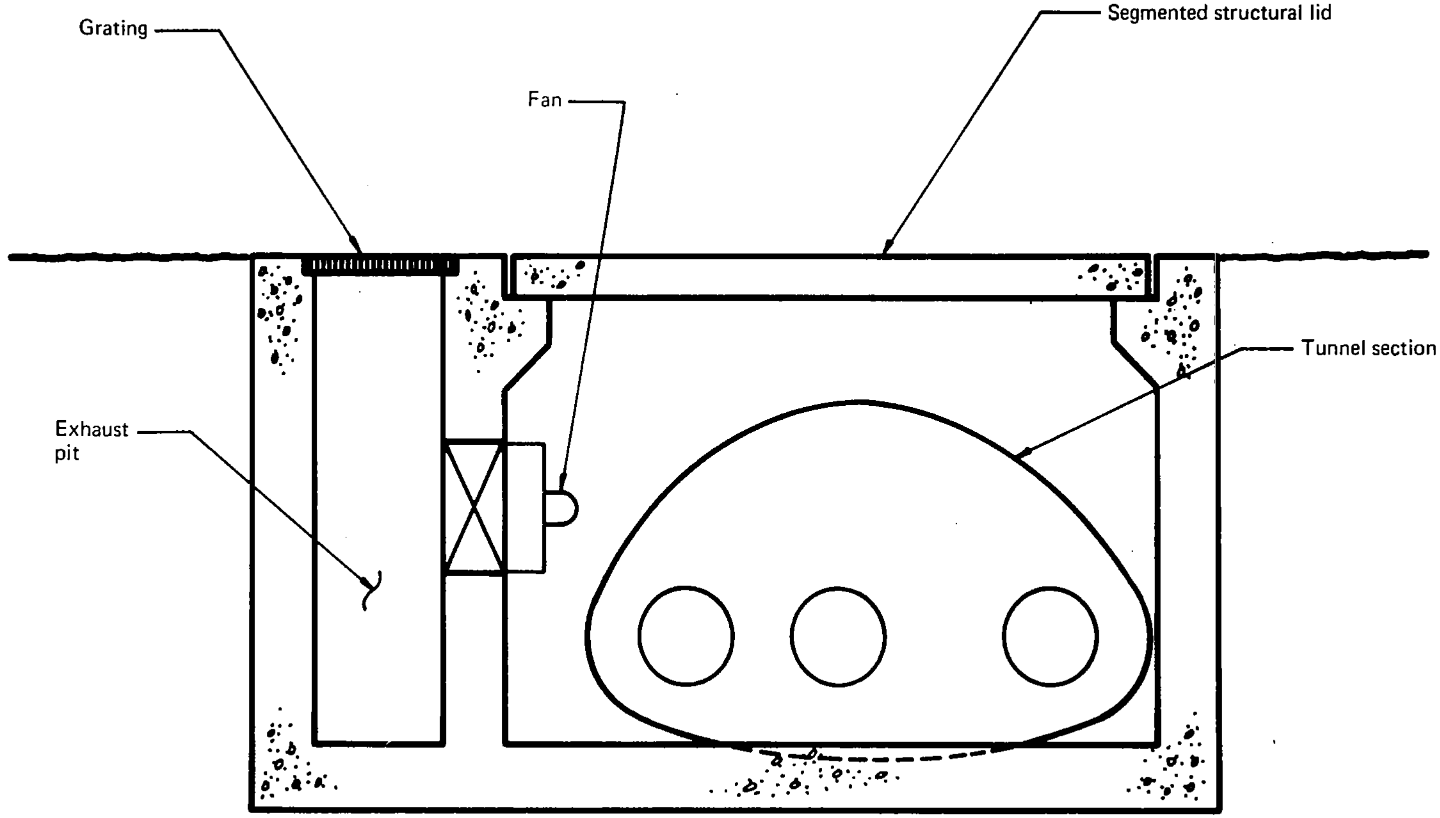


Figure 39.—Tunnel Access and Ventilation Structure

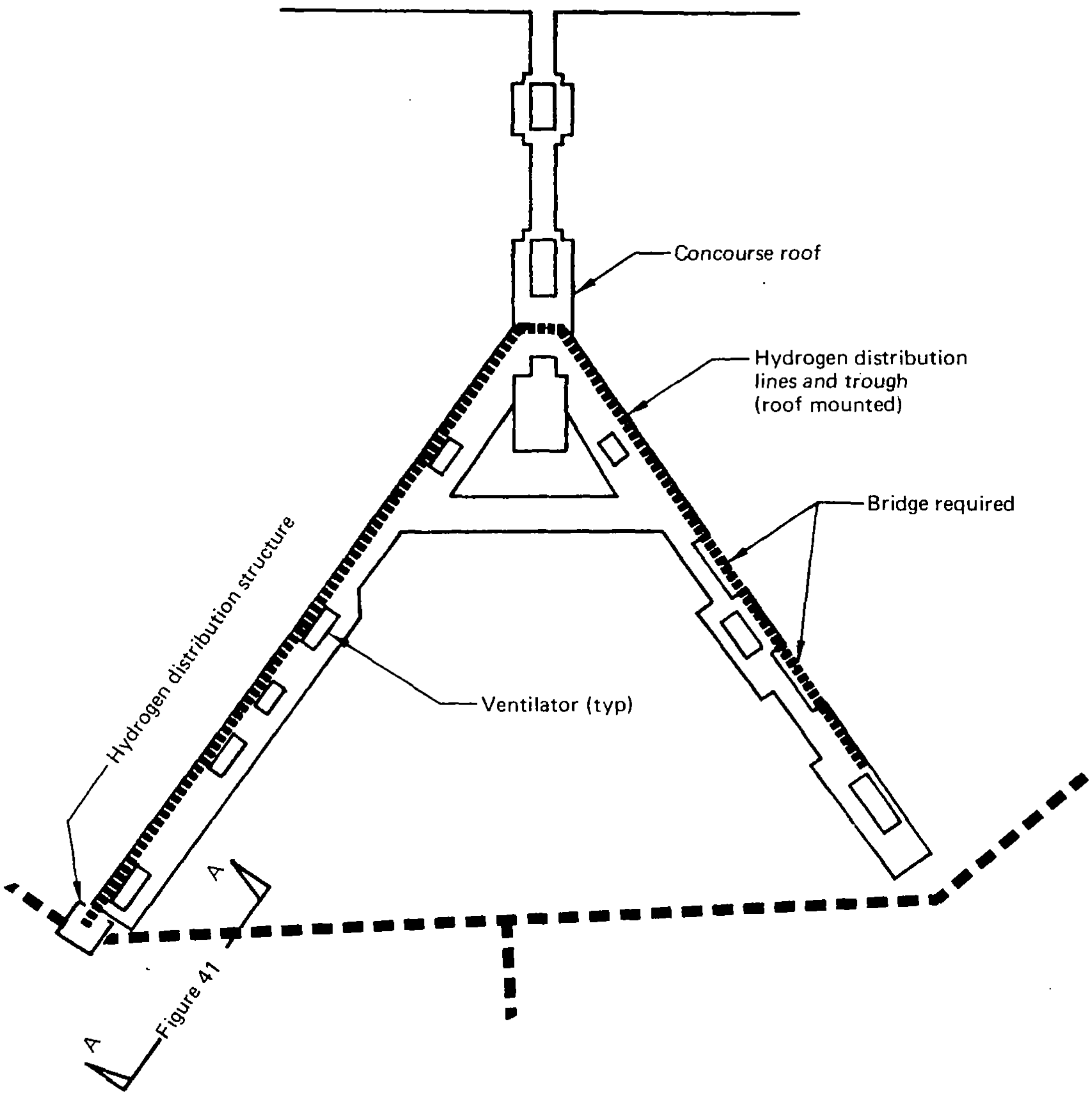


Figure 40.—Hydrogen Distribution UAL Concourse E—F

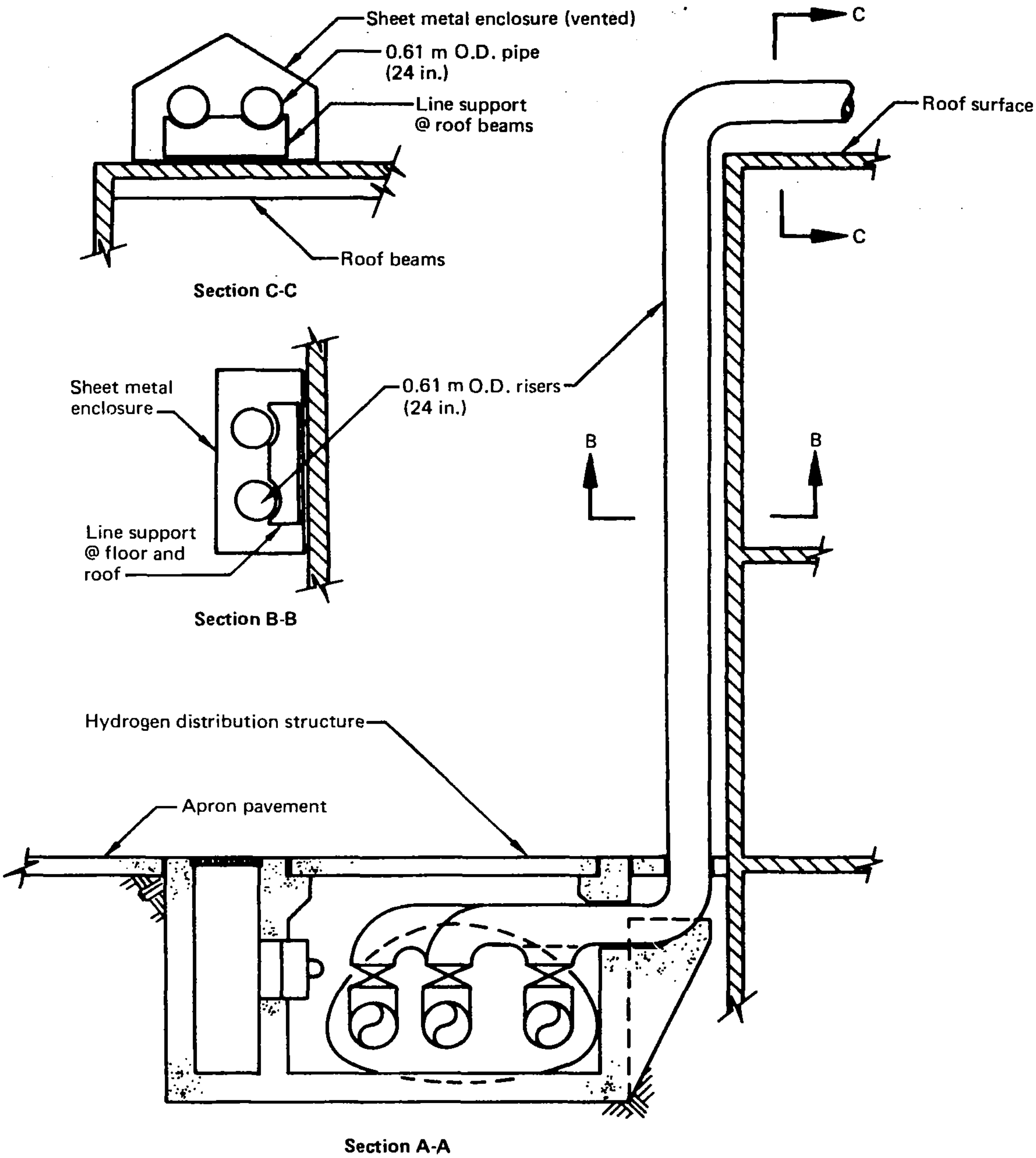


Figure 41.—Line Installation Details

5.6 GROUND OPERATIONS

Ground operations performed during normal ramp servicing of the LH_2 airplane are shown in figures 42 and 43 for turn-around and through-stops, respectively. They are conducted within the ground times allotted to current widebody transports. Many of the functions are accomplished with existing equipment and procedures. However three areas require special consideration due to the unique characteristics of the fuel and the double deck arrangement of the study configuration. These three areas–fueling, passenger loading, cabin and galley servicing–are discussed below, following a brief description of the airplane parking method and general service functions.

Many approaches were investigated to find solutions to the problems posed in these areas, that were compatible with airline/airport ground operations. The selected solutions are covered in this section of the document, with brief descriptions of alternate solutions contained in appendix C.

5.6.1 AIRCRAFT PARKING

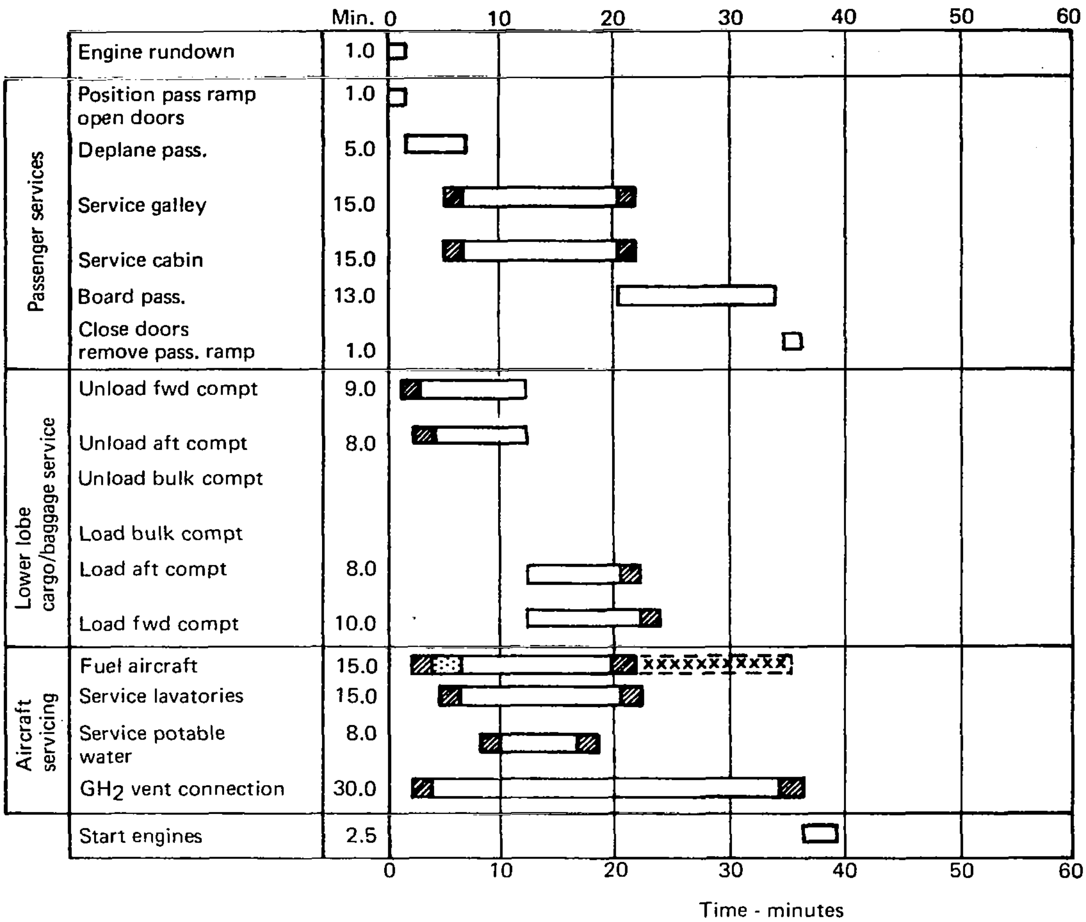
The LH_2 airplane will be parked nose-in to the terminal, however at some gates it may be necessary to park at an angle to allow sufficient clearance for ramp movements. It will dock under its own power, as is the present practice, and be moved out by a tug. In order to reduce the length of the passenger loading bridges and the refueling booms mounted on the building, the airplane will be parked approximately 4.57 m (15 ft) from the terminal building.

5.6.2 AIRPLANE SERVICING

As shown in figure 44, the airplane is serviced by conventional positioning of the servicing vehicles on the right hand side, leaving the left hand side for passenger loading. Since the body has an exceptionally high ground clearance of approximately 3.048 m (10 ft), compared to the 2.13 m (7 ft) to 2.43 m (8 ft) clearance of existing widebodies, the parking or movement of vehicles under the body and wing can be used to advantage.

Evaluation resulted in the identification of the following ramp services which can be provided using conventional equipment.

1. Potable water
2. Cargo loading
3. Lavatories
4. Conditioned air
5. Electrical power, air start, and air conditioning are services normally supplied by the APU. External connections for these services will be available.



Notes:

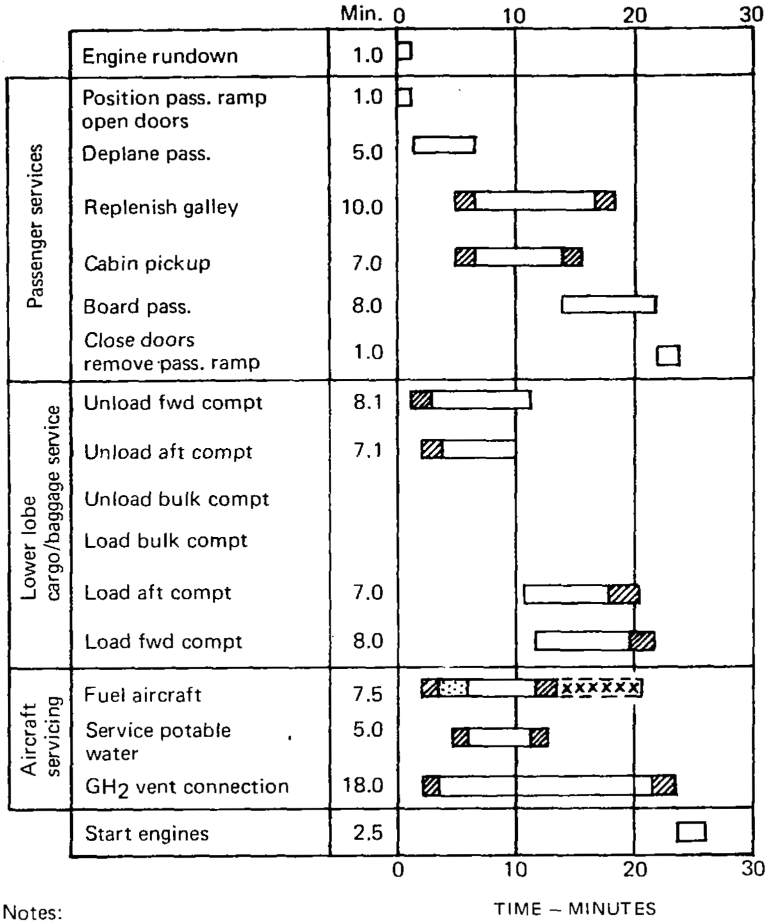
- 100% load factor, 100% passenger and baggage exchange
- 400 passengers handled using ramps at doors 1 and 2, left hand
- Half-width lower lobe baggage/cargo containers: 12 fwd, 14 aft
- 13 608 kg (30 000 lb) of LH_2. Hydrant fueling through service boom at 907.2 kg/min (2000 lb/min).
- Lavatory servicing using 1 truck single manifold system
- APU supplies electric power and engine start
- The time and capacities shown are for aircraft capabilities

Position/remove activity (not included in total time shown)

LH_2 tank blow down

[xxx] Possible overrun if all service ports in operation

Figure 42.—Servicing Time Estimate—LH_2 Aircraft (40 minute Turnaround)



Notes:

- 100% load factor, 60% passenger and baggage exchange
- 400 passengers on board. Passenger handling using ramps at doors 1 and 2, left hand
- Half-width lower lobe baggage/cargo containers: 10 fwd, 12 aft
- 6 804 kg (15 000 lb) LH_2 loaded. hydrant fueling through service boom at 907.2 kg/min (2000 lb/min)
- Lavatory servicing deferred to turnaround station
- Limited galley service
- APU supplies electric power and engine start
- The time and capacities shown are for aircraft capabilities

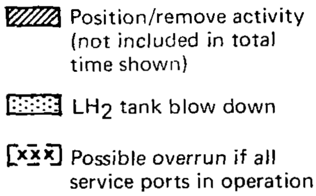


Figure 43.—Service Time Estimate—LH_2 Aircraft (25 Minute Through Stop)

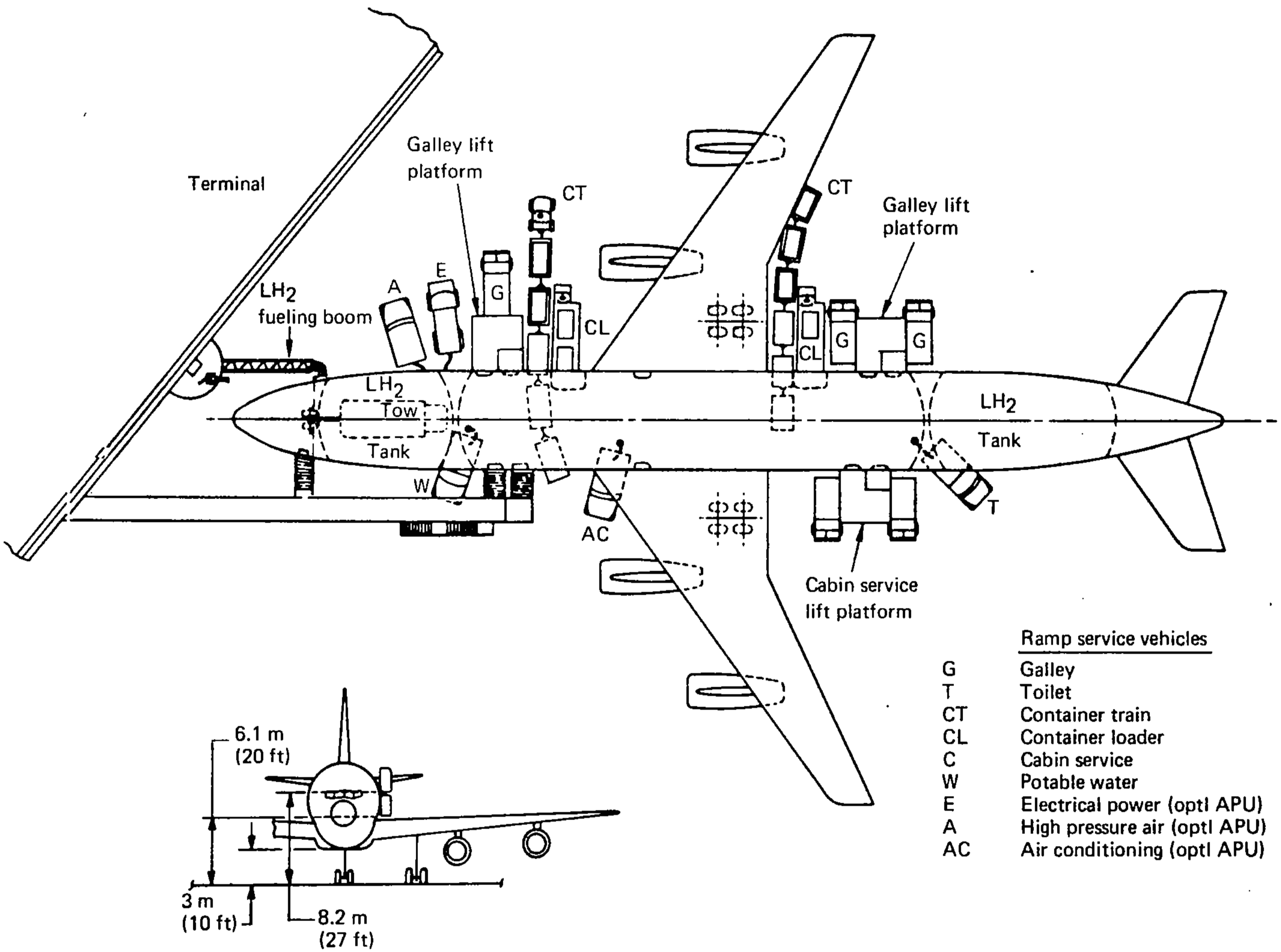


Figure 44.—Servicing Arrangement—LH$_2$ Aircraft

5.6.3 FUEL TRANSFER

Many concepts for transferring LH_2 to the airplane were investigated. The terminal mounted boom system at the right side of the forward LH_2 tank was chosen as the most acceptable arrangement.

Other concepts investigated, such as the hydrant-to-airplane LH_2 transfer truck, offered versatility in parking the airplane, but added to the congestion at the ramp. A fixed boom system built into the ramp reduced the congestion, but was expensive and limited airplane parking positions. These alternate systems are described in appendix C.

Terminal Boom Fueling Concept

As shown in figure 45, the selected fueling concept is by boom from the terminal building. The boom contains LH_2 supply and GH_2 vent lines which connect to the airplane at the forward fuel tank location. It is controlled by an operator in an enclosure at the base of the boom, who guides it to the airplane receptacle by means of electronic sighting controls.

The fueling receptacle is located in the right side of the forward fuselage to permit use of the air bridge by passengers and crew during the fueling cycle. The GH_2 vent line and the LH_2 supply line remain connected to the airplane, for recovery of hydrogen boiloff, while the airplane is parked. The height of the fueling receptacle is approximately 6.1 m (20 ft) above the ground, which would be compatible with fueling from a tanker truck in remote locations.

The selected concept reduces the normal congestion caused by ground equipment in the ramp area and eliminates the potential of damage to the fueling hookup system by ground vehicles. It was reviewed by the airline subcontractor and Chicago Department of Aviation representatives and was recommended from the standpoint of airline and airport operations. Modifications to this basic concept, which have merit but require further study, are contained in appendix C.

LH_2 Tanker Truck

Figure 46 shows a tanker truck LH_2 fueling and vent recovery system, with remote controlled booms for connecting to the airplane receptacles. The truck has a capacity of 56 775 liters (15 000 gal). Both the fuel tank and the fuel vent connect lines on the truck are insulated.

The tanker truck is used to fuel or defuel LH_2 airplanes parked at remote places such as maintenance or cargo areas. The tanker truck also will be used to offload LH_2 from a disabled airplane in preparation for recovery operations. The boom system is controlled by the driver of the truck and guided into the airplane receptacles by electronic sighting controls. The truck design also incorporates a hydrogen leak detection system and an extinguishing agent for control of fires. Each airport servicing LH_2 airplanes will need the services of one or more of these trucks. The use of the tanker truck as the principal means of fueling would be slow, expensive and would congest the ramp areas.

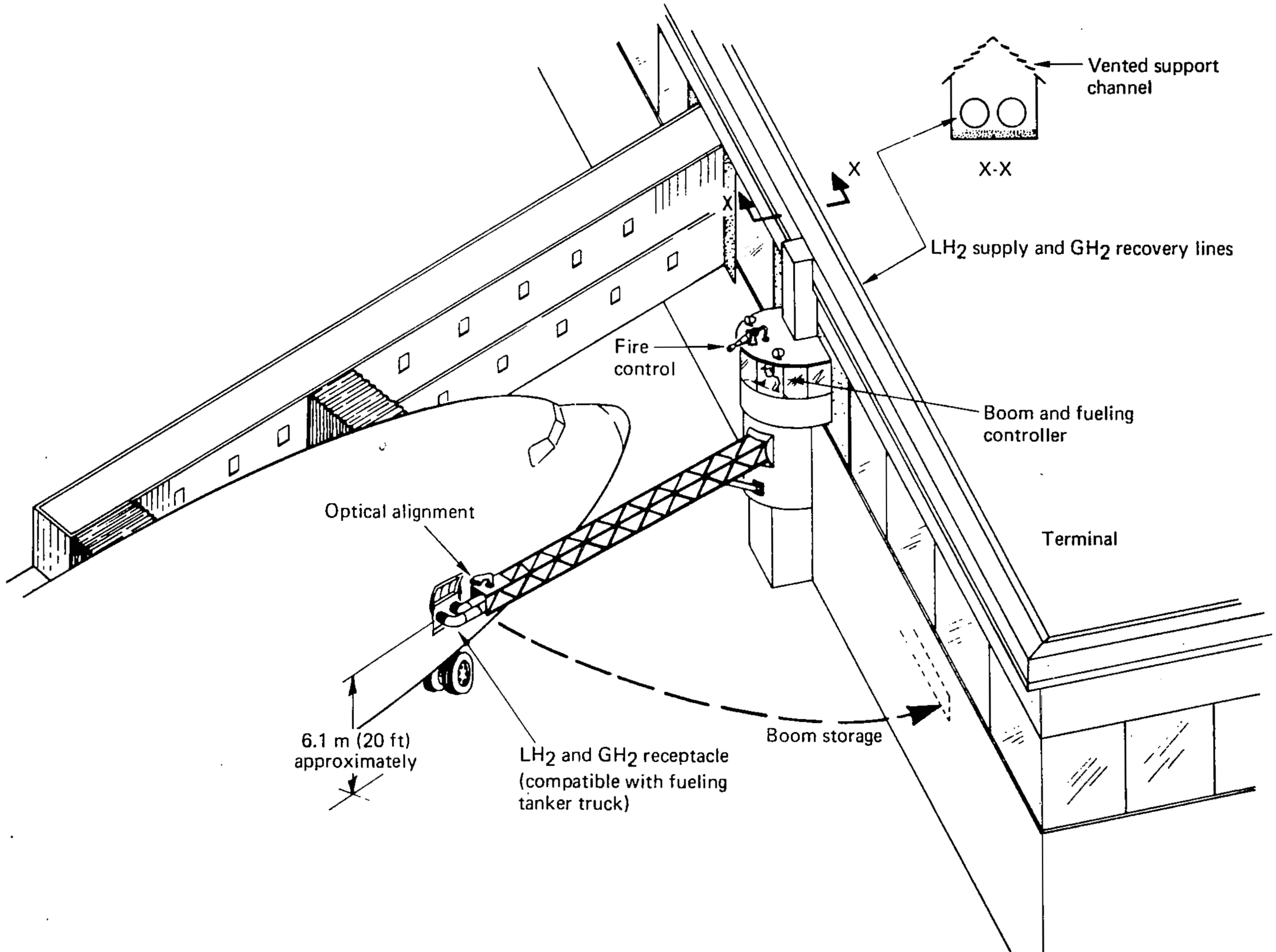


Figure 45.—Air Terminal Boom Fueling System

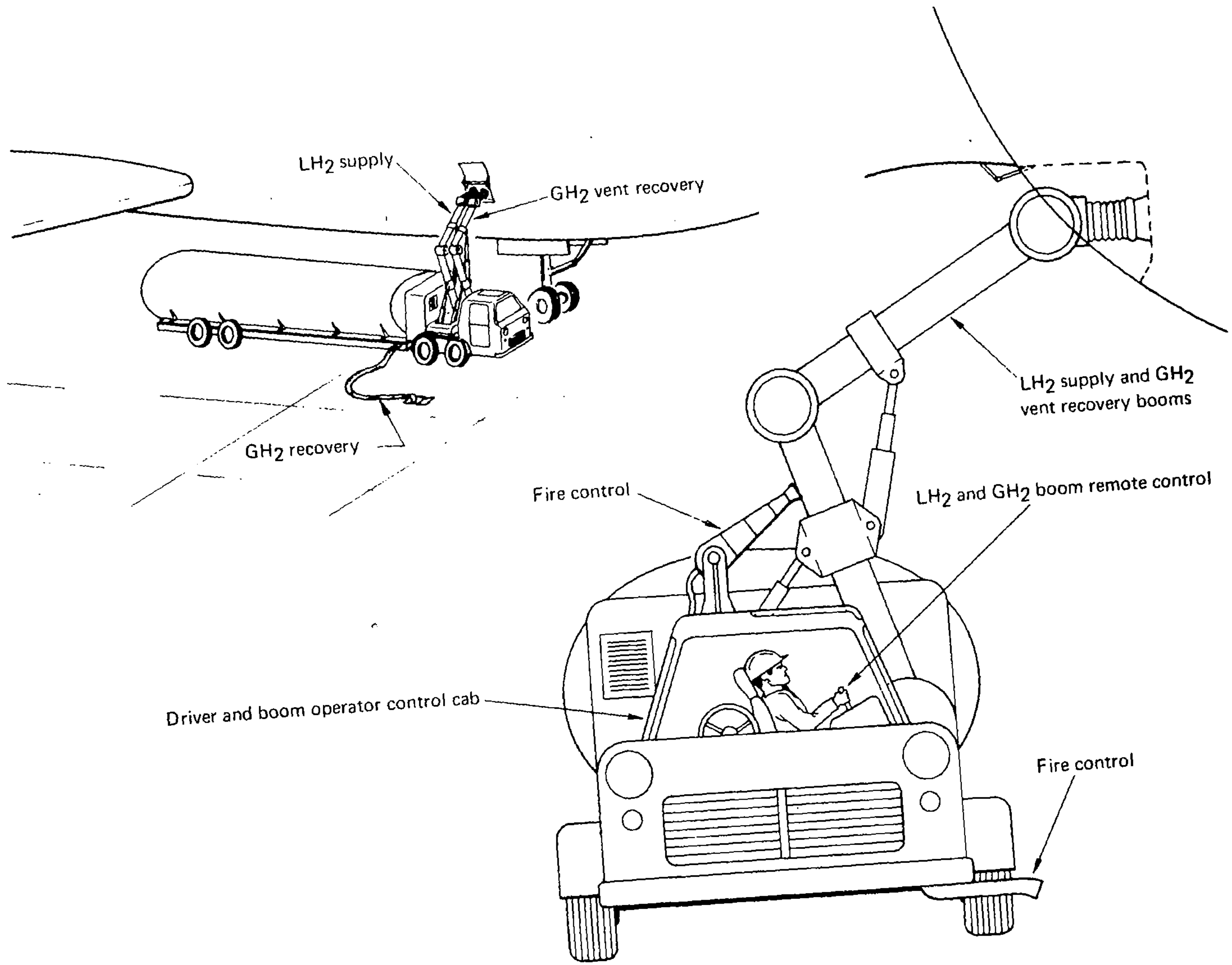


Figure 46.—Liquid Hydrogen Tanker Truck

5.6.4 PASSENGER LOADING–DOUBLE DECK BRIDGE

Figure 47 shows the preferred method of loading passengers into the upper and lower decks of the LH_2 airplane. The bridge is a single enclosed unit with two decks fixed to the ramp and equipped with extendable ends at the airplane entry doors to adjust for various entry door positions.

The passenger terminal must be altered to establish the two levels for movement of passengers into the two-deck loading bridge. The upper level of the bridge will be reached by an escalator system or ramp within the terminal waiting area. This system was recommended by the airline subcontractor for ORD terminal facilities.

The use of mobile airstairs for loading passengers at remote parking sites would allow entry into only the lower deck. The passengers would be required to use the stairways in the airplane to reach the upper deck in this situation. An airstair system to reach the upper deck at 8.22 m (27 ft) height would require a sophisticated design which would not adapt to ramp mobility.

5.6.5 GALLEY SERVICE

Galley servicing will be similar to the present system of containerized loading from trucks. However, since the upper deck is 8.22 m (27 ft) and the lower deck is 6.09 m (20 ft) above ground, there is no existing equipment adaptable to service the galleys. A conventional galley service truck revised to reach the service door levels is not considered practical to meet requirements for wind stabilization at these heights. An alternate method, utilizing a stable lifting platform was selected.

Figure 48 shows a lifting platform designed to elevate galley containers to the height of the upper and lower decks. It is 3.9 m (12 ft) wide and has no chassis springs, to provide platform stability. It will span both upper and lower deck service doors without moving the unit. The unit will be confined to relatively low speed operation at the airport (no highway usage) because of its width and lack of springing. It could be self-propelled or towed into position. Galley containers will be delivered to the platforms by conventional low bed service trucks parked along side the platform.

The lifting platform is an expensive unit to build, however, it can also be used to support cabin cleaning and cargo loading. It would be the fastest method of servicing the upper deck galleys.

5.6.6 CABIN CLEANING

As shown in figure 44, the vehicle used to supply the cleaning crew is parked at the left-hand service doors and will utilize the lifting unit as designed for the galley service operation.

The cleaning operation is accomplished in the same manner as is now employed on widebody aircraft, except there are two crews to handle the upper and lower decks. The cleaning equipment is conventional.

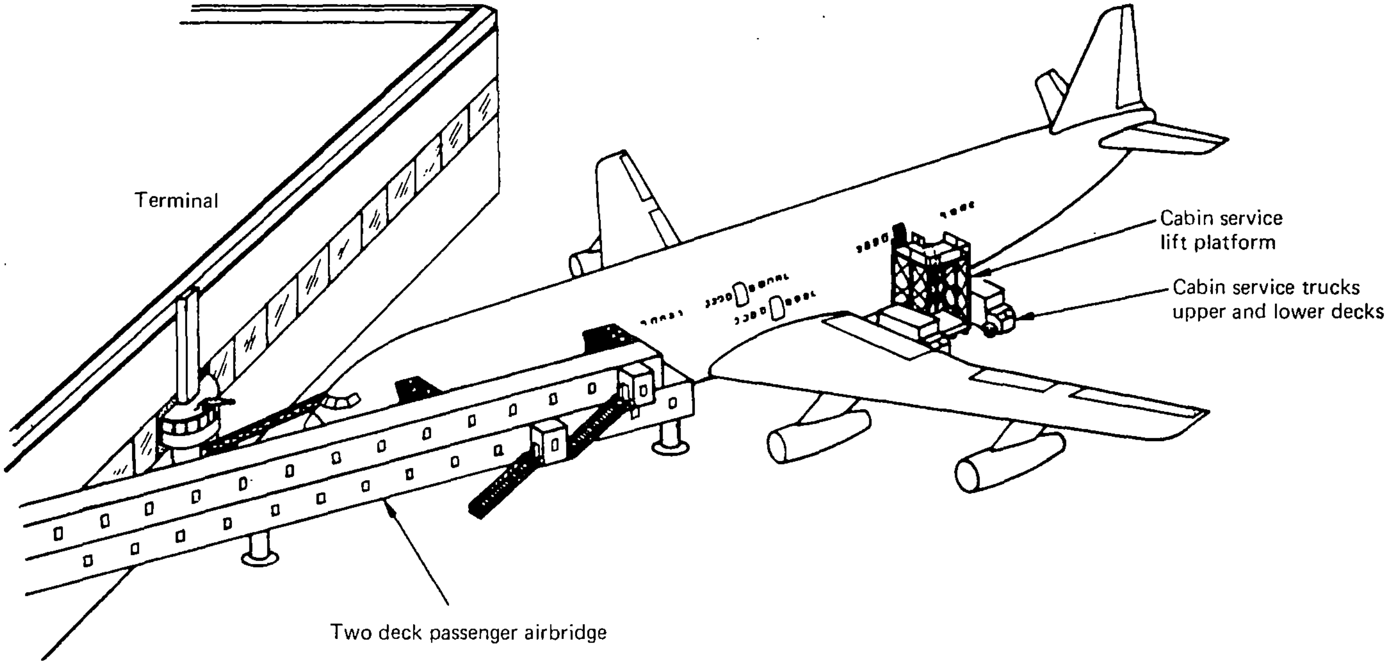


Figure 47.—Passenger Loading and Cabin Service

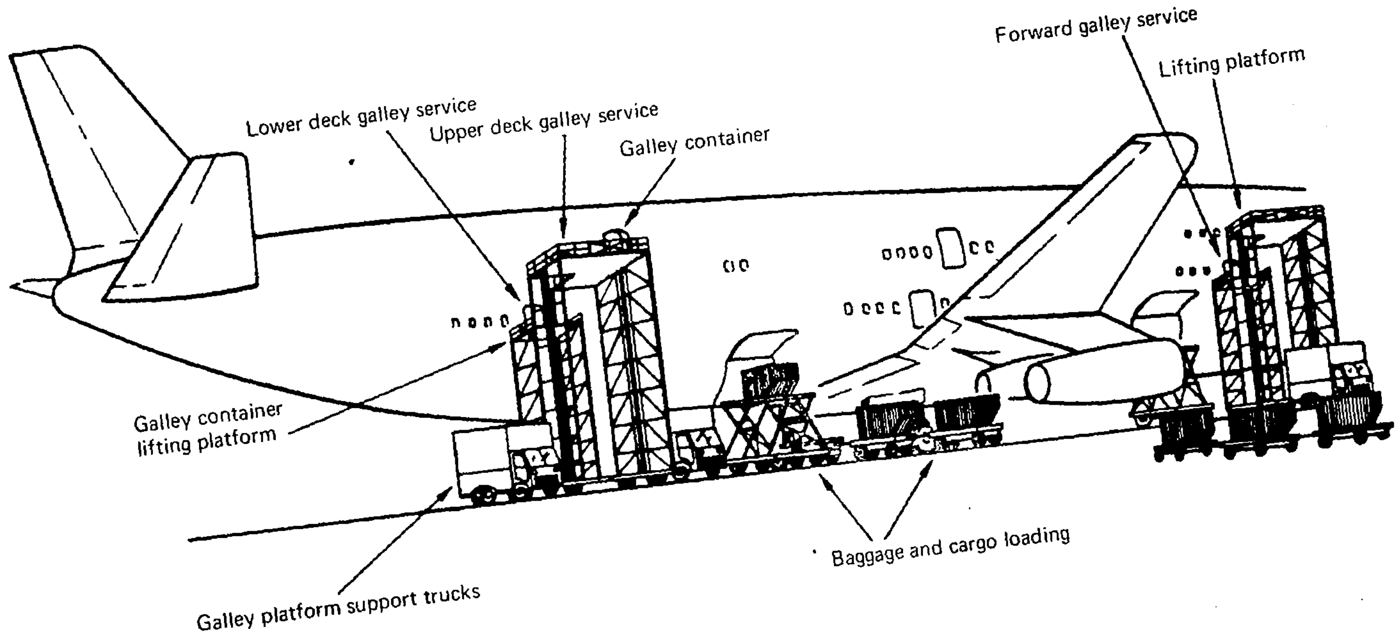


Figure 48.—Ramp Service to LH_2 Aircraft

5.6.7 MAINTENANCE CONCEPT

Major scheduled maintenance of liquid hydrogen airplanes will normally occur at the airline maintenance base. The present levels of maintenance currently accomplished on widebody airplanes at ORD will require changes in maintenance facilities only to the extent described in section 5.4.4.

Light maintenance and maintenance inspections will be conducted on the ramp at the same level and arrangement as for conventional widebody airplanes. The crews will be specially trained for the LH_2 airplane and will use equipment that is designed to be used on the LH_2 airplane.

5.7 EQUIPMENT, FACILITIES AND TRAINING

5.7.1 TERMINAL BUILDING MODIFICATIONS

The terminal concourse must be altered to accommodate the two-deck passenger loading bridge, as shown in figure 47. This change will include an additional ramp or escalator to reach the upper deck of the two-level passenger loading bridge. These provisions can be added to the existing passenger waiting areas and will require revision to the roof line, only, in the immediate area.

The terminal concourse also must be altered to incorporate the refueling boom system, as shown in figure 45. This change includes the boom operator's control center and boom support structure, mounted as a structurally independent unit on the existing terminal wall. The fire (or heat) control water spray system is installed on the building and boom control center. The LH_2 supply and GH_2 vent lines are contained in a vented channel mounted along the edge of the roof of the concourse, to avoid air conditioning system penthouses. The channels will not require alteration to the concourse structure.

5.7.2 MAINTENANCE HANGAR MODIFICATION

Since the maintenance hangars at ORD are used principally for light and emergency maintenance of widebody airplanes, plus programmed maintenance of some aircraft subsystems (not LH_2-related), the alterations to accommodate the LH_2 airplane will be minimal. There will be times when the airplane is parked inside with LH_2 on board, therefore, it is necessary to have a GH_2 recovery system in operation inside the hangar. This will consist of an extension of the recovery system from the passenger terminal area. The ventilation system in the hangars must be updated to have the capability of changing hydrogen-contaminated air volumes once every minute when the hydrogen leak sensing system initiates the alarm.

5.7.3 SPECIAL GROUND EQUIPMENT

Special equipment for ramp service includes the major equipment described in section 5.6, plus smaller items such as spark resistant wrenches, flame resistant clothing for some maintenance operations, and hydrogen leak detectors (portable and stationary).

5.7.4 PERSONNEL AND TRAINING–MAINTENANCE AND OPERATIONS

Personnel shall be thoroughly trained to understand the properties and characteristics of liquid hydrogen. They must understand the potential hazards, how to recognize unsafe situations and how to remedy them quickly. Maintenance personnel will be thoroughly familiar with hydrogen fire fighting techniques.

More study is needed on the techniques of fighting LH_2 fires. Since the potential of fire, if LH_2 is spilled, is imminent, and the fire burns at maximum intensity within seconds, maintenance personnel will probably be the only people available to control the fire. Therefore, they must be well trained in proper and safe fire fighting methods. This training must be a continuing function of updating techniques and practices.

6.0 ALTERNATE CONCEPT

This section summarizes the results of an investigation into an alternate LH_2 fuel system concept which includes a new passenger terminal. The purpose of the new terminal is to provide physical separation between the fueling of LH_2-fueled airplanes from those using JP fuel.

6.1 CONCEPT DESCRIPTION

The basic approach to this concept was based on the assumption that a facility separate from the current O'Hare passenger terminal would be provided to accommodate LH_2 aircraft. Since future plans for this airport include a new international passenger terminal, and since some of the aircraft that serve international traffic are widebody, a concept that serves both international and domestic LH_2 aircraft was selected for study. Several possible sites were discussed with the airport authority. A site south of Runway 9R-27L and west of Runway 14R-32L, as shown in figure 49, was selected.

6.1.1 REQUIREMENTS

Utilizing the concept of a separate facility for loading international and domestic LH_2-aircraft results in the following requirements:

- Passenger terminal accommodating the widebody domestic passenger fleet

- Passenger terminal accommodating the widebody international passenger fleet

- Passenger terminal accommodating the narrowbody international passenger fleet

- Separation of fueling operations–that is, separate aprons for loading widebody airplanes with liquid hydrogen and for loading narrowbody airplanes with JP fuel

- Segregation of international passengers from domestic passengers

6.1.2 SELECTED TERMINAL CONFIGURATION

A potential configuration for a new terminal which satisfies the requirements shown above is illustrated in figure 50. It is divided into three parts: domestic concourse, international concourse, and passenger services. A change in passenger boarding gate utilization is reflected in this concept. Boarding gate space in the existing ORD terminal (and in domestic terminals generally) is leased to, and dedicated to the use of, a single airline. However, in this concept gates are assigned to requestors on a schedule demand basis. During congested periods when gate demand is high, gate occupancy time is limited to a specific time period. If the unloaded airplane is scheduled for an extended ground time before departure, it is required to move to a layover position, where hydrogen tank venting facilities are provided.

The domestic concourse is shown serving 14 LH_2 airplanes which contain 5600 seats (14 x 400). At 17 650 m^2 (190 000 ft^2), this concourse has a ratio of area to available seats of 3.2 m^2 (34 ft^2) per seat. It is therefore ample to serve the boarding lounge area requirement of reference 7. The 14 LH_2 airplanes also are parked in accordance with the requirements of reference 7.

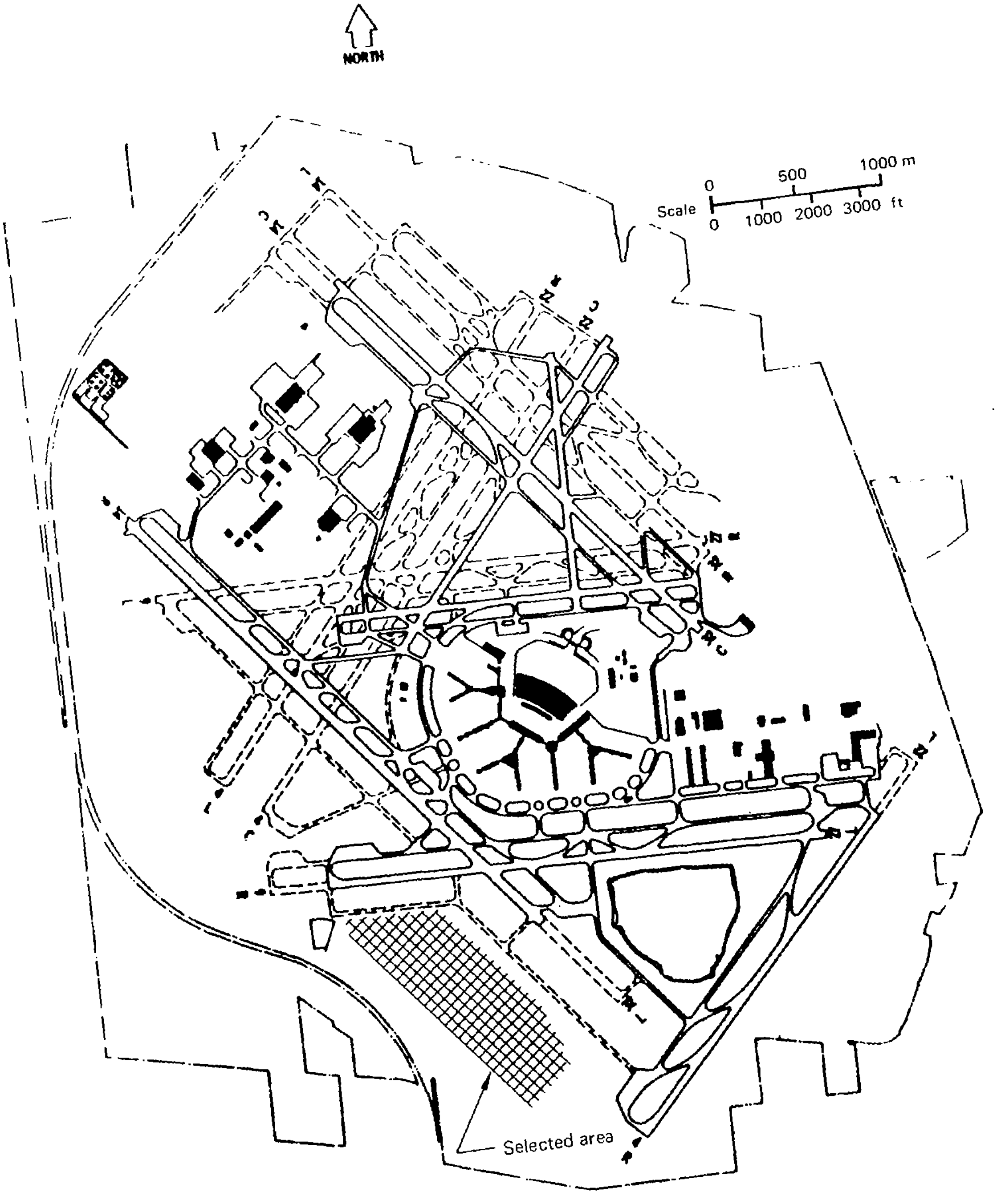


Figure 49.—Site Location—Alternate Concept

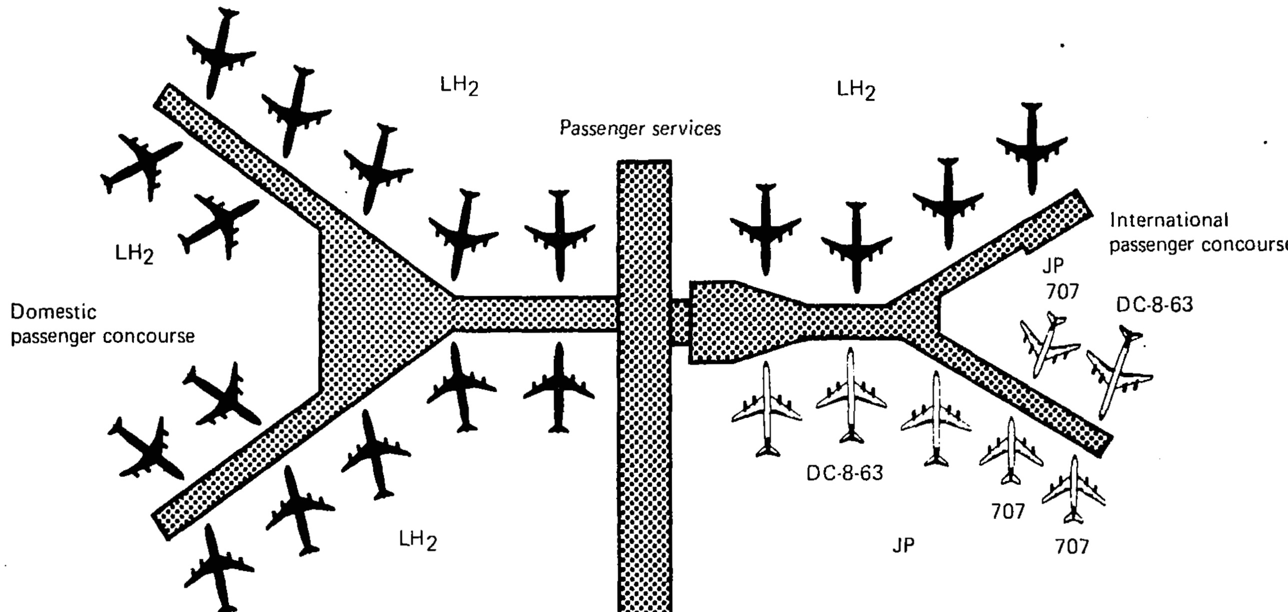


Figure 50.—Passenger Terminal—Alternate Concept

The international concourse is a duplicate of the B-C Concourse presently handling all international passenger traffic at the existing ORD terminal. It is shown serving four widebody LH_2 airplanes along one side, with the other side accommodating seven narrowbody, JP-fueled airplanes. All airplanes are parked according to reference 7.

Traffic schedules require gates for four widebody and five narrowbody airplanes during a peak 1-hour period. The parking arrangement shown is adequate to the demand. Since maximum demand for narrowbody gates occurs at different hours of the day than that of widebody, then theoretically, the 2 narrowbody gates shown inside the "Y" could be "swing" space-equipped to handle either two small or one large airplane at different times.

The underlying objective for presenting this concept is to provide for separation of fueling operations–isolate JP fueling from LH_2 fueling. The terminal layout and parking arrangement shown accomplishes that objective by shielding the JP-fueling apron with the projections of the building. There is no direct line-of-sight between a parked narrowbody (JP-fueled) airplane and a parked widebody LH_2 airplane.

6.1.3 HYDROGEN LIQUEFACTION AND STORAGE

The airport surface area between the conceptual "separate fueling" terminal and the airport perimeter road (relocated Irving Park Road) is utilized for facilities required to liquefy and store the hydrogen fuel. After providing safety isolation from the public roads and nearest runways, this plot amply fulfills the space requirement for LH_2 facilities, and is located adjacent to rail service. Figure 51 is a plot plan showing the location of these new facilities.

6.1.4 DISTRIBUTION SYSTEM

As in the baseline concept, all underground hydrogen distribution lines are installed in tunnels. Figure 52 shows the routing of this piping in the vicinity of the new passenger terminal.

6.2 LH_2 SYSTEM

The fuel system serving widebody airplanes at the alternate terminal, as well as at the cargo and maintenance areas, is shown in figure 53. The same basic three-line system is used as in the baseline concept, with the prime difference being that complete separation between LH_2 and JP fuel is provided.

6.2.1 LIQUEFACTION AND STORAGE

A schematic of the alternate LH_2 ground system is presented in figure 54. The liquefaction plant and storage area are located to the south of and adjacent to the new terminal.

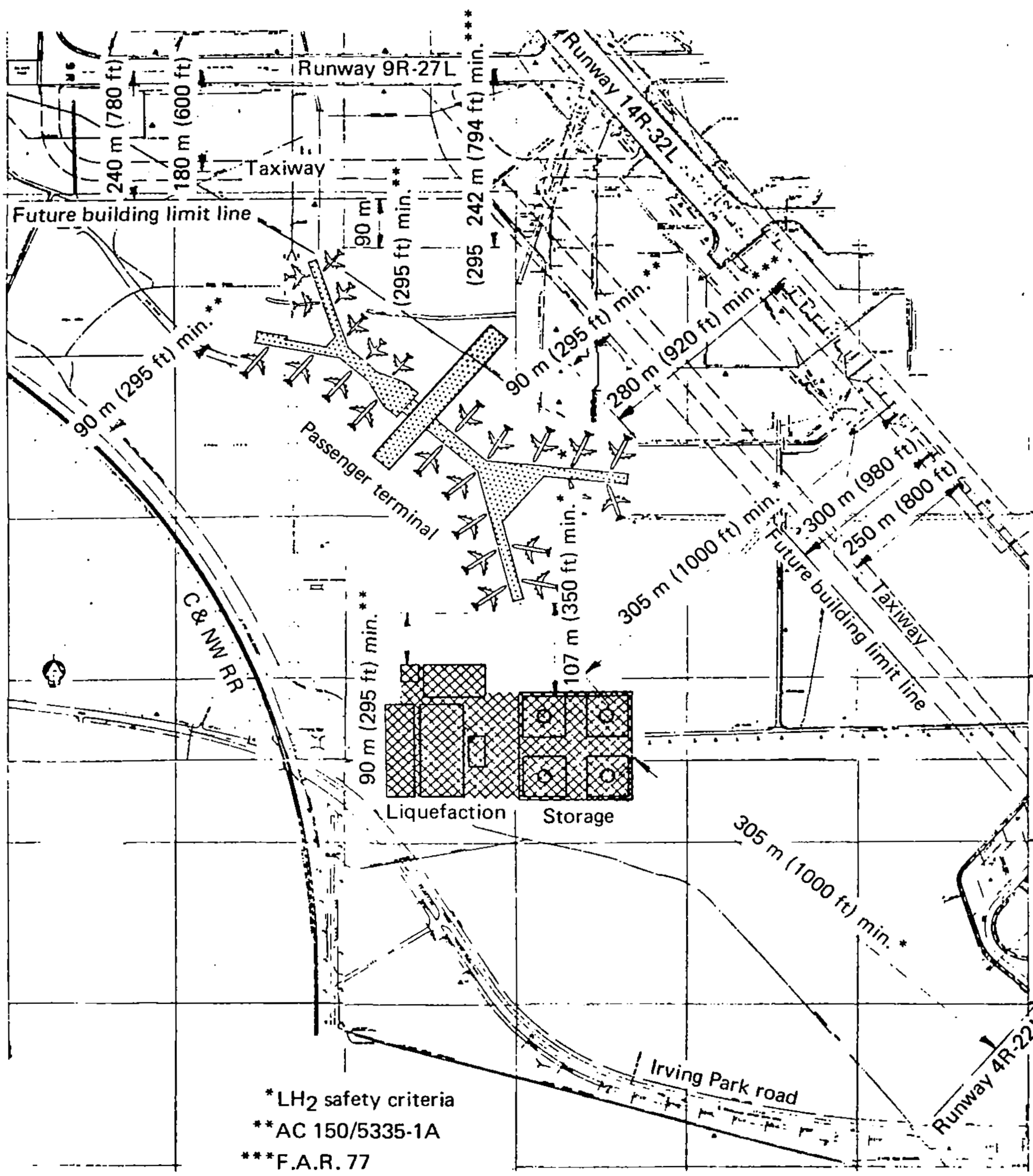
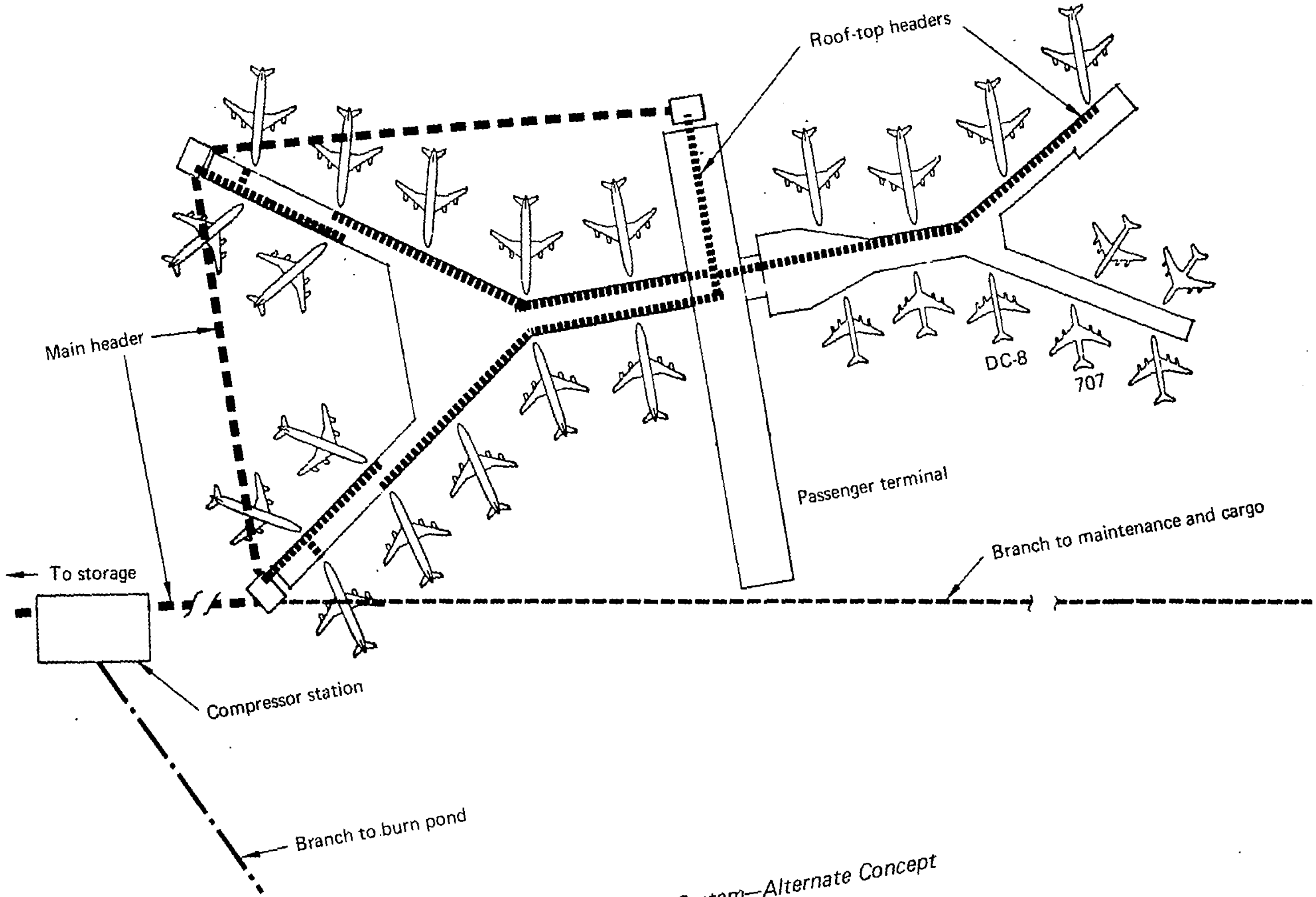


Figure 51.—Plot Plan—Alternate Concept



...ution System—Alternate Concept

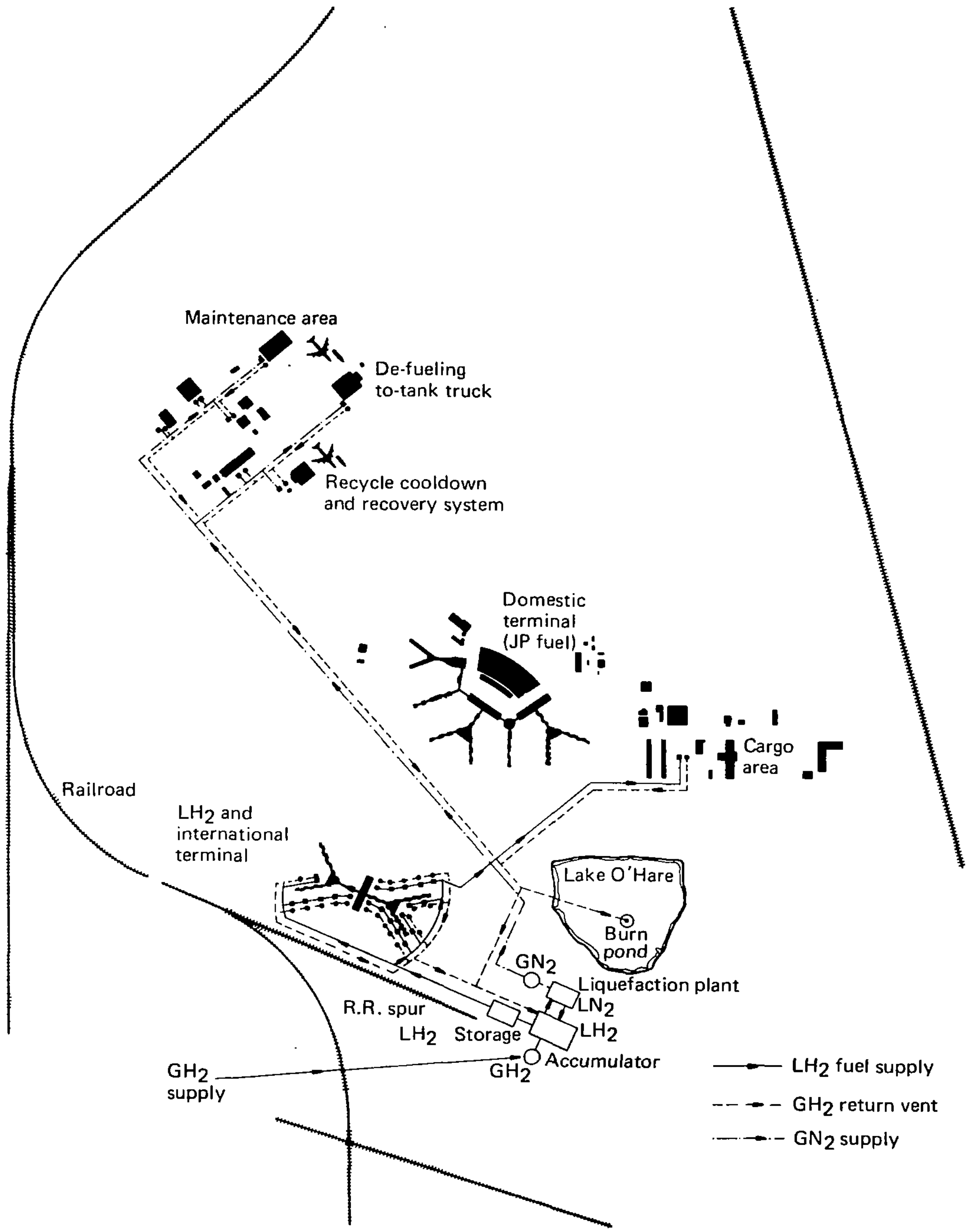


Figure 53.—Fuel System—Alternate Concept

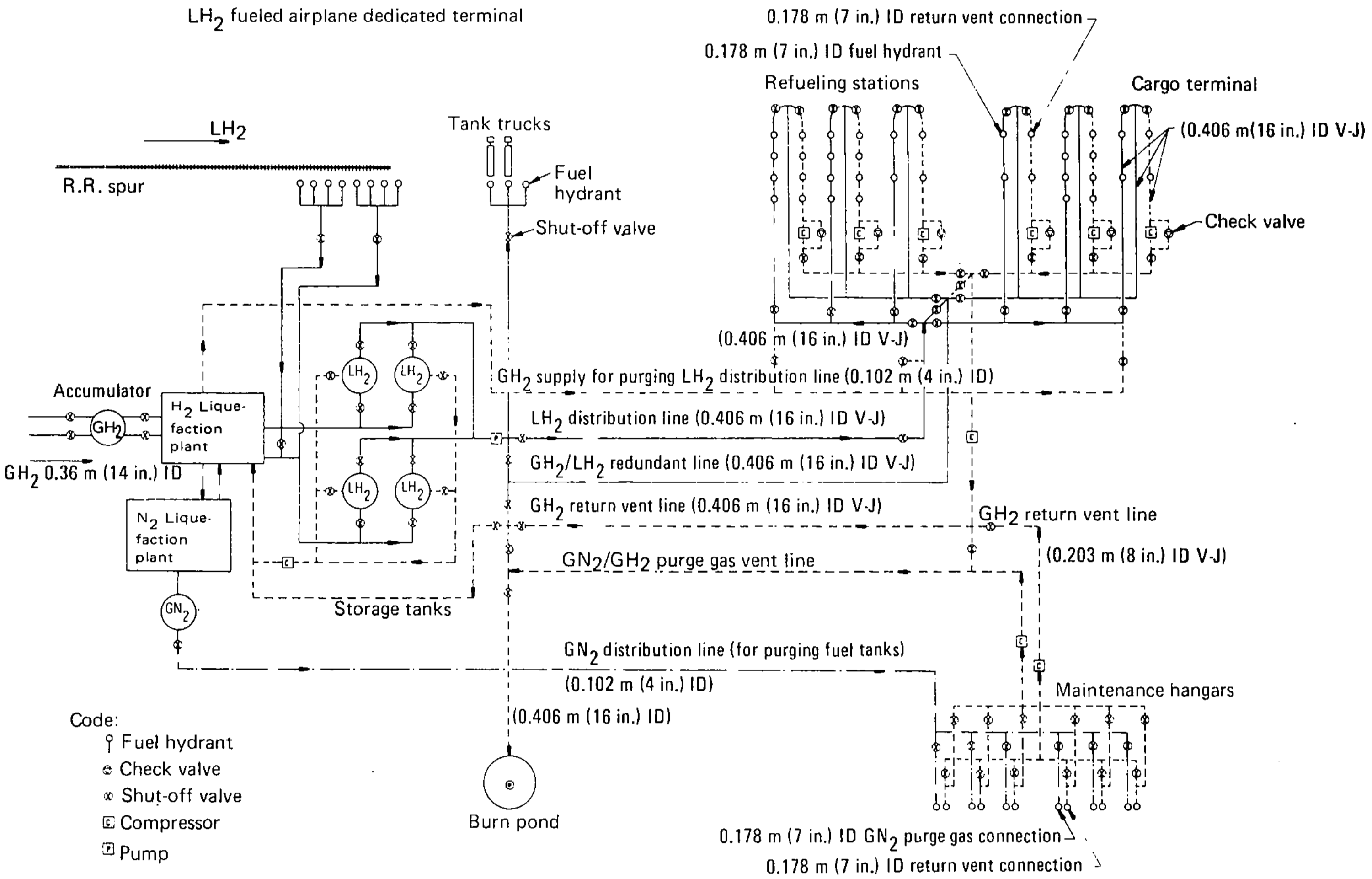


Figure 54.—Fuel System Schematic—Alternate Concept

6.2.2 DISTRIBUTION SYSTEM

LH_2 supply and vent return lines are essentially the same as the baseline system except the distribution and return lines are considerably shorter, with the number of hydrants and return vent connections reduced. A redundant line extends from the LH_2 pumping station to the end of each passenger terminal branch line. This redundant line serves as a back-up system and can be used as either LH_2 supply or GH_2 return vent in the event the main trunk or any of the branch lines must be shut down for maintenance work. Distribution system line diameters and liquefaction plant capacity are the same as the baseline system.

6.3 GROUND OPERATIONS

Airplane servicing and line maintenance functions, normally accomplished at the passenger gates during turnaround/through-stops, would be carried out essentially as described in section 5.6 for the baseline concept. However, there are two aspects of ground operations that would be affected. Both are related to the passenger terminal side of operations, rather than the airplane side.

Domestic through-passengers changing airplanes at ORD are required to transfer between terminals when their arrival and departure flights are in different types of aircraft (LH_2-fueled versus JP-fueled). This is an inconvenience to the passenger, even if accomplished via an underground rapid transit system. Moreover, the airlines have learned through experience that a split operation of this type results in lost patronage. Passengers will seek an alternate departure flight (alternate airline) rather than be inconvenienced by the transfer from one terminal to another. Airlines operating out of both terminals would have to provide expedient baggage transfer and probably some inducement to passengers to prevent a potential loss of traffic.

The alternate concept, as developed in this study, includes a terminal building tailored to the requirements of ORD domestic LH_2 and all international traffic. It provides only the number of gates necessary to accommodate those segments of the traffic. As a result, gates and concourse areas would be utilized by the various airlines on a demand basis, rather than by assigned or leased areas. This concept of operation is undesirable from the airline standpoint because of gate scheduling problems associated with arrival or departure flight delays. It also produces passenger confusion and irritation. These unfavorable aspects of operation could be overcome with additional personnel for gate scheduling and for directing passengers/visitors to the proper gates.

7.0 ANCILLARY STUDIES

The mainstream study effort was devoted to investigation of a set of factors combined to produce the most feasible air terminal concepts, considering overall airport and airline operations. These factors included GH_2 delivery to the airport, the internal tank airplane configuration, fueling at passenger gates through an installed system and the assumption of ORD as an element of a mature LH_2 air transportation system.

In the following paragraphs results of evaluating the effects of some alternate factors, applied to the baseline concept, are reported. These include: (1) the impact of LH_2 delivery on the airport hydrogen fuel system, (2) the impact of a fleet of external tank airplanes on fuel requirements and LH_2 plant size, (3) qualitative analyses of fueling at a remote area, (4) fueling by tanker truck at passenger gates, and (5) the development of a potential scenario showing the impact on ORD of a domestic LH_2 air transportation system during introduction and evolution into a mature system.

7.1 LH_2 DELIVERY TO AIRPORT

In this alternative to the baseline concept, LH_2 rather than GH_2, is delivered to an airport storage facility by railroad tank cars and/or tank trucks. The objectives established for the baseline concept in section 5.0 were also applied to this concept. Figure 55 identifies and locates the major system components.

7.1.1 HYDROGEN SYSTEM DESCRIPTION

Figure 56 is a layout of the hydrogen system. The primary distribution and vent return portion of the system and their operation are identical to the baseline concept described in section 5.3.3. The primary differences between this concept and the baseline are the size and function of the liquefaction plant and the capacity and facilities for loading the storage tank farm.

LH_2 Storage

Liquid hydrogen is stored in six spherical tanks. The total capacity of these tanks (2 176 800 kg (2400 tons)) is equivalent to a 3-day LH_2 fuel demand to account for the greater likelihood of supply disruption due to railroad or highway problems. Four of the tanks are maintained in a full condition to provide sufficient fuel reserve in the event of interruption in fuel shipment caused by various reasons. The other two tanks are used as active storage to handle the daily variations in full demand and vent gas reliquefaction. Approximately 64 800 m^2 (16 acres) of clear land is required for the storage facility.

LH_2 Delivery

Two alternatives, rail and tank truck, were considered for delivery of LH_2 to the airport. (A third delivery method, by pipeline from an LH_2 plant adjacent to the airport, might also be attractive if additional markets developed in the immediate area-lower LH_2 costs might result from the expanded operation. Evaluation of this potential concept was beyond the scope of this study.)

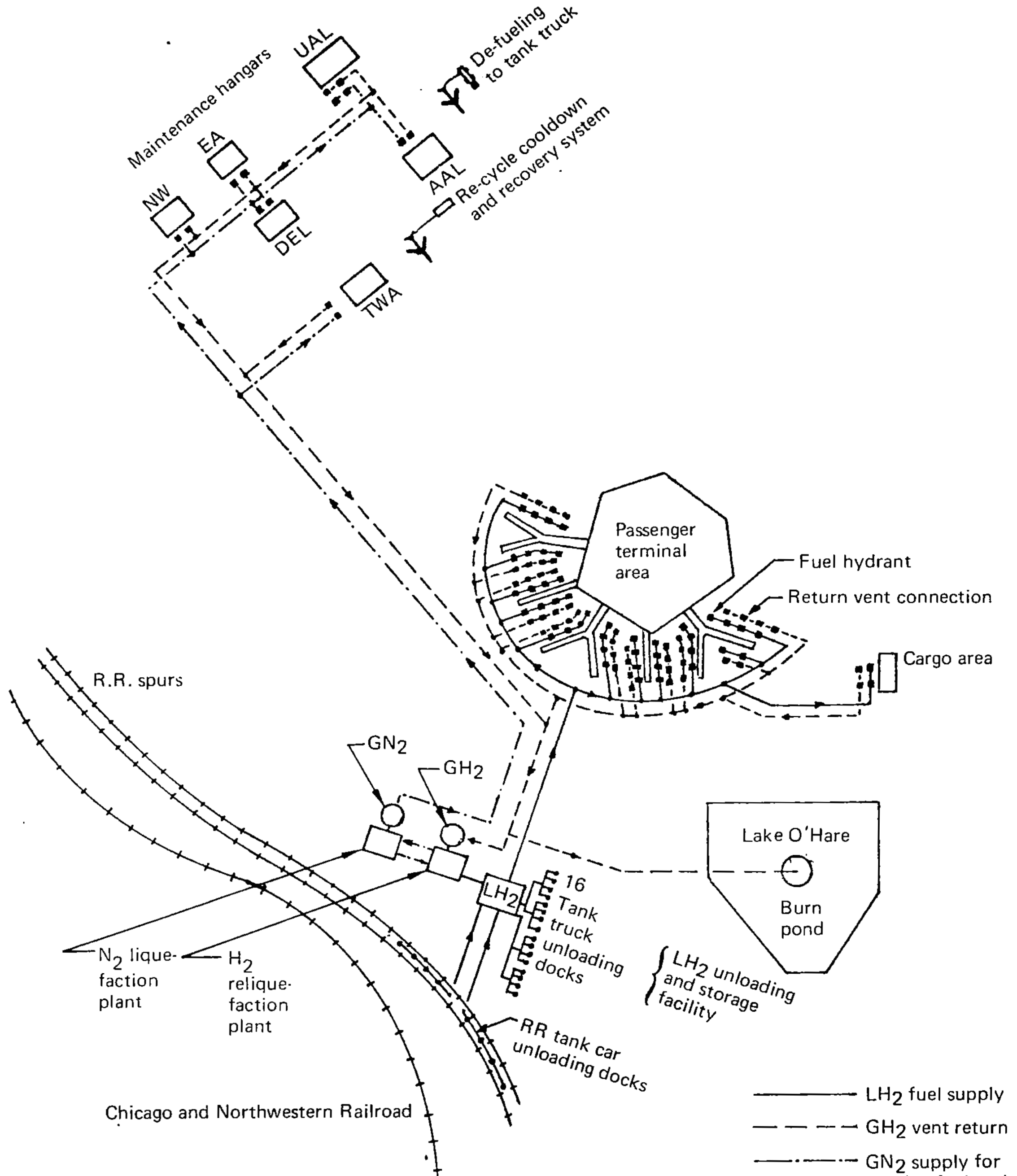


Figure 55.—Fuel System—LH_2 Delivery

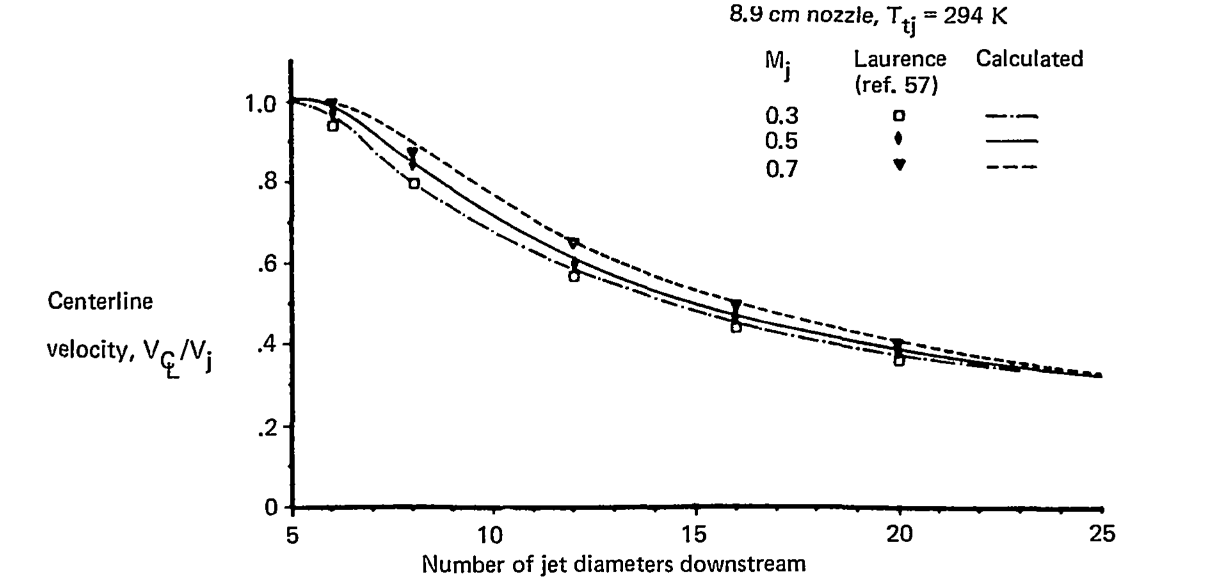


Figure 56.—Centerline Velocity Decay of a Single Subsonic Round Jet, No Ambient Flow

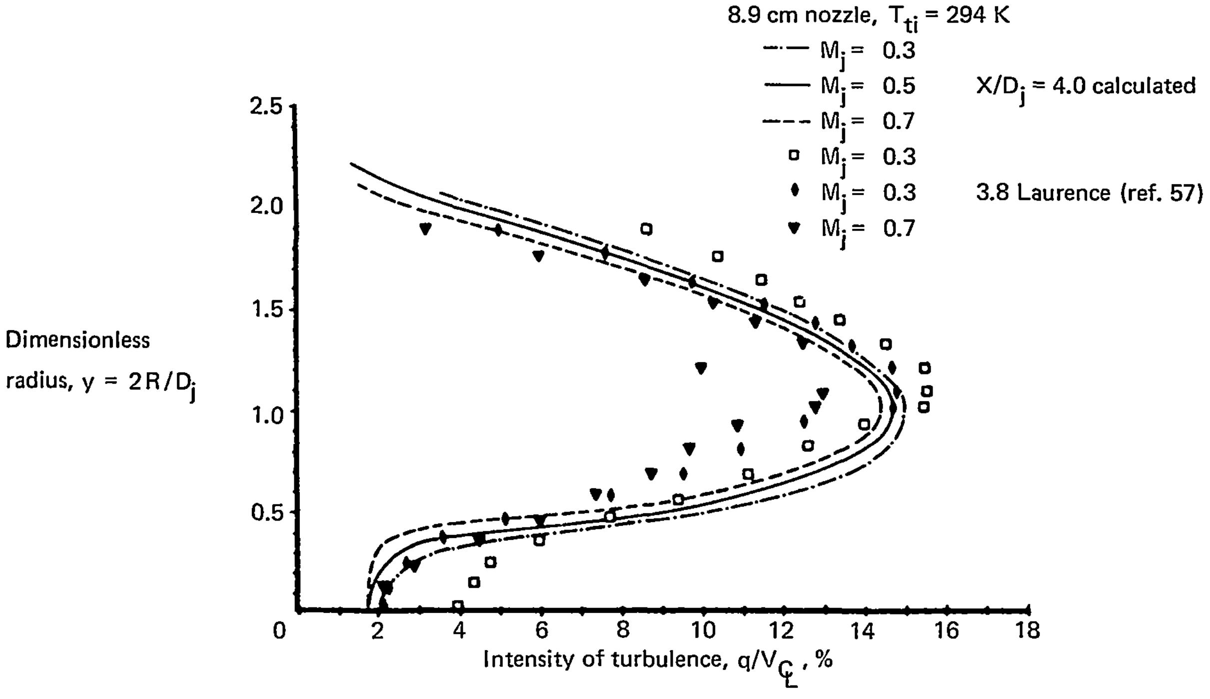


Figure 57.—Turbulence Intensity of a Single Subsonic Round Jet Near the End of the Jet Core, No Ambient Flow

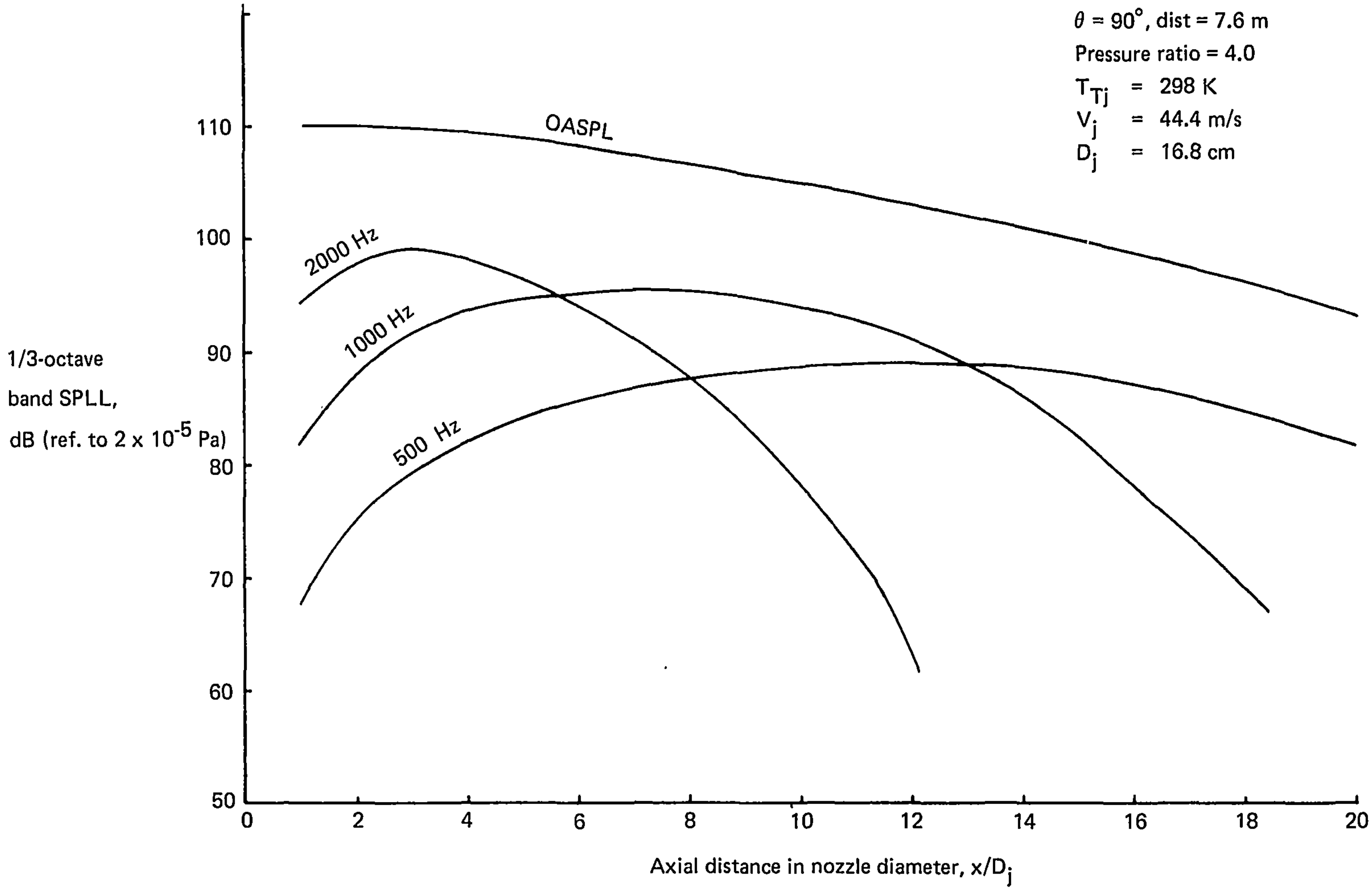


Figure 58.—Overall and 1/3-Octave Band Sound Pressure Levels Per 1-Die Length of Jet Versus Axial Distance From Nozzle Exit

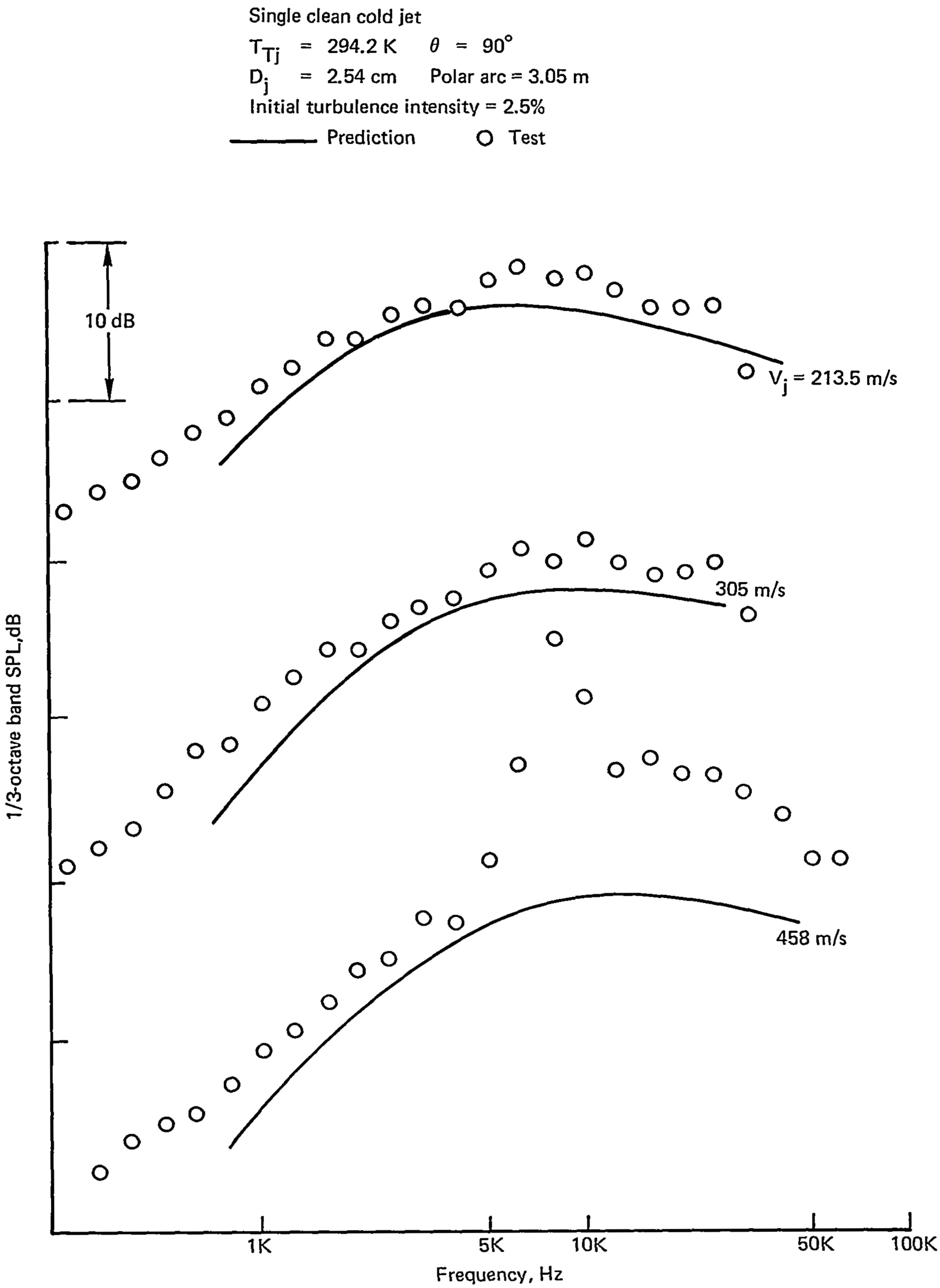


Figure 59.—Spectral Comparison (Single Jet), Flow/Noise Program

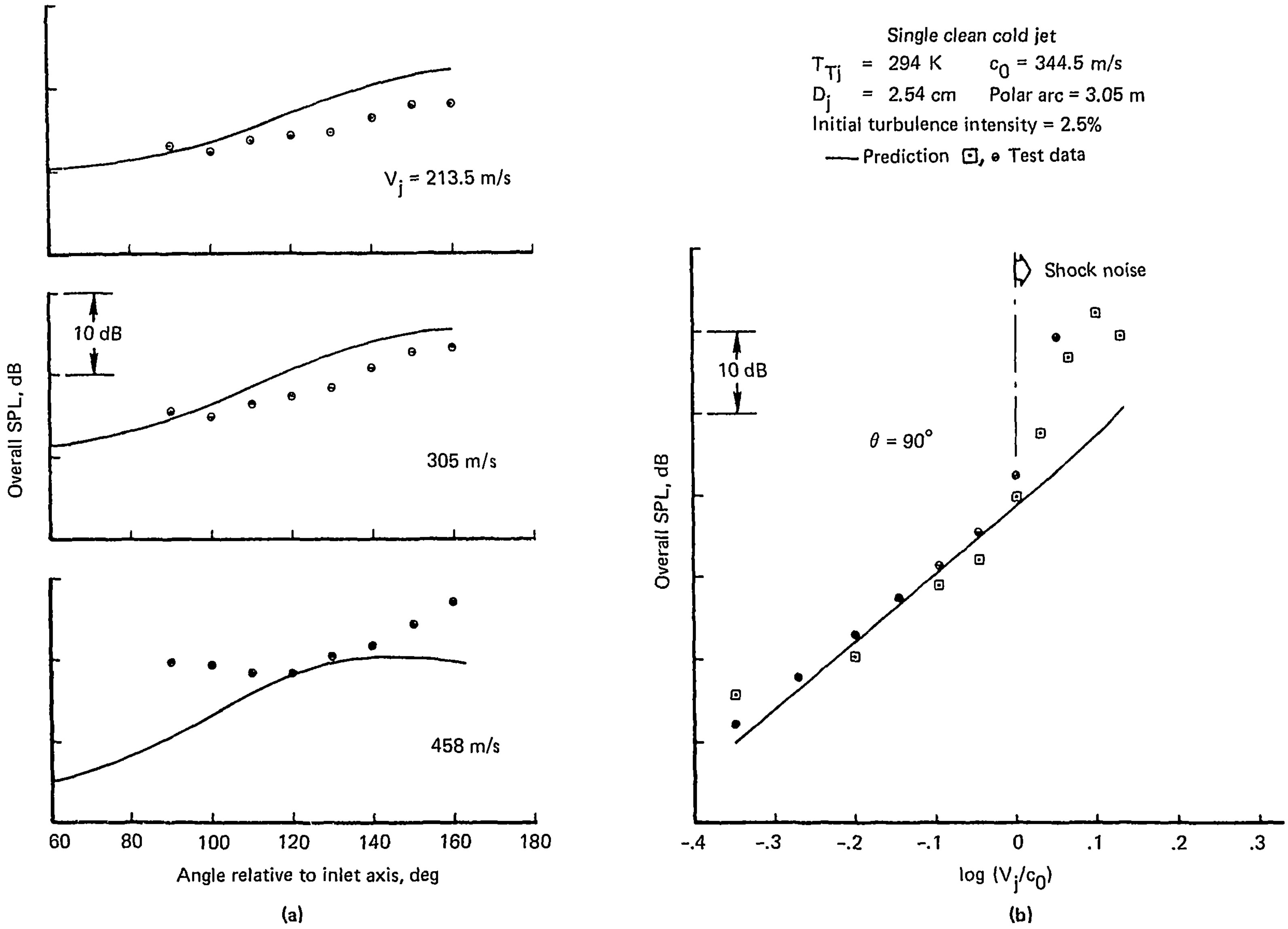


Figure 60.—Overall Sound Pressure Level Comparisons (Single Jet), Flow/Noise Program

7.1.3 GROUND OPERATIONS

Airline operations at the airport are identical to those described for the baseline system. A possibly greater chance for hydrogen delivery interruption resulting from weather or accident has been accounted for by increased LH_2 storage capacity. There is, however, a possibility for an airport shutdown resulting from a prolonged rail/truck industry strike. No method was found for reasonably counteracting this possibility.

7.2 EXTERNAL TANK AIRPLANE

7.2.1 EXTERNAL TANK AIRPLANE CHARACTERISTICS

The external tank airplane configuration of reference 1 is shown in figure 59. The configuration has a design maximum gross weight of 198 132 kg (436 800 lb), a maximum payload of 39 917 kg (88 000 lb), a design range of 10 186 km (5500 nmi) and a cruise Mach number of 0.85. The airplane has an operating empty weight of 121 474 kg (267 800 lb) and carries a total fuel weight of 36 742 kg (81 000 lb). This configuration is very distinctive because of the very large fuel tanks, 31 m (101 ft) long by 4.6 m (15 ft) diameter, mounted over both wings. (Each tank is slightly larger than the fuselage of a Boeing 737 airplane.)

This configuration was not selected to be the baseline LH_2 airplane because of its much higher fuel usage. For example, over the short ranges which constitute most of the ORD traffic, the external tank configuration requires almost 40% more block fuel and produces over twice the vented GH_2. Because of its high fuel consumption, analysis of this configuration was pursued only to determine its impact on ORD fuel requirements, in the event that the internal tank airplane was found to be unacceptable for technical or operational reasons.

7.2.2 IMPACT ON BASELINE LH_2 SYSTEM SIZE

The fuel requirements for a fleet of external tank LH_2 airplanes was determined using the same technique discussed in sections 4.4 and 4.5. The resultant fuel requirement is:

LH_2 EXTERNAL TANK FLEET BLOCK FUEL-ORD

Case 1.	Minimum LH_2 loaded for each mission – kg/Day (tons/day)	750 000 (825)
Case 2.	Tanks topped off for each mission–kg/Day (tons/day)	815 000 (900)

7.2.3 OPERATIONAL CONSIDERATIONS

The external tank LH_2 airplane could be serviced with the same equipment designed for the internal tank baseline configuration; however, there is a high potential for damage to the external tanks from galley loaders servicing the upper deck. The external tanks must be protected from damage due to engine burst, resulting in a weight penalty which would significantly degrade the performance of this configuration. Fuel tank

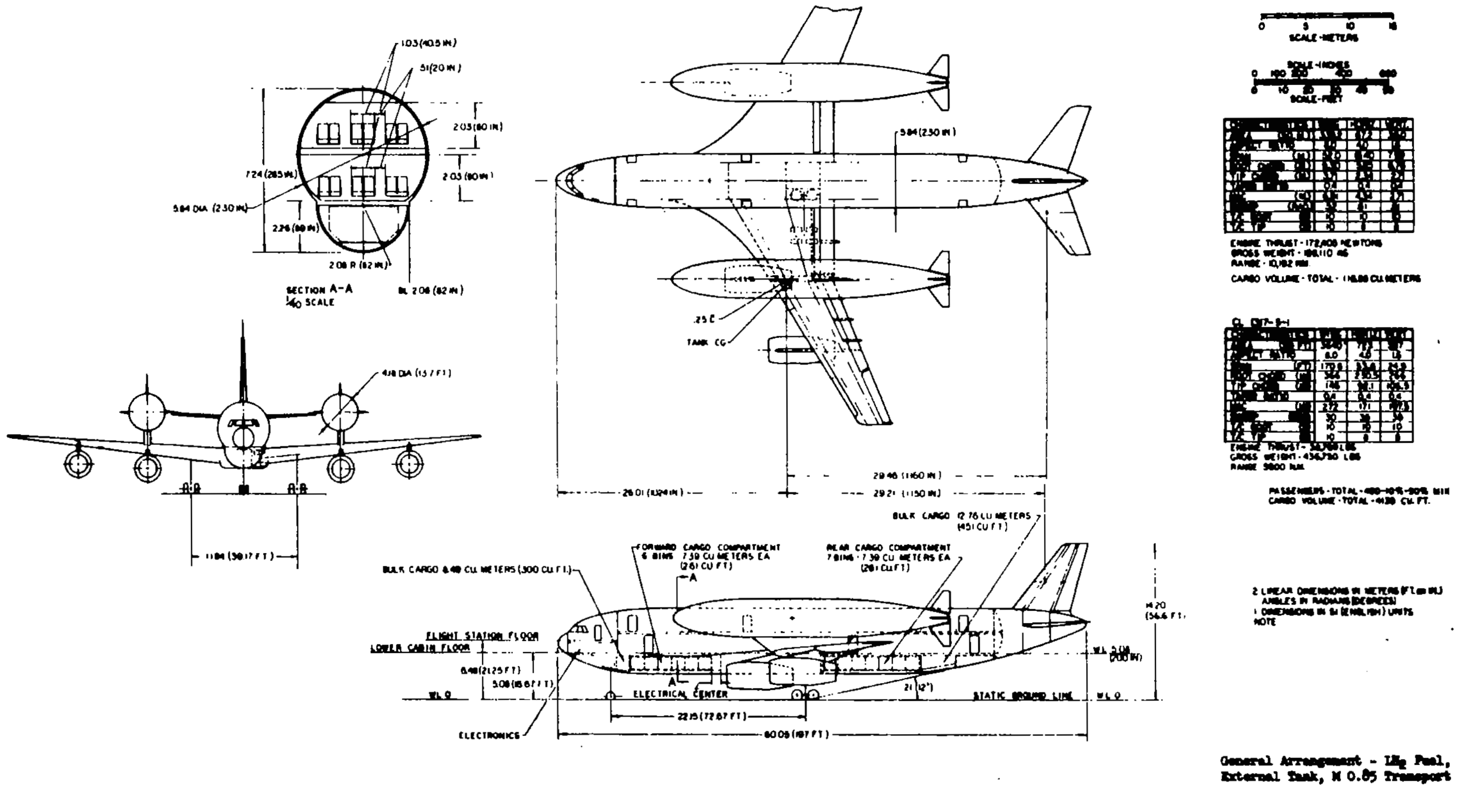


Figure 59.—External Tank Configuration

maintenance may be somewhat easier. The LH_2 tanks could be removed before the airplane is placed in a hangar, thereby eliminating a major fire hazard. There appears to be no other operational advantage of the external tank configuration over the internal tank baseline.

7.3 REMOTE FUELING CONSIDERATIONS

Remote fueling is defined herein as a concept in which fueling is accomplished in a dedicated area remote from the passenger terminal, before loading passengers and/or cargo. After fueling, the airplane is moved to a passenger gate, where passengers are enplaned and other normal service functions are performed.

Two benefits accrue to this concept. There is much less exposure of passengers and ground personnel to the possibility of a hydrogen-associated accident, and airport fuel system costs can be reduced by locating the fueling facility near the LH_2 storage area.

This concept was not considered to be valid for ORD because it would completely disrupt the complex traffic system at that airport. Some of the reasons for rejecting this method of fueling at ORD are listed below.

- ORD is a major hub airport with most of its widebody traffic involving through-flights; less than 10% of the flights originate at ORD. As a result, a large percentage of the flights are restricted to ground times of approximately 1 hour, or less. These short ground times would not be possible with remote fueling.

- The towing of LH_2 airplanes across active runways, to and from a refueling area, could not be tolerated at ORD. Landing and takeoff frequencies are greater than 1 per minute during several hours of the day. The two areas potentially available for a fueling station, that meet the runway constraint, are as far from the liquefaction plant site as is the passenger terminal, thereby nullifying any potential reduction in distribution system costs.

- Ground traffic (aircraft and ground vehicles) at ORD is currently at the saturation point, resulting in frequent delays in the ramp area, while awaiting taxi clearance to a gate. The additional taxiway and ramp congestion, caused by slowly towing aircraft to and from the fueling area, would further add to these delays. (The concept of transporting several busloads of passengers to and from each airplane would also be unacceptable from the standpoint of ground vehicle traffic congestion.)

A coastal airport, with a high percentage of originating widebody flights, might be more amenable to the remote fueling concept than an inland hub airport, such as ORD. Originating flights generally are preceded, at such airports, by ground times of from 1 hour to an overnight stay. Under these circumstances, flight schedules might be maintained using the remote fueling concept, depending on airport geometry and ramp area congestion.

7.4 TANK TRUCK FUELING

This concept is based on the concept that all fueling of LH_2 aircraft would be accomplished by tank truck. The LH_2 distribution system as described for the baseline and alternate concepts would be replaced by tank trucks shuttling between the liquefaction plant and the terminal areas. Hydrogen gas from the airplane tanks during blowdown, fueling and normal boiloff would be vented to the atmosphere. This would amount to about 72 600 kg (80 tons) per day.

It is estimated that 18 trucks of 56 800-l (15 000-gal) capacity would be required at the terminal gates during peak fueling demand time. An additional four trucks should satisfy cargo and maintenance area requirements, and eight additional trucks would be required to account for truck loading time, plant-to-gate shuttle time, and down time for maintenance. A total of 30 tank trucks results.

This method of fueling LH_2 airplanes at ORD was rejected because:

- The safety (and probably environmental) impact of venting 72 600 kg (80 tons) of hydrogen gas into the O'Hare atmosphere would be unacceptable.
- The long term cost of GH_2 lost in venting plus the cost of purchase and operation of the tanker trucks woulu increase system operating costs substantially, compared to the system which returns vented gas to the liquefaction plant.
- The added ground vehicle congestion would be unacceptable at ORD. This was verified by representatives of the Chicago Department of Aviation.

Although the tank truck concept of fueling might be suitable at airports with a low volume of widebody traffic, and must be available for use in maintenance areas and for emergency defueling, it would not be an acceptable method for general fueling at ORD.

7.5 AIR TRANSPORT SYSTEM IMPACT

Results of the mainstream study, which focused on the O'Hare airport, provided a basis for evaluating the broader implications that the introduction of LH_2 would have on the air transportation system. Several interrelated areas of interest become important during an evaluation of this nature. These include:

- Identity of airports that would be likely candidates for adapting to LH_2 transport operations
- Characteristics of LH_2 transports and ground support systems that are critical, or that lend themselves to initiation and buildup to a fully functioning system network
- Potential methods by which LH_2 transport operations could develop from the first LH_2 airplane and airport to a mature airplane/airport complex covering the domestic and worldwide route-network

- The relative timing involved to bring various system elements to an active status, considering needed research and development effort and implementation periods.

Although several scenarios could be postulated as to how all, or a portion of, air transportation could convert to LH_2, there are fundamental factors that would affect any that are considered. These include:

- To warrant serious consideration, the portion of the air transport system devoted to the use of LH_2 must be large enough (in terms of minimizing the impact of cost and/or shortage of JP fuel) to attract the required implementation capital. This implies that a significant portion of the total air traffic, in the domestic and the international fleet/route network handling that traffic, must ultimately be postured to operate using LH_2. A large portion of the airlift capacity, and the several airports serving the passenger, cargo and transport traffic must therefore be included in the mature LH_2 system complex.

- A reasonably well coordinated plan of implementation would be necessary because of the financial commitment and the long lead time required to provide the fuel supply, and airport provisions (over wide geographical areas), as well as the aircraft. Because of these factors, it is doubtful that a single operating airline would unilaterally adopt LH_2. Rather, a joint decision between the major airlines to proceed in that direction, or a government policy to support such a decision, would be involved. In either case, some form of system planning and direction would be involved.

- It would not be practical to delay start of operations until fuel sources and the LH_2 aircraft fleet were available on a total system basis. Again, lead time for conversion of the airport facilities, together with reasonable aircraft production rates, must be taken into account. These factors suggest that the implementation concept should be based on a gradual growth that is time-phased to a schedule consistent with facility lead time and airplane production rate.

As a means of making a preliminary evaluation of the several areas of interest, a limited study was conducted within the framework of the fundamental factors discussed above Recognizing that several scenarios could be considered, only one was evaluated based on the following ground rules:

- A total system planning approach

- Initial startup at two airports (ORD and SFO, selected arbitrarily because one is on the west coast and the other a current major eastern hub)

- Two airports per year added to LH_2 network

- Airports having LH_2 facilities serve as home base for LH_2 aircraft during the system growth period

- Airplane production buildup to 5/month

- Airplanes assigned to traffic on the basis of 1975 widebody operations

- LH_2 airplanes operated over existing widebody route network

- Truck LH_2 fueling capability provided at non-LH_2 airports to provide incremental fuel required for airplane to return to normal home base, as normal or emergency operation

- 10 hours/day utilization of LH_2 airplanes

7.5.1 SYSTEM PLANNING

The program to convert from petroleum to hydrogen fuel would be a very large undertaking and in the national interest. It is therefore assumed that a system management function would be established to integrate the development of hydrogen production and transportation systems, the development of transport aircraft and the development of airport facilities. These major system elements would be developed to a master schedule to be operational on a predetermined date. This date, shown in figure 60, for the initial two airports, coincides with the airplane "certification" date. It represents the date on which airline service would begin in the U.S. with LH_2-fueled aircraft. As discussed in section 7.5.2, initial service would be out of two airports, with additional airports coming "on line" during succeeding years. Development schedules for these additional airports and their system elements would be shorter, and would be time-phased to coincide with their operational dates.

The schedule of figure 60 provides a 16-year period for development of the hydrogen supply. This includes planning, construction and checkout of the hydrogen production system and the H_2 transportation system. The airplane program could be initiated two years after beginning the H_2 supply program. It includes parallel technology and concept development efforts, followed by prototype DDT&E. Prototype test and evaluation would include both flight test and operational feasibility testing. (Flight and operational feasibility testing would be conducted separate from scheduled airline operations. The limited fuel quantities required would be provided by rail/tank truck delivery.) The production program commences upon completion of flight test and leads to certification (initial delivery to an airline) 17 years after total hydrogen program initiation.

7.5.2 INITIAL OPERATION AND GROWTH

The airport on-site LH/2 facilities require about 12 years for planning, construction and checkout. Operational readiness of the first two facilities, ORD and SFO, would coincide with airplane certification date. Installation of LH_2 systems at other major airports, at a rate of two per year, would follow. Installation priorities would be based on widebody traffic and distance from Chicago and San Francisco. A suggested sequence that would accommodate the growing geographical coverage, as shown in figure 61, is: JFK & LAX, HNL & IAD, ATL & DFW, SEA & MIA, DEN & ANC. (These 12 airports account for approximately 90% of the total U.S. current widebody operations.)

Operations from ORD and SFO would be over essentially the same route system currently used. This would be accomplished by taking advantage of a full tank

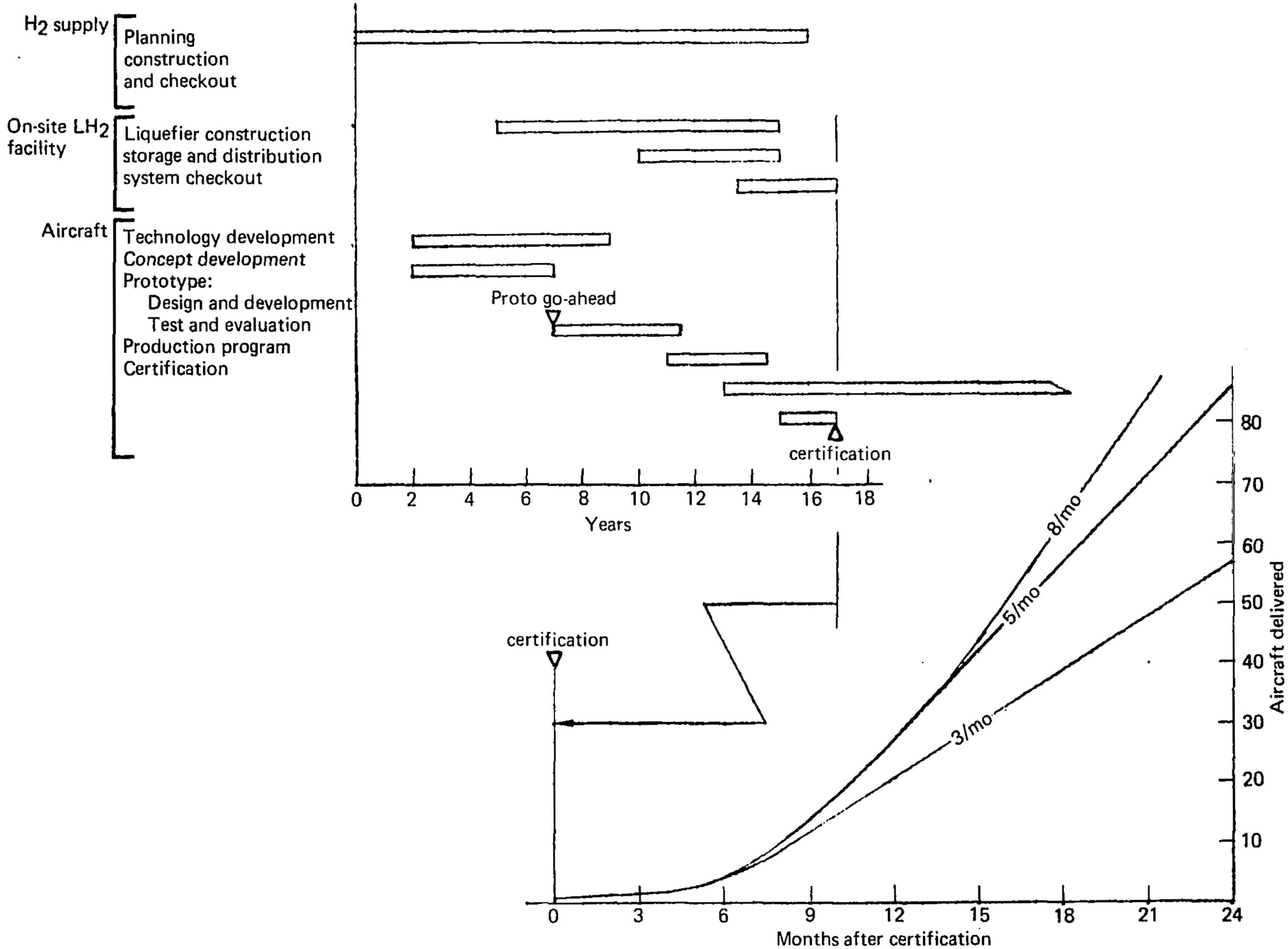


Figure 60.—LH_2 System Implementation Schedule

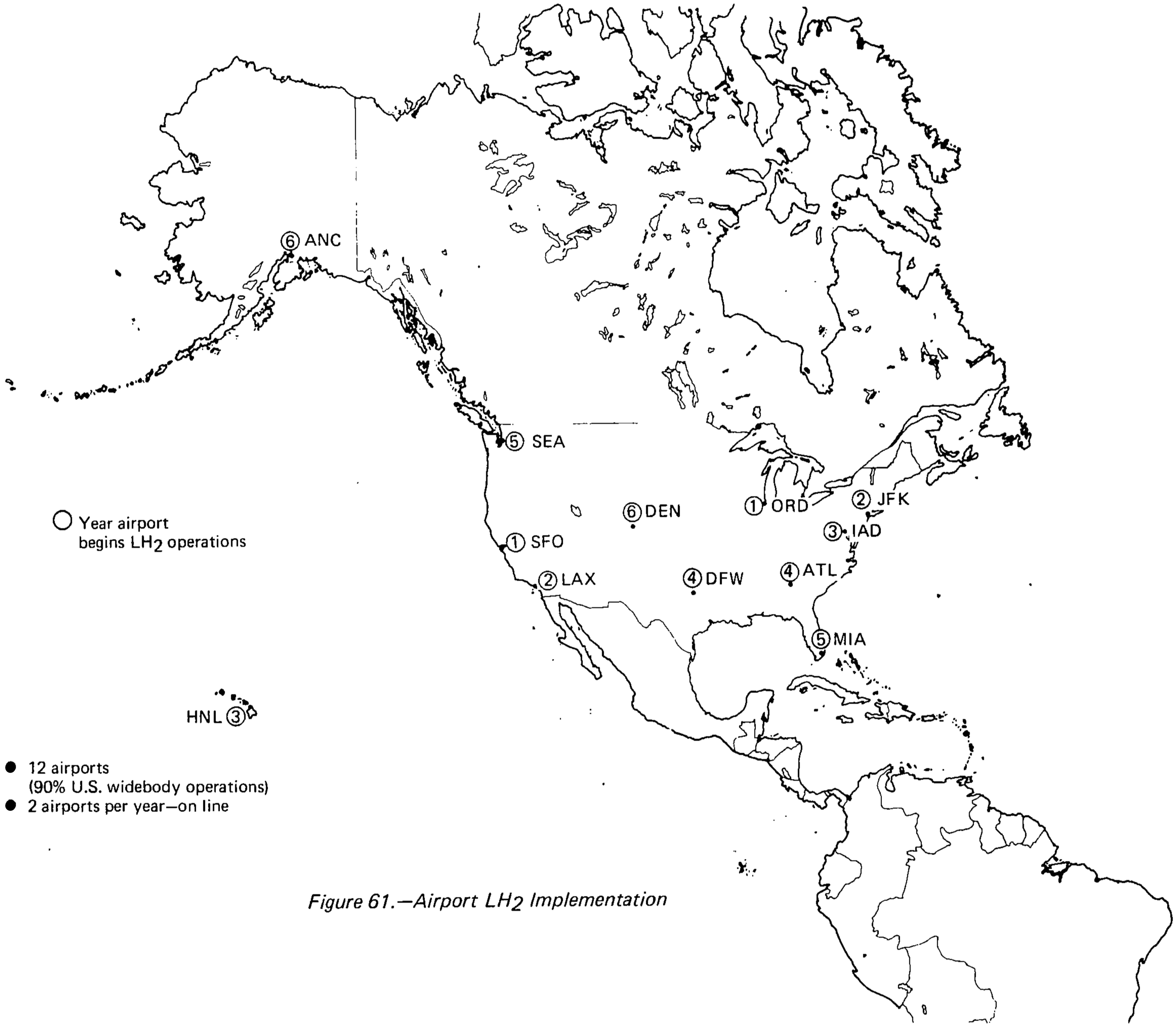


Figure 61.—Airport LH_2 Implementation

philosophy each time the airplane departed from ORD or SFO. As indicated previously (figure 11), the LH_2 airplane incurs considerably less penalty than one using JP fuel when operated in this manner. Incremental fuel required to return to home base would be provided by rail/tank truck delivery during the periods when an LH_2 capability was being implemented at other airports.

Airplane delivery schedules, typical for large widebody aircraft, are shown in figure 60. Deliveries based on the intermediate production rate of 5/month, total 28 at the end of the first year of service and 88 at the end of the second year.

As the number of airports capable of handling LH_2 fueled aircraft increases, a portion of the fleet is allocated to each airport proportional to its 1975 widebody traffic. The fleet distribution during the first 8 years of introduction is shown in table 10, and in figure 62. Airports added at the rate of 2/year for the first 6 years would provide geographical coverage of U.S. domestic traffic (including Hawaii and Alaska). It is logical to assume that major foreign airports would come into the picture about this time, and that system expansion beyond the sixth year would be predominantly foreign.

By the end of the eighth year 84 LH_2 airplanes would be flying ORD traffic. This would represent a mature operation in which 84 airplanes handle the 112 daily widebody flights out of Chicago. A detailed analysis of airplane scheduling, by tail number, in the Chicago route structure, was beyond the scope of this study.

7.5.3 ORD OPERATIONS DURING GROWTH PERIOD

During the first year of operation the 28 airplanes in service (table 10 and figure 62) are provided LH_2 fuel at two airports, ORD and SFO. On the basis of 1975 widebody operations at these airports, 19 airplanes would use ORD as their primary fueling source and nine airplanes would use SFO. The routes served by the small initial fleet would be selected to produce maximum utilization (to minimize boiloff losses) considering the temporary fueling limitations during the system growth period. Some emergency fuel should be available at remote airports during this period to take care of problems resulting from unscheduled maintenance. This could be provided by tank trucks which would later be utilized for certain fueling/defueling operations when those airports become active LH_2 airports. (This may require limited expansion or additions to current LH_2 production capability at strategic locations around the route network, that are remote from the initial home base airports.)

Initially, LH_2 aircraft would operate with full tanks when departing from ORD. Assuming 10 hours/day utilization per airplane, each airplane would require approximately 22 680 kg (25 tons) per day of LH_2 block fuel, or a total daily fleet block fuel of 430 920 kg (475 tons), provided by ORD at the end of the first year. In addition, heat losses in the LH_2 ground system and aircraft raise the total liquefaction requirement to 466 300 kg (514 tons) per day, as shown below:

airplane block fuel	(475 T/day)	430 920 kg/day
airplane cooling losses	(20)	18 144
ground system cooling losses	(19)	17 237
Total Liquefaction Requirement	(514 T/day)	466 300 kg/day

Table 10.—LH_2 Fleet Distribution During System Introduction

Yrs of operation		1	2	3	4	5	6	7	8
Total fleet		28	88	148	208	268	328	388	448
Airport	W/B Flts/day	% Fleet/no. aircraft per airport							
ORD	112	68%/19	31%/27	27%/40	23%/48	20%/54	19%/62	19%/73	19%/84
SFO	53	32/ 9	14/12	13/19	11/23	9/24	9/30	9/35	9/40
JFK	90		25/22	21/31	18/37	16/43	15/49	15/59	15/68
LAX	112		31/27	27/40	23/48	20/54	19/62	19/73	19/84
HNL	43			10/15	9/19	8/22	7/23	7/28	7/32
IAD	9			2/ 3	2/ 4	2/ 5	2/ 5	2/ 6	2/ 7
ATL	47				10/21	8/22	8/26	8/31	8/35
DFW	24				5/10	4/11	4/13	4/16	4/18
SEA	35					6/16	6/19	6/23	6/25
MIA	33					6/16	6/19	6/23	6/25
DEN	28						5/15	5/18	5/21
ANC	10 (est.)						2/ 5	2/ 6	2/ 6

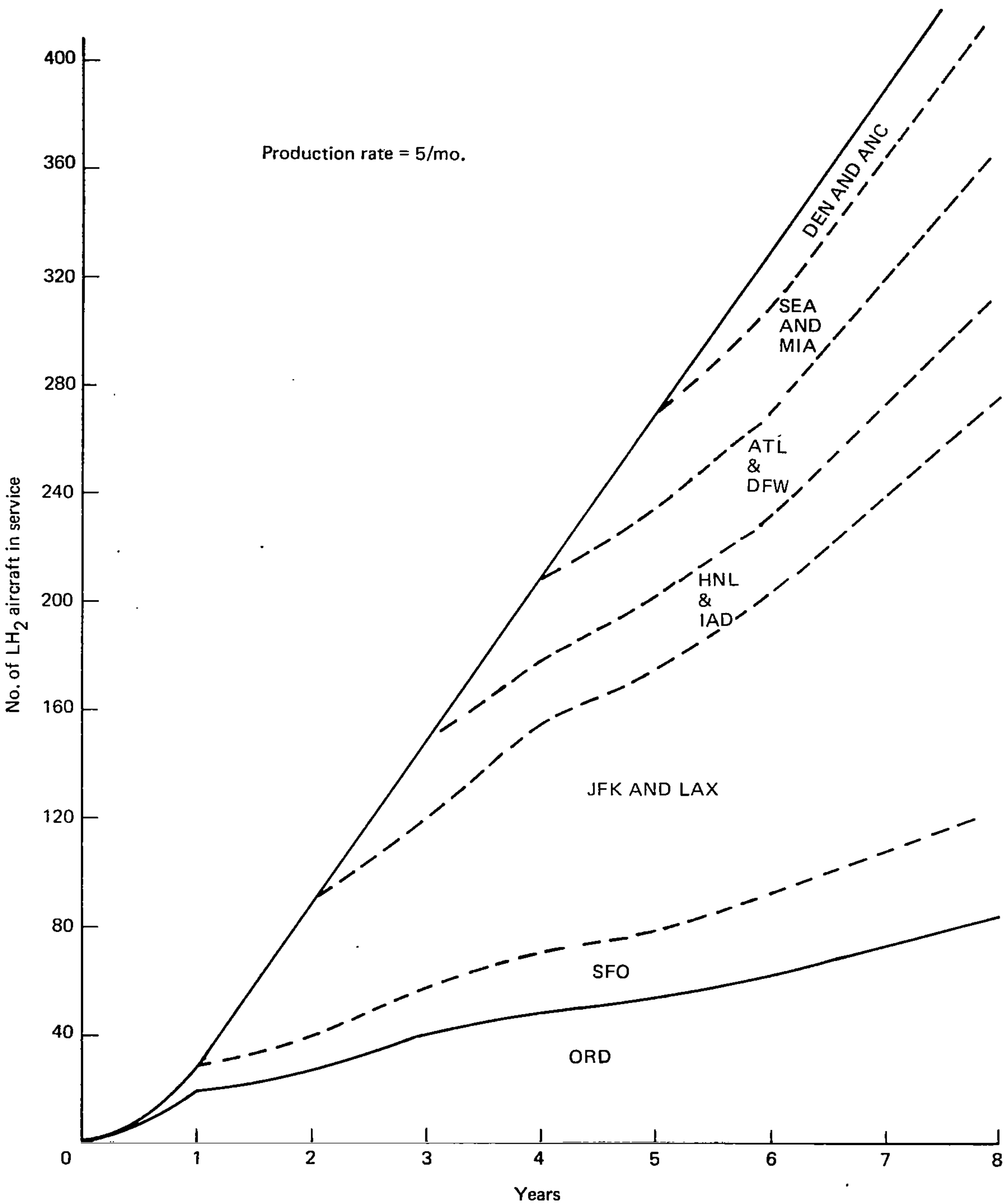


Figure 62.—LH_2 Airplane Fleet Distribution

The ORD facility defined during the mainstream study includes three 242 222 kg (267 tons) per day liquefication modules when fully implemented. As shown in figure 63, with two of the three modules on-line, the liquefaction demand at the end of the first year could be met with an 18 144 kg (20 tons) per day excess for contingencies.

By year-end of the second year, 27 airplanes would depend upon ORD for fuel. Continuing the first-year fueling policy (no LH_2 fueling at other airports), airplane block fuel would increase to 675 tons/day. Cooling losses would increase to 43 638 kg (47 tons) per day for a total liquefaction demand of 655 000 kg (722 tons) per day. At this time the three module plants would be operating at nearly design capacity.

During the third year, with six airports capable of providing LH_2, the fueling policy would phase into the normal airline practice of basing fuel load on flight length (considering other factors, such as fuel availability, fuel price and scheduled ground time at destinations). At this time the six airports with LH_2 would provide refueling capabilities on the east and west coasts and Honolulu, in addition to Chicago. The demand for full tank operation from ORD would be progressively reduced as these additional airports become a functional part of the LH_2 system. Coverage of the domestic route system with strategically located fuel sources would be essentially completed by the sixth year, with the additions of Atlanta, Dallas-Fort Worth, Seattle, Miami, Denver and Anchorage. Although the scope of this preliminary study did not permit detail evaluation, it is expected that the characteristics of their startup operation would be similar to that for Chicago (ORD).

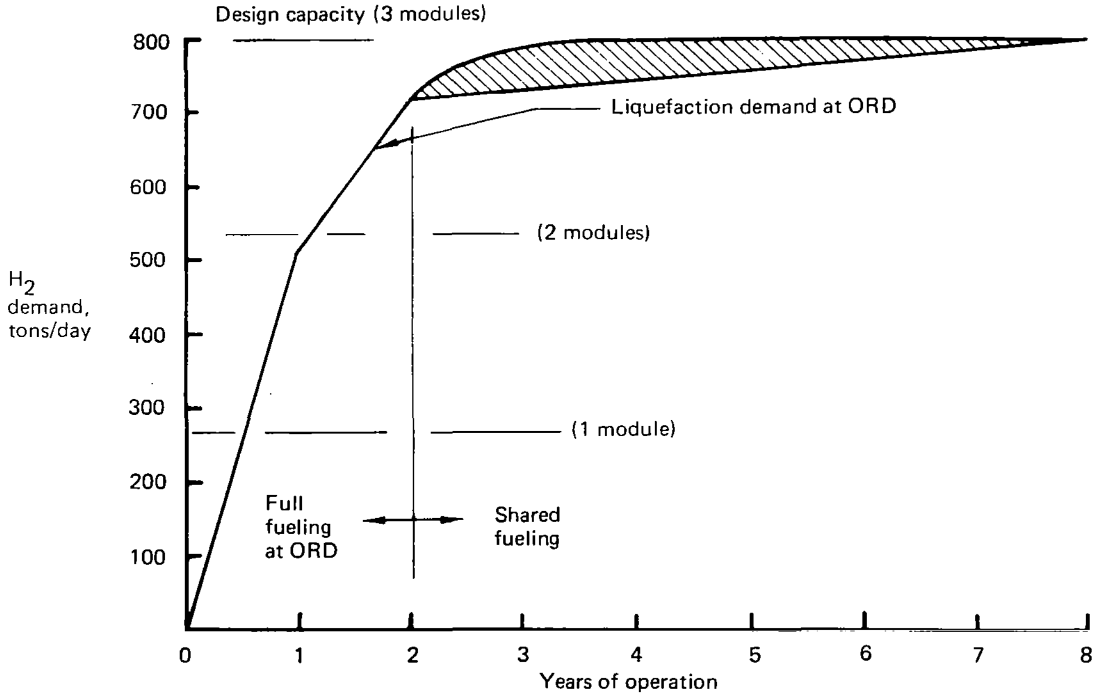


Figure 63.—LH_2 Fuel Demand at ORD

7.5.4 AIR TERMINAL SYSTEM COST IMPACT

Of the airports considered candidates for LH_2 operations, six were selected as having sufficiently differing characteristics to justify a cursory cost comparison with the baseline concept at O'Hare. Table 11 shows the comparison of major physical characteristics and cost elements of ORD, JFK, LAX, ATL, HNL, SEA, and MIA. The daily widebody departures were obtained from reference 4. The distance flown was estimated from the general route structure peculiar to each airport and weighted, for purposes of determining block fuel requirements, by the stage length, e.g., shorter stage lengths receive heavier weighting due to an increase in fuel required per mile flown. The daily fuel requirement of the airports and the plant size were scaled from the baseline by the one power and the 0.7 power, respectively, of the daily weighted distance flown.

The capital cost elements of the selected airports were also scaled from the baseline O'Hare facility. The major cost elements (hydrogen system, airport facilities and ground operational equipment) were broken down into subelements so that approximate scaling could be effected, e.g., the hydrogen system was scaled from the baseline by way of required plant capacity, whereas the distribution system was scaled via the required line length and the diameter required to meet respective peak fuel demands.

Since the dominant capital cost of the airport liquefaction and distribution system is the liquefaction plant itself, it is understandable that the total capital investment quantities listed in table 11 compare in a fashion similar to that of the fuel required for the various airports.

Table 11.—LH_2 Airport Conversion Comparison

	ORD	JFK	LAX	ATL	HNL	SEA	MIA
Daily widebody departures	112	90	112	47	43	35	33
Daily weighted distance flown							
1000 km	272	394	391	93	239	100	74
(1000 nm)	(147)	(213)	(211)	(50)	(129)	(54)	(40)
Fuel required							
1000 kg/day	726	1052	1043	245	635	263	200
(tons/day)	(800)	(1160)	(1150)	(270)	(700)	(290)	(220)
Plant size							
1000 m^2	101	129	129	49	93	49	40
(acres)	(25)	(32)	(32)	(12)	(23)	(12)	(10)
Land acquisition	None	None	None	None	Fill	None	None
Capital cost elements							
Hydrogen system—$M	436	536	521	209	355	213	176
Airport facilities—$M	23	23	21	10	9	9	13
Ground operational equipment—$M	10	12	15	7	7	4	5
Total capital investment—$M	469	571	557	226	371	226	194

A direct relationship between total capital investment and fuel required is not seen, however, due to the fact that, in the range considered, plant size enjoys economics of scale, i.e., doubling plant size results in less than double the cost.

8.0 CONCEPT APPRAISAL

An overall appraisal to determine the impact of introducing a major change to the air transportation system (such as introduction of LH_2 to a portion of expected operations) entails multiple areas of interest. Individually and collectively, the airports that would be involved constitute one of those areas. The airport complex existing in the United States provides very important functions in our society. It constitutes the link between people and cargo that must be transported and the operating airlines which, competitively, provide that transportation. (In reality, this extends beyond the borders of the United States into a global air transportation system.) Additionally, individual domestic airports are a vital part of their local environment. A major change to the characteristics of an individual airport can, therefore, produce or reflect changes in the global transportation system and local communities adjacent to airports.

This exploratory study concentrated on only one airport of the domestic and loosely defined global system–the O'Hare airport at Chicago. Considering the above comments, results of the study provide the following:

- Relatively firm data for appraisal of the technical and economic impact on the airport and airline operations at the ORD airport

- Some quantitative data, and a base for qualitative evaluation of the impact on the people, (community) and services, in the immediate vicinity of the ORD airport

- Limited insight into the potential impact of LH_2 on other potentially affected domestic airports, the domestic air transportation system, and to a very limited extent, the global system. (The global system is vitally important since LH_2 best adapts to large and long-range aircraft. Results of a cursory examination of this subject are provided in section 7.5. It should be the subject of more detailed evaluation before firm conclusions are drawn relative to the adoption of LH_2, or other alternative fuels.)

The following analyses were developed with the above considerations in mind, and apply to the specific situation at ORD, which in turn generally applies to other major domestic airports and some global airports.

Economic impact can be reflected in different fashions, depending on the policy and procedures followed by the government and private organizations involved in each locality, or region. In this study, both public and private financing methods were considered. Undoubtedly, several other options would be open to an undertaking of this magnitude.

8.1 TECHNICAL APPRAISAL

The study provided the opportunity to identify and define the major technical design and installation characteristics of the liquefaction, storage, distribution and airplane fueling portions of an LH_2 system. No basic flaws were found that would undermine the technical feasibility of the baseline system concept. All technical problem areas would appear to be responsive to straightforward engineering solutions and productive research and technology advancement efforts. Those efforts should emphasize approaches that minimize implementation and operations costs. Future decisions regarding exercise of the option to use LH_2 should, therefore, largely depend on economic rather than technical considerations.

The technical characteristics of the baseline dual-fueling concept are compatible with the objective of allowing commercial airlines to operate their total (JP and LH_2-fueled) fleet on a closely-coupled integrated basis. It also meets the objective of not permitting uncontrolled release of hydrogen on the airport.

The previous analysis of the baseline concept fuel requirements (table 1) indicates the allocation of LH_2 produced by a 725 760 kg/day (800 ton/day) liquefaction plant capacity. The allocation includes an allowance of 544 320 kg/day (600 tons/day) for usable block fuel and 80 740 kg/day (89 tons/day) for airplane tank conditioning and boiloff venting. An additional 81 648 kg/day (90 tons/day) is provided for demand variations that occur because of airplane scheduling peaks. Losses due to thermal aspects of the ground installation amount to only 19 051 kg/day (21 tons/day). Thus overall productivity of the ground system is 97.4%.

The productivity is actually greater since the gaseous boiloff is at low temperature when returned for reliquefaction–and does not require as much power to reliquefy as the warm GH_2 delivered to the liquefaction plant.

Review of study results with the Chicago Department of Aviation revealed no significant exception to the facilities, methods or procedures defined during the study. The land area required for the liquefaction and storage facilities is available. Current construction techniques permit the LH_2 distribution system to be installed in compliance with their ground rule that "Operations on runways and taxiways shall not be disrupted." Some local disruption would occur at gate areas, however, which would impact airline rather than airport operations. The Department of Aviation representatives indicated that their police, fire department and general housekeeping functions would only be affected because of additional personnel training. They foresaw no major impact on airport security.

Of the major utilities serving ORD, the electrical power demand for liquefaction and distribution (approximately 350 MW) would present the largest impact. Coordination with The Commonwealth Edison Company of Illinois revealed that a load of that magnitude could be accommodated providing proper lead time and planning preceded the period of implementation. The demand on other utilities such as water and sewers would be nominal, considering the current provisions in the local industrialized area adjacent to ORD.

Environmental impact on the community adjacent to ORD should not present severe problems. It is quite possible that the community would welcome the system introduction if it were preceded by proper public relations regarding the non-pollution aspects of LH_2 and its contribution to alleviate energy problems in this country.

The LH_2 system design relies heavily on technology, design and procedures that have been proven reliable during the space program and in the industrial use of LH_2 and other cryogens. Although no basic current technology limitations were found to preclude implementation of a workable LH_2 fueling system, several items were identified that warrant research and technology advancement to enhance the safety, economics and operational features of the system. Significant items in this respect are:

- Airplane servicing
- LH_2 system *efficiency* and *control*

Specific recommendations for action to be taken on the above items are included in the research and technology recommendations section. In addition, the double-deck airplane, used as a focal point for this study, may require specialized service equipment. This is, however, more of a characteristic of double-deck airplanes than being unique to LH_2 transports.

8.2 OPERATIONAL APPRAISAL

Day-to-day operations at a major airport such as ORD primarily involve two major organizations, the airport authority and the several operating airlines. Both organizations serve the public, who depend on those organizations to provide the necessary facilities, equipment and procedures needed to fulfill their travel desires in a safe and economical manner. The introduction of LH_2 would impact the two primary organizations in different ways during three significant, sequential time periods, following a commitment to convert part of the transport fleet operations to LH_2. These periods are system implementation, operational introduction, and full scale operations. Appraisal of the impact predicted during each of the three periods follows:

- System Implementation Period:
  Other than financial arrangement and planning implications involving both organizations, and the physical construction on airport property, the airlines would experience a minor impact during this period. Construction of the facilities could proceed without general disruption of routine airport activities. Each airline converting to LH_2 would experience disruption while the fueling system, and changes to specialized passenger loading provisions for the LH_2 airplane, were installed. It should be possible to limit this disruption to a small number of gates at any given time–in the same manner that many existing improvements have been made. Changes in the maintenance areas, such as improved ventilation, should also be accommodated without significant disruption. Required additional training of airport and airline personnel should be completed during this period. Arrangements should also be made for obtaining maintenance and servicing equipment for specific LH_2 transports.

- Operational Introductory Period:
  Again the airlines would experience the only significant impact during this period, starting with delivery of the first LH_2 transport. Evaluation indicates only one major difference would exist, when compared to a new large conventional transport; namely, that upon docking, the LH_2 transport would remain connected to the terminal fueling facilities throughout the period it is positioned at the gate.

Assuming the study 400 passenger transport configuration, all ground movements of the airplane at the airport should be very similar to those of the model 747.

The dual fueling concept will permit flexibility of gate assignments. Many of the current ramp service operation procedures and equipment will be adaptable. Assuming a double-deck configuration is necessary, operations such as galley and cabin servicing, and passenger loading will require new or modified equipment. Proper training and awareness of the ground crew (through training), can permit the turn-around operation to proceed in a safe and reliable manner–not greatly different from current operations.

The importance of the fueling crew cannot be over-emphasized. They must be adequately trained, and must understand the fueling system, the limitations of its operation and the procedures to follow in case of a malfunction. Details of the fueling function and the implication on training, selection and makeup of the fueling crew deserve detail evaluation. During this introductory period, the "operational bugs" present in any new transport, would be worked out, primarily by the airlines and the airframe manufacturer. No significant change in the role of the airport authority is foreseen, unless it should assume responsibility for operation of the ground portion of the LH_2 fueling system.

The LH_2 ground fueling system operation will be a critical function during this period. It will be possible only to simulate operational problems prior to this time. Operational bugs will have to be worked out. Again, a highly qualified LH_2 system operating crew will be required that is fully familiar with the plant, storage and distribution system facility and its operation.

Introduction of additional aircraft, by several airlines, will benefit from the procedures that are developed during the introductory period. As indicated in section 7.5, the mode of operation at initial LH_2 airports could change during this period when the overall domestic (and global system) is adapted to LH_2. Assuming that ORD is one of the initial airports, this should not change the basic roles of the airport authority, the airlines or other involved organizations.

- Full Scale Operations
  As the LH_2-fueled fleet grows to a mature status, the only foreseeable impact on ORD would be due to the increased size of individual transports that make up the widebody fleet. Gate spacing and apron operations may be constrained by the present facilities. Some limitations now exist in accommodating current widebody airplanes at individual ORD terminal facilities. This varies from airline to airline and may require re-allocation of leased areas or expansion of terminal facilities.

In summary, conversion of a portion of the fleet to LH_2 fuel and provisioning of the necessary fueling facilities does not present insurmountable operational problems. This conclusion applies only from the standpoint of implementing the concept within the constraints of the contract Statement of Work. It also ignores the total system economic considerations involved. Whether this conclusion would hold after consideration of implementation of the total fleet/route network as it would in turn affect ORD, remains open for further evaluation.

8.3 ECONOMIC APPRAISAL

The economic appraisal consisted of aggregating the individual equipment and construction cost estimates (1975 dollars) to arrive at the total capital investment required for the construction of each candidate LH_2 facility at O'Hare airport. With the total capital investment figure as a base, it was then possible to estimate periodic costs and conclude the estimated annual cost to the airlines of the required LH_2 fuel excluding the cost of electrical power and the hydrogen delivered to the plant.

8.3.1 CAPITAL INVESTMENT DETERMINATION

In an attempt to achieve high credibility in the cost estimates, several representatives of the equipment manufacturing and construction industries were consulted. Included were Air Products and Chemicals, Inc. for several items within the plant, storage and distribution systems; Ingersoll-Rand Co. for pumps; Metal Bellows Co. for pipes; Armco Steel Co. for tunneling; and Jetways (an affiliate of Stanray Corp.) for skybridges.

The items found to have the greatest impact on the cost of the facility are required plant capacity, required storage capacity, length and extent of the distribution system, and the number of passenger gates required. Plant capacity is dictated by the block fuel requirements of the airplanes serviced. Storage capacity is dictated by block fuel requirements and the state of the hydrogen delivered to the airport (liquid or gaseous). The length and extent of the distribution system is dependent on the location of the plant with respect to passenger and cargo terminals and to the maintenance hangars. The number of passenger gates is dictated by the number of daily widebody departures.

Table 12 contains the buildup of the major cost estimates of the baseline and alternate concepts as well as those for the effects of utilizing LH_2 rather than GH_2 supply, and the use of the external tank airplane configuration. The following major factors pertinent to the methodology used were applied during the economic appraisal.

- Liquefaction and Pumping Facility–costs provided by Air Products and Chemicals, Inc.–Included in this category are costs for plant, equipment, interest during construction, start up capital and working capital. These costs enjoy economics of scale, i.e., doubling plant capacity, results in less than double the cost.

- Master Control System–cost estimated at 1% of the cost of the Storage and Distribution Systems.

- Storage System–costing includes tanks, valves, distribution line, etc., with the dominant cost attributable to the storage tanks.

- Distribution System–costing includes distribution lines, valves, pumps, compressors, tunnels, ventilation systems, etc. The dominant cost is that of the distribution lines, particularly the 40.6 cm (16 in) ID vacuum-jacketed lines. The distribution system costs for the alternate concept are less than that of the

Table 12.—Capital Investment Summary

(Costs in 1975 $)

	Concepts		Trades	
	Baseline	Alternate	LH_2 Delivery	External Tank config.
Physical characteristics				
Hydrogen delivery state	GH_2	GH_2	LH_2	GH_2
Fueling concept	Dual	Separate	Dual	Dual
Aircraft tank configuration	Internal	Internal	Internal	External
LH_2 required capacity—1000 kg/day	726	726	100	1089
(tons/day)	(800)	(800)	(110)	(1200)
Aircraft block fuel required—1000 kg/day	544	544	544	816
(tons/day)	(600)	(600)	(600)	(900)
Capital cost elements—$M				
Hydrogen system—$M				
Liquefaction and pumping facility	300.00	300.00	85.00	400.00
Master control system	1.34	1.20	1.51	1.50
Storage system	32.92	32.92	49.42	48.53
Distribution system	101.29	87.55	101.29	101.29
Airport facilities—$M				
Passenger loading bridges	12.00	5.40	12.00	12.00
Terminal refueling booms	4.20	2.00	4.20	4.20
Passenger terminal modifications	2.00	0	2.00	2.00
Maintenance hangar modifications	4.80	4.80	4.80	4.80
Ground operational equipment—$M				
Tanker truck and boom systems	2.00	2.00	2.00	2.50
Galley and cabin service lifting platforms	8.00	8.00	8.00	8.00
Total capital investment—$M	468.55	443.87	270.22	584.82

baseline concept primarily due to shorter line lengths made possible by closer plant-terminal proximity and fewer passenger gates.

- Airport Facilities–based on 40 passenger gates for the baseline and trade configurations, 18 passenger gates for the alternate concept and two cargo gates and six maintenance hangars for both concepts and both trades. Passenger terminal modifications were not included in the costing for the alternate concept as it is assumed that the initial terminal construction for this concept would be compatible with the double-deck passenger loading bridges.

- Ground Operational Equipment–the number of tanker trucks was estimated from the number required to fuel/defuel an airplane in a reasonable time period, with spares for the fuel "loop" and for maintenance down time.

8.3.2 ANNUAL COST DETERMINATION

The airport, the operating airlines and probably the chemical industry, would be involved in the relatively large financial commitments necessary to implement the LH_2 system on the airport. The degree of involvement would depend on the method employed to finance the capital investment. The two more logical methods of financing the complete system are:

- Airport Financing
  Current provisions at ORD, including the JP fuel system, have been funded through revenue bonds issued by the airport authority. This was done following completion of agreements with the operating airlines. Those agreements cover commitment by the airlines to ultimately absorb the financial costs through user fees–over a period of time consistent with the payoff schedule for the bond issue. This maintains airport ownership of all property and provides an assured source of revenue to retire the bond obligation. This procedure is followed by many airports. Usually it can yield lower interest rates for the required capital, and better tax considerations are available when compared to direct private funding by the airlines or other industry organization.

- Private Financing
  This method would involve the airlines and one or more members of the chemical industry as far as planning, financial arrangements and implementation is concerned. The airport would function primarily in an overseer role with review and approval authority over changes to the airport facilities. The separate financing arrangements would minimize the bonded indebtedness of the airport–a factor that is of increasing concern. Construction and operation of the facility probably would be the responsibility of a member of the chemical industry–an arrangement that is somewhat standard in that industry.

In addition to these two financing methods, there are undoubtedly several other feasible approaches. One plausible approach would be a combination of private and airport financing, e.g., private financing for the liquefaction and storage facilities and airport financing for the distribution system and airport facilities. Regardless of the method selected, considerable planning and commitment agreements between the airport, airlines and chemical industry organizations would be necessary.

The total annual cost to the airlines for the LH_2 fueling system at ORD was estimated assuming financing of the complete system by the airport and by private sources. Costs computed by these two approaches are considered to represent the range of annual charge for the system to be levied on the airlines. Costs based on airport financing represent the low end of the range due to lower cost of capital and absence of federal income taxes. Costs resulting from a privately financed enterprise represent the high end due to higher cost of capital and federal income tax obligations. In both cases, however, state and local taxes were omitted to afford comparability between the facility at ORD and facilities located elsewhere.

Table 13 summarizes the costs associated with the LH_2 fueling system for each financing approach discussed. The capital investment is independent of the financing approach selected as is the annual operating cost. However, the cost of capital recovery markedly differs between the two approaches. Capital recovery is defined as the annual charge levied on the airlines to cover amortization of the capital investment, return on investment, and federal income tax liability, if applicable. In the case of airport financing, it was assumed that the required capital would be generated through the issuance of 8% revenue bonds with a 20-year maturity. With no federal income tax liability resulting from the issuance and repayment of the revenue bonds, the capital recovery for the airport financing method is simply the amortization of principal at 8% over the assumed 20-year lift of the system. In the case of private financing, a figure of 20% of the initial capital investment was chosen for the annual capital recovery. This figure is considered representative of today's investment requirements of chemical industries and existing federal tax laws. As an example, the following list of financial criteria would reduce to an annual capital recovery requirement of 20% of initial investment:

Return on Investment (Discounted Cash Flow)	14%
Capital Structure	100% Equity
Economic Lift	20 Years
Federal Income Tax Rate	48%
Depreciation Schedule (double declining balance for first year; sum-of-years'-digits thereafter)	9 Years

While the above list of criteria is considered to fairly represent the kind of enterprise being investigated here, it is but one of any number of possible sets which can reduce to a capital recovery requirement of 20% of investment.

The operating costs for both financing approaches are identical and made up of operating labor, utilities (excluding cost of electrical power), maintenance, taxes and insurance, and overhead. Maintenance was estimated at 2% of investment and taxes and insurance were estimated at a combined figure of 1% of investment. Overhead was estimated at 10% of the sum of labor, utilities, maintenance, taxes and insurance, and system depreciation expense (20-year, straight line).

Table 13.—Economic Summary

(Costs in 1975 $)

	Concepts		Trades	
	Baseline	Alternate	LH_2 Delivery	External Tank config.
Airport financing (revenue bonds)				
Total capital investment—$M	468.55	443.87	270.22	584.82
Annual capital recovery—$M	46.86	44.39	27.02	58.48
Annual operating cost—$M	21.00	20.06	11.42	26.15
Total airline annual cost*—$M	67.86	64.45	38.44	84.63
Private financing				
Total capital investment—$M	468.55	443.87	270.22	584.82
Annual capital recovery—$M	93.71	88.77	54.04	116.96
Annual operating cost—$M	21.00	20.06	11.42	26.15
Total airline annual cost*—$M	114.71	108.83	65.46	143.11

*Excludes cost of power and GH_2 or LH_2 delivered to plant

The total airline annual cost, listed as the sum of capital recovery and operating costs, is exclusive of the cost of electrical power required for liquefaction and the cost of LH_2 or GH_2 delivered to the plant. Figures 64 and 65 illustrate the impact of the cost of power and feedstock on the cost of LH_2 fuel for systems financed privately and publicly, respectively. The plots on the left of each figure reflect the impact of costs amortized over total airplane block fuel, 544 x 10^3 kg/day (600 tons/day). The plots on the right of figures 64 and 65 show costs amortized over the total fuel delivered to the airlines, 626 x 10^3 kg/day (689 tons/day). The difference of 80.7 x 10^3 kg/day (89 tons/day) is the vent gas returned to the liquefaction plant, which could be credited to the airline accounts. The true ultimate cost to the airlines is somewhere between that shown for block fuel and that shown for delivered fuel, for the two financing methods of figures 64 and 65. The figures illustrate the severe impact of the cost of electrical power at moderate to high rates. The total cost of power was computed to include a 10% allocation for overhead which is additional to the cost per kilowatthour.

Figure 66 summarizes the economic appraisal of the baseline and alternate concepts excluding the cost of gaseous hydrogen delivered to the plant. A comparison of the costs based on private and public financing methods illustrates the substantial advantage which airport financing would accrue to the airlines if such an undertaking were financially and technically feasible.

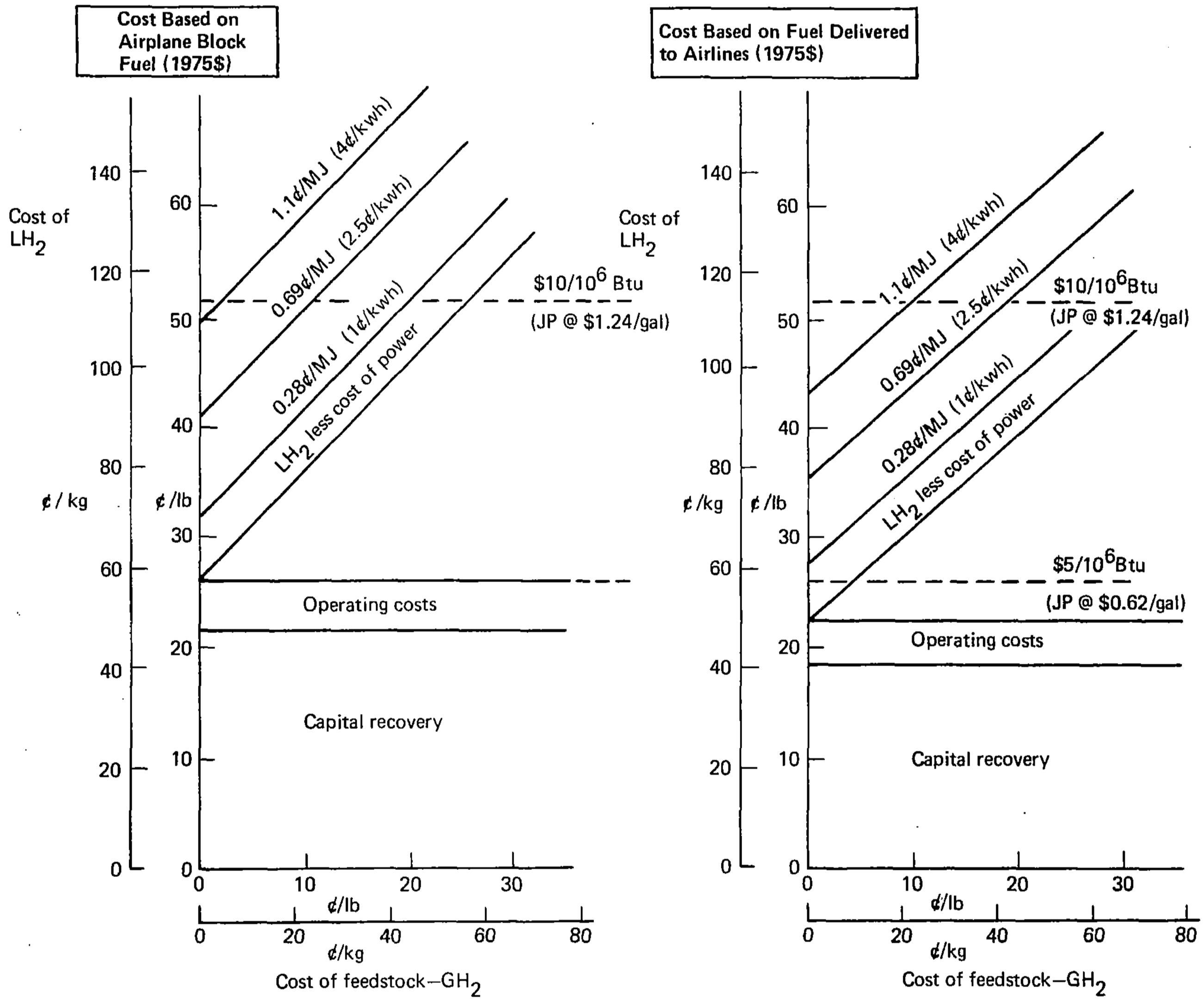


Figure 64.—Cost of LH_2—Private Financing (Baseline Concept)

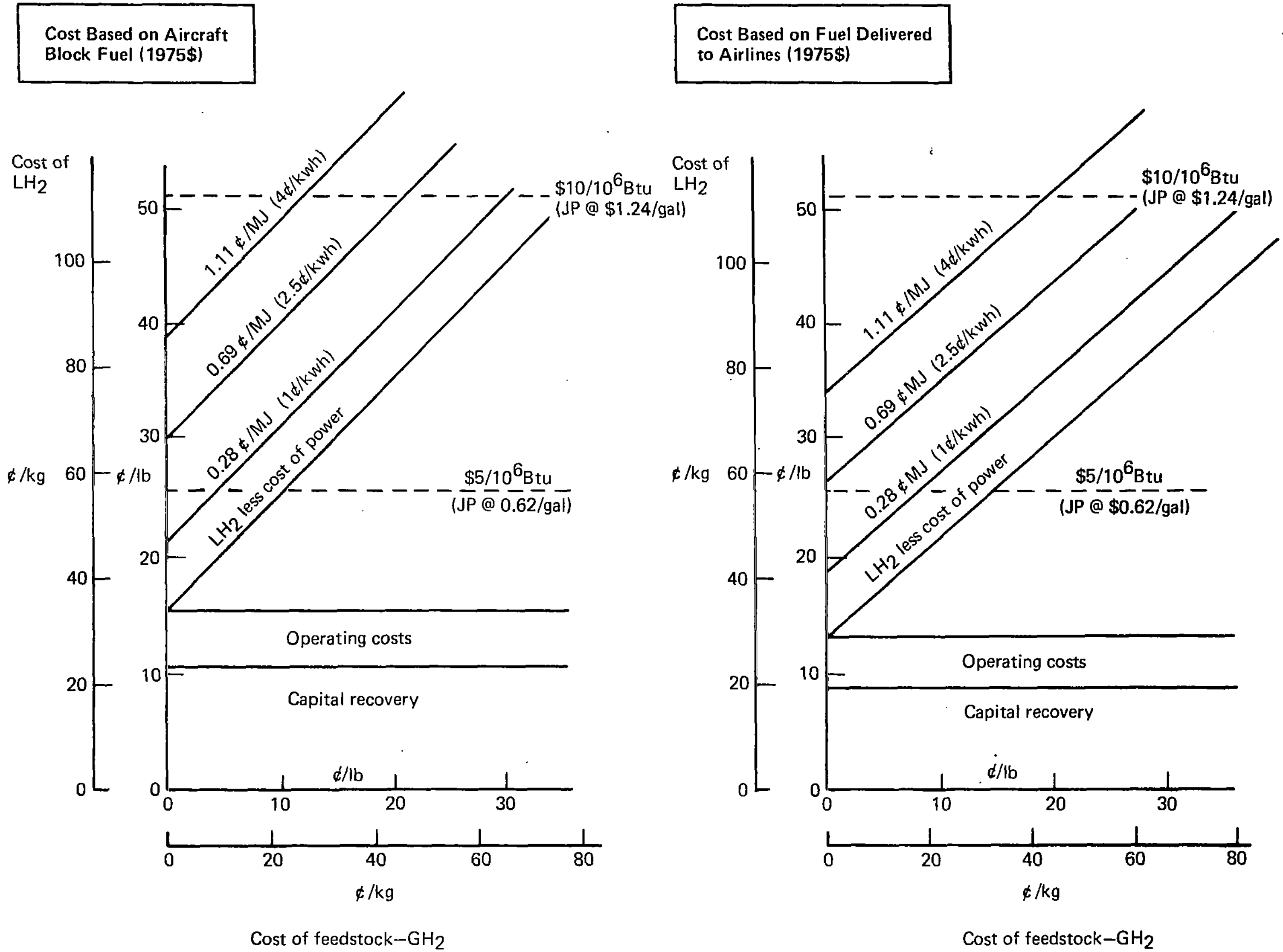
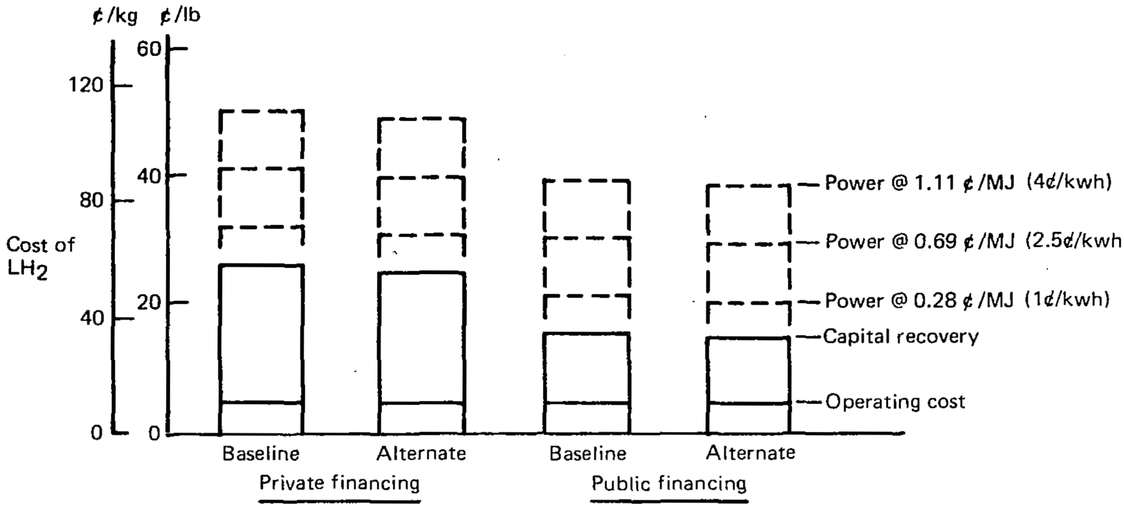
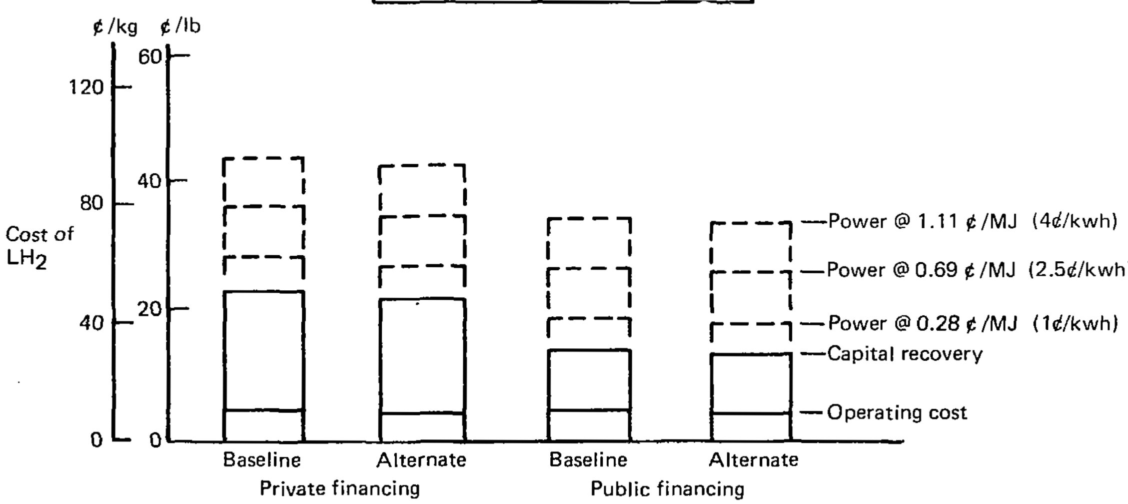


Figure 65.—Cost of LH_2—Public Financing (Baseline Concept)



Cost of LH_2 Based on Aircraft Block Fuel

Costs in 1975 $
Costs Exclude Costs of Feedstock



Cost of LH_2 Based on Fuel Delivered to Airlines

Figure 66.—Cost of LH_2 Fuel to Airlines

9.0 DESIRED CHANGES TO AIRPLANE CHARACTERISTICS

Throughout the development of requirements and air terminal concepts, certain changes to the baseline airplane characteristics were noted which would improve the efficiency of ground operations, particularly during aircraft fueling and servicing. Results of this action were consolidated and reviewed in total, and are summarized below.

9.1 AIRPLANE FUELING

It is recommended that the fueling and venting ports be moved from the tail of the airplane, as located in the reference 1 study, to a position on the right forward fuselage approximately 6 m (20 ft) from the ground (see fig. 45). The reason for the change is to accommodate the boom fueling and venting concept which reduces ground vehicle congestion in the ramp area and precludes the chance of damage to the fueling system, by ground vehicles or other aircraft. The recommended location also reduces the time and number of personnel required to refuel the airplane by using an adjustable swing boom mounted on the passenger terminal, containing probe and drogue-type fuel and vent connectors. This arrangement would also maximize the time the GH_2 scavanging system is connected to the airplane.

9.2 MAIN LANDING GEAR

It is recommended that the main landing gear be shortened by up to 0.6 m (2 ft). This would lower the height of the container deck to approximately 3 m (10 ft) above ground, where it can be serviced with existing equipment. The reduction in ground clearance to current widebody levels should have no adverse effect on airplane performance, because rotation angles and engine clearance would be adequate with the shortened gear. The change should also result in a substantial savings in landing gear weight and improved cornering ability.

9.3 CREW ACCESS

A flight crew access hatch and ladder in the nose gear wheel well would facilitate crew access at airports not equipped with the special loading bridges with provisions for crew access. It would also permit direct access to the cockpit by maintenance personnel. Many smaller airports without LH_2 facilities might have one or two gates capable of receiving widebody aircraft, but with only a single level airbridge capable of reaching the lower deck of the LH_2 airplane. The relatively small number of boarding passengers could use the two stairways inside the airplane to reach the upper level. Such airports would not be inclined to add a special airbridge just to accommodate the flight crew.

9.4 SERVICING ACCESS

To ease the heavy congestion of service vehicles required for quick turn around times desired for the LH_2 airplane, it is recommended that: (1) the front and rear cargo container access hatches be relocated closer to the wing to allow room for additional galley service vehicles, and (2) the aft cabin door stagger between the upper and lower decks be decreased to facilitate upper and lower deck galley servicing from a single galley lift loader, and (3) the airplane be equipped with a single-point toilet servicing manifold to reduce the number of vehicles around the airplane. All suggested external changes are noted in figure 67.

The recommended changes to the cabin interior arrangements are shown in figure 68. These changes move the center galleys to either end of the passenger cabin so they can be readily serviced. The wing prevents direct galley servicing through the center cabin doors. Additional changes noted are recommended to streamline galley service.

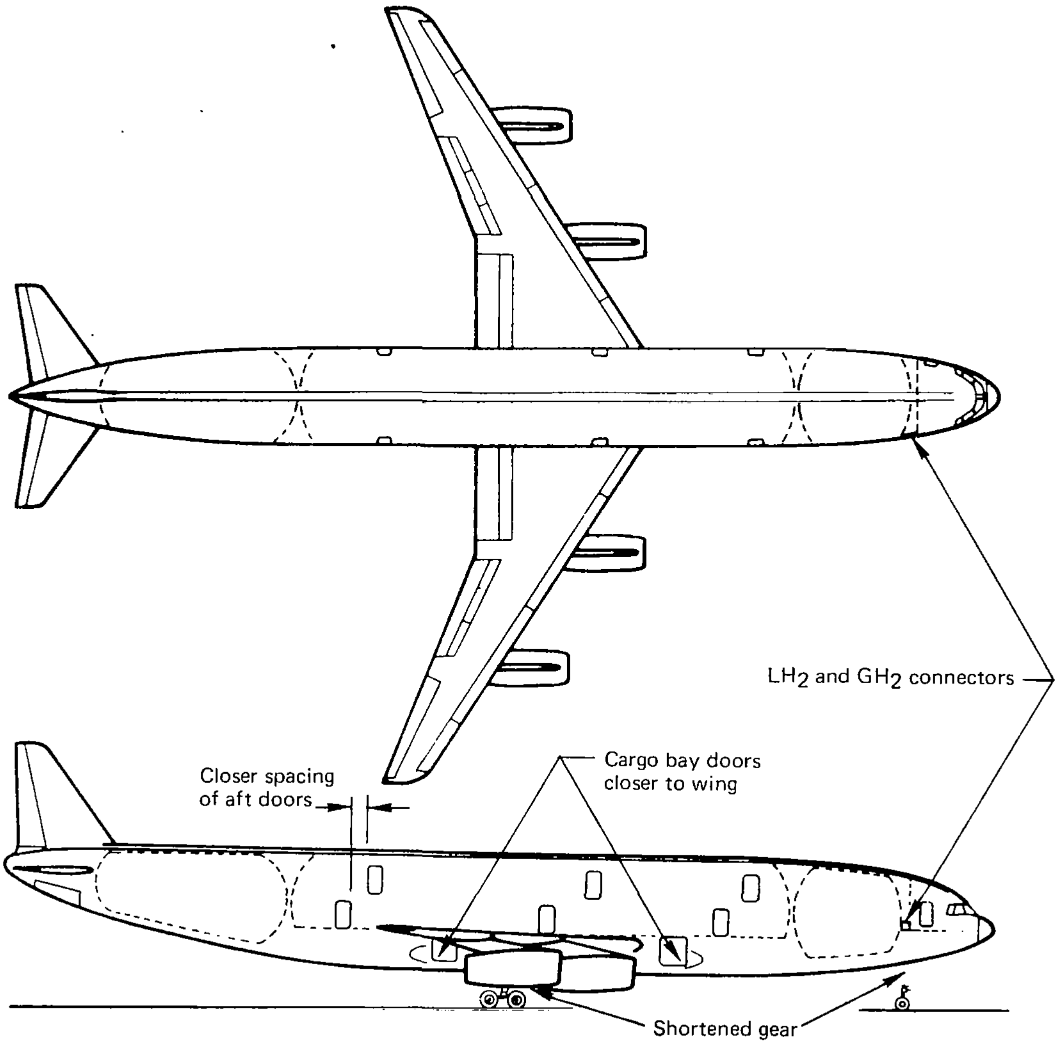


Figure 67.—Recommended External Changes

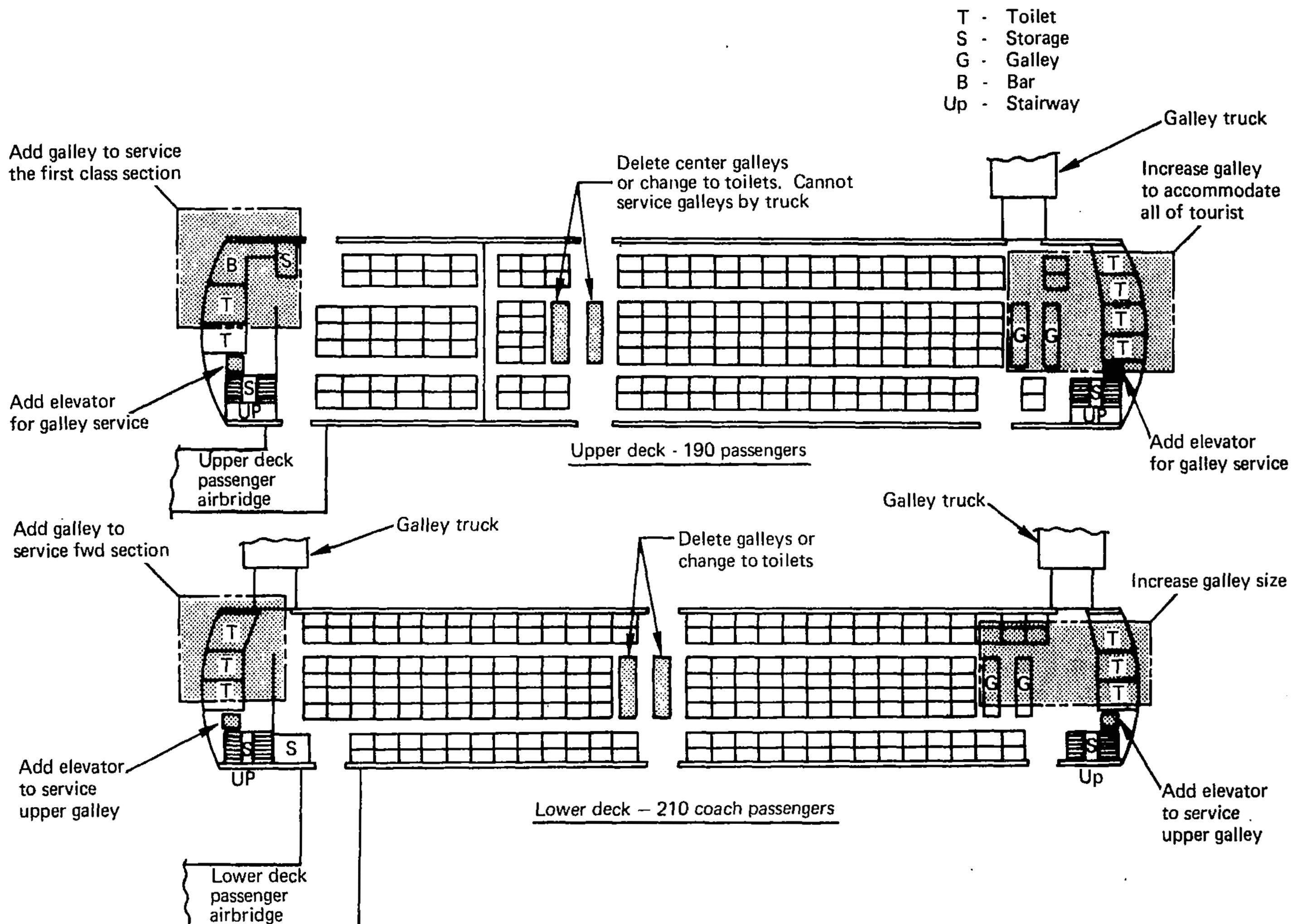


Figure 68.—Recommended Changes to Cabin Arrangement

10.0 RESEARCH AND TECHNOLOGY RECOMMENDATIONS

Generally, the LH_2 system defined during the study is based on the adaption of facilities, equipment, procedures and construction methods that have been proven on the space program or during application of LH_2 and other cryogens in the industrial area. Ultimate application of LH_2 to the operational situation at airports and the air transportation systems in general could benefit from research and technology efforts in the three following categories of interest:

- Airplane servicing
- LH_2 system efficiency and control
- Additional airport impact

A discussion of the specific needs and recommendations are provided under the headings below.

10.1 AIRPLANE SERVICING

The methods and procedures to be applied during the fueling and venting operations in the apron area deserve considerably more evaluation than was possible during this study. Several feasible concepts were identified. These ranged from semiautomatic devices (lines and disconnect valves) that connected to the airplane from a retracted position in the apron, to a boom system mounted on the terminal structure.

The boom concept offered the advantages of eliminating the need to tunnel beneath the apron for LH_2 system lines and also cleared the general airplane servicing area on the apron of all fueling equipment. No objections to the boom concept were made by the airport authority or the airline subcontractor. However, the concept calls for mounting the LH_2 and vent lines on the terminal and the actual connection to the aircraft would be a remote operation. The safety aspects of the concept, considering potential line leaks or major spills and the overall practicability of the concept, should be evaluated considering more definitive reqirements.

It is recommended that a more detailed evaluation study be conducted on two or more concepts using safety and cost as the major figures of merit. The most attractive concept should be designed in sufficient detail to determine specific components such as nonspill disconnects that deserve research and technology effort.

10.2 LH_2 SYSTEM EFFICIENCY AND CONTROL

In the technical appraisal, section 8.1, it was noted that there are several areas that would benefit from an advancement in technology and/or further evaluation. These involve:

1. Improving the efficiency of the hydrogen liquefaction plant
2. The development of new techniques for distribution system installation, checkout, and monitoring

3. **The development of advanced design movable joints and connects**

Improvements to hydrogen liquefaction plant efficiencies will require the development of process cycles specifically tailored to the plant capacities associated with the conversion of major airports to hydrogen. It is recommended that a detailed evaluation of large plant cycles be initiated with a company involved in gas liquefaction processes. Improved plant efficiencies could lead to significant reductions in the power required (and cost) of liquefying hydrogen.

The development of new techniques for distribution system installation, checkout and monitoring could lead to a significant saving in both capital investment and operating cost. Prompt detection of a system malfunction could prevent what might become an extended disruption of airport operations. It is recommended that the concepts developed in this study be utilized in a detailed analysis considering these items in terms of component design and application.

The development of advanced design movable joints and connects is required to lower maintenance costs and ensure gate area safety. This is the one area in which current component technology is marginal toward satisfying airport ground system component life and reliability requirements. An early development of movable joints and connects is recommended with emphasis on providing a design through model testing, rather than through conjecture based on analysis.

10.3 OTHER AIRPORT IMPACT

A limited evaluation of the gross impact of LH_2 on several airports other than ORD was made during this study. When compared to ORD, some of the additional airports were found to exhibit considerably different characteristics that would affect the nature of LH_2 fuel system installation and operations. The available area, type of terminal and apron characteristics, and passenger/transport traffic characteristics, including quantity and peak hour movements, were some of the differences that would affect the nature of an LH_2 system at airports other than ORD. The gross evaluation made to date indicates that airports such as Miami, Los Angeles, Seattle and Honolulu would offer a more significant challenge than ORD. In addition, it would be desirable to extend the present study to include a more thorough evaluation of the domestic and international air transportation system as it would be affected by LH_2.

It is recommended that a study be initiated to cover the probable route network that would be impacted by LH_2. Airports that appear to exhibit more severe characteristics should receive exploratory evaluation similar to that applied to ORD. The study should also consider the hydrogen supply system to serve the airport network during the implementation period and after the complete network becomes functional.

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May 1976

APPENDIX A
AIRPORT FUELING AND TRAFFIC DATA

This appendix contains data which support study results pertaining to widebody traffic and fueling, and international traffic at ORD. It also contains airport layouts used in developing the estimates of LH_2 fuel system requirements for six of the airports included in the expanding network discussed in section 7.5.

Table 14, extracted from reference 4, is a listing of daily widebody flights through ORD. It identifies the carrier, origin and destination airports, arrival and departure times and flight numbers. Table 15 shows the hourly LH_2 hydrant demand at ORD by each domestic airline and the foreign airlines. The data in this table were derived from figure 8, in the body of the report.

Table 16 is a consolidation of widebody fueling data obtained from the six principal operators at ORD. The actual fuel loadings shown represent approximately 83% of the ORD widebody flights. In table 17, these data were extrapolated to include all the flights, from which the daily JP fuel totals were obtained. The information from this table is shown in summary form in figure 12.

Total widebody and narrowbody international flights are shown in table 18. These data were used to determine the number of gates required in the alternate concept developed in section 6. Table 19 is included for reference in identifying airports by code symbol.

Figures 69 through 74 are layouts of six major domestic airports, showing runways and major facilities. LH_2 liquefaction plant and storage area requirements were estimated from the number of widebody operations and network average route lengths shown in table 20. Plant areas are represented by a circle drawn to scale, located in what appeared to be available areas not too distant from the passenger terminal, cargo area/maintenance area. The three principal elements of the distribution system are identified. They are:

(1)	Main System:	LH_2 and redundant GH_2 lines to the passenger gate area
(2)	Vent & N_2 Lines:	To the maintenance areas
(3)	Branch Lines:	LH_2 and GH_2 lines connecting the main system to passenger gate hydrants and to the cargo area hydrants

Figure 75 shows average delays experienced at ORD, by month, for the years 1972 and 1973. These data were taken into account in establishing airplane block fuel requirements.

Table 14.—Widebody Operations at ORD

(From: Reference 4)

	CA	OAP	DLT	Flt in	Flt out	OLT	DAP
747	NW	MSP	0137	244	244	0230	JFK
	NW	JFK	0305	245	245	0405	MSP
	UA	HNL	0545	990	990	0715	CLE
	UA	ITO	0605	118	118	0730	PIT
	NW	HNL	0800	16	17	1315	HNL
	UA	HNL	0730	992	723	1025	LAS
	UA	CLE	0915	953	953	1030	HNL
	NW	JFK	1105	3	3	1205	ANC
	UA	PIT	1147	107	107	1300	LAX
	UA	EWR	1208	993	993	1320	HNL
	UA	DTW	1450	129	129	1545	SFO
	KL	AMS	1540	611	612	1730	AMS
	TW	LHR	1500	771	771	1745	SFO
	NW	MSP	1554	442	443	1655	MSP
	AP	YUL	1545	31	30	1730	YUL
	LH	FRA	1620	430	431	1815	FRA
	UA	LAX	1610	104	115	1825	LAX
	BA	LHR	1630	569	570	2030	LHR
	SK	YUL	1700	941	942	1840	YUL
	NW	ANC	1824	6	6	1925	JFK
	UA	LAS	1850	218	218	1950	BOS
	TW	SFO	1810	770	770	1930	LHR
DC-10	UA	SFO	0002	282	217	0820	DEN
	AA	LAX	0540	196	196	0700	EWR
	CO	LAX	0529	906	921	0810	DEN
	NW	SEA	0549	26	26	0700	ATL
	UA	SEA	0555	158	158	0700	BOS
	UA	HNL	0620	186	101	0835	LAX
	AA	PHX	0604	246	57	0955	MEX
	UA	SFO	0620	136	136	0744	YYZ
	CO	DEN	0747	606	607	0900	LAX
	AA	BUF	0813	181	181	0900	LAX
	AA	YYZ	0824	265	265	0908	SFO
	UA	BOS	0906	123	123	1010	SFO
	NW	EWR	0912	95	95	1000	SEA
	UA	JFK	0915	225	225	1010	SAN
	NW	MSP	0913	750	750	1010	TPA
	UA	PHL	0903	143	143	1005	SEA
	UA	PIT	0910	103	103	1010	LAX

Legend:

CA – Carrier
OAP – Origin Airport
DLT – Destination Local Time (O'Hare Arrival)
Flt in – Flight No. Inbound
Flt out – Flight No. Outbound
OLT – Origin Local Time (O'Hare Departure)
DAP – Destination Airport

Table 14.—Widebody Operations at ORD (Continued)
(From: Reference 4)

	CA	OAP	DLT	Flt in	Flt out	OLT	DAP
DC-10 (cont.)	NW	YWG	1017	704	704	1105	ATL
	NW	JFK	1120	29	29	1215	SEA
	NW	EWR	1105	47	47	1155	PDX
	NW	MSP	1138	426	125	1240	MSP
	UA	BDL	1201	121	121	1300	SFO
	NW	EWR	1254	71	71	1345	SEA
	AA	EWR	1204	213	213	1300	SFO
	UA	EWR	1208	147	147	1305	SEA
	UA	PHL	1201	463	463	1300	DEN
	AA	SYR	1215	197	197	1300	LAX
	UA	YYZ	1213	345	345	1315	LAS
	CO	DEN	1305	926	605	1540	DEN
	UA	DEN	1338	236	236	1430	CLE
	UA	HNL	1340	100	155	1550	SEA
	NW	PDX	1307	46	46	1400	DTW
	UA	PDX	1335	142	142	1430	EWR
	NW	TPA	1325	729	729	1425	MSP
	UA	CLE	1448	203	203	1545	DEN
	CO	LAX	1445	608	941	1830	DEN
	AA	MEX	1454	104	66	1725	DTW
	NW	SEA	1415	94	94	1500	DTW
	AA	SFO	1419	220	220	1515	BOS
	AA	LAX	1537	184	184	1630	LGA
	AA	SFO	1552	182	182	1645	EWR
	NW	ATL	1654	27	27	1740	SEA
	NW	SEA	1610	72	72	1700	EWR
	CO	DEN	1655	914	903	1800	LAX
	UA	LAX	1610	358	358	1710	EWR
	AA	PHX	1644	66	66	1725	DTW
	UA	YVR	1605	144	144	1659	PHL
	UA	SFO	1610	126	145	1830	PDX
	SR	BOS	1715	164	165	1845	BOS
	CO	LAX	1740	908	905	2200	LAX
	NW	MSP	1713	444	445	1810	MSP
	NW	SEA	1710	28	28	1755	CLE
	AA	LAX	1839	188	188	1940	JFK
	NW	MIA	1808	723	723	1900	MSP
	AA	SFO	1853	214	214	1945	YYZ
	AA	SYR	1919	47	47	2010	SFO
	UA	DEN	1905	492	492	2000	EWR
	UA	LAX	1905	108	108	2005	PIT
	NW	MSP	1904	458	728	2100	TPA
	UA	SAN	1900	786	786	2000	CLE
	UA	SEA	1905	150	150	2000	BOS
	UA	SFO	1905	128	128	2005	BDL

Table 14.—Widebody Operations at ORD (Concluded)

(From: Reference 4)

	CA	OAP	DLT	Flt in	Flt out	OLT	DAP
DC-10 (cont.)	NW	TPA	1914	751	751	2000	MSP
	AA	BOS	2014	157	157	2100	SFO
	UA	BOS	2020	117	117	2125	LAX
	AA	DTW	2030	107	107	0900	PHX
	UA	EWR	2020	237	237	2120	DEN
	CO	LAX	2040	902	911	0100	DEN
	UA	SEA	1330	140	111	1550	LAX
	CO	DEN	2105	910	907	1200	LAX
	UA	DEN	2127	916	210	1140	DTW
	CO	LAX	2335	904	917	1500	LAX
	NW	SEA	2327	12	415	0800	MSP
L-1011	DL	JAX	0108	1196	1139	0725	TPA
	EA	ATL	0118	954	949	1015	SJU
	TW	LAX	0540	20	20	0700	PHL
	DL	ATL	0715	1192	1135	0900	MIA
	TW	BOS	0910	117	117	1000	LAX
	TW	PHL	0907	711	711	0955	LAS
	TW	BOS	1052	195	195	1145	LAS
	DL	ATL	1102	1038	1039	1215	MIA
	TW	PIT	1114	25	25	1200	LAX
	TW	LAS	1501	102	102	1550	BOS
	DL	MIA	1512	1136	1151	1640	TPA
	DL	MCO	1655	1138	1133	1815	TPA
	TW	LAX	1745	36	36	1845	PIT
	TW	LAS	1815	780	135	0900	SFO
	DL	ATL	1832	1148	1091	2100	ATL
	EA	SJU	1920	948	957	2100	ATL
	DL	ATL	2212	1132	1193	0120	ATL

Table 15.—Hourly Widebody Hydrant Demand—ORD*

Time of Day, Hr

	24	1	2	3	4	5	6	7	8	9	10	11	Noon	13	14	15	16	17	18	19	20	21	22	23	Total Departures*
AA							1		3	1			2		1	1	3	1		3	1				17
DL	1						1		1			1				1		1			1				7
TW							1		1	2		2				1	1		2						10
UA							3	3		5	1		6		3	3	2	2		6	2				36
CO	1							1	1			1			2			2				1			9
EA										1											1				2
NW			1	1			1	1		2	1	3	2	3	1		2	3	2	1	1				25
Foreign																	2	3		1					6
Total	2		1	1			7	5	6	11	2	7	10	3	7	6	10	12	4	11	6	1			112

*Widebody cargo flts not included (approx. 2/day)

Table 16.—Airline Fueling Data—ORD

Air-line	A/C	Flt no.	Flts/wk	Total fuel (gal/wk)	Average fuel/flt (gal)
NW	747	–	32	354 788	11 087
	DC10	–	118	594 229	5 036
DL	L-1011	–	49	152 003	3 102
AA	DC10	–	104	658 165	6 329
CO	DC10	911	5	21 998	4 400
	DC10	921	6	24 673	4 112
	DC10	607	7	51 612	7 373
	DC10	907	7	50 891	7 270
	DC10	917	7	48 105	6 872
	DC10	605	7	28 652	4 093
	DC10	903	5	39 526	7 905
	DC10	941	7	33 708	4 815
	DC10	905	7	64 879	9 268
TW	747	770	7	186 162	26 595
	747	711	6	71 240	11 873
	L-1011	711	7	48 500	6 929
	L-1011	195	7	52 034	7 433
	L-1011	25	6	48 346	8 058
	L-1011	102	7	31 239	4 463
	L-1011	36	7	21 573	3 082
	L-1011	780	7	18 489	2 641
UA	747	107	7	*	10 385
	747	115	7	–	10 118
	747	118	7	–	6 593
	747	129	7	–	6 356
	747	218	7	–	4 119
	747	723	7	–	9 111
	747	953	7	–	30 222
	747	990	3	–	3 140
	747	993	3	–	28 889
UA	DC10	101	7	–	7 733
	DC10	103	7	–	7 467
	DC10	108	7	–	2 281
	DC10	111	7	–	7 348
	DC10	123	7	–	8 504
	DC10	128	7	–	7 052
	DC10	142	7	–	2 844
	DC10	144	7	–	3 556
	DC10	145	7	–	7 881
	DC10	147	7	–	7 289
	DC10	155	7	–	7 852
	DC10	157	7	–	5 985
	DC10	158	7	–	5 244
	DC10	203	7	–	3 793
	DC10	210	7	–	4 370
	DC10	225	7	–	8 474
	DC10	236	7	–	1 807
	DC10	237	7	–	4 622
	DC10	345	7	–	6 281
	DC10	358	7	–	3 348
	DC10	463	7	–	8 207
	DC10	492	7	–	2 993
	DC10	640	7	–	5 719
	DC10	786	7	–	1 748
	DC10	217	7	–	8 652

*United Airlines data received for a "typical day".

Gallons x 3.785 = Liters

Table 17.—Widebody Fueling Characteristics—ORD

Airline	A/C	Flts/day(1)	ORD fuel load—gal Min	Max	Avg	Total	Total Capacity	ORD fuel / Total capacity
UA	747-100	9	3 140	30 222	12 104	108 933	423 900	
TW	-100	2	11 873	26 595	19 234	38 468	94 200	
NW(2)	-100	4	4 162	9 195	6 772	27 088	188 400	
	-200	2	20 243	30 222	25 233	50 465	102 800	
SK(3)	-200	1				4 300	51 400	
KL(3)	-200	1				26 700	51 400	
AF(3)	-100	1				4 300	47 100	
LH(3)	-100	1				29 000	47 100	
BA(3)	-100	1				26 700	47 100	
		22			14 362	315 954	1 053 400	30%
UA	DC10-10	25	1 748	8 652	5 642	141 050	652 500	
AA(2)	-10	15	6 023	6 651	6 329	94 928	391 500	
CO	-10	9	4 093	9 268	6 234	56 108	234 900	
NW(2)	-40	17			5 036	85 612	612 000	
SR(3)	-40	1				3 875	36 000	
		67			5 695	381 573	1 926 900	20%
TW	L-1011	6	3 080	7 433	5 434	32 606	157 200	
DL(2)	L-1011	7			3 102	21 715	183 400	
EA(3)	L-1011	2	5 500	12 700	9 100	18 200	52 400	
		15			4 835	72 521	393 000	18%
		104			7 404	770 048	3 373 300	23%

Notes:
Gallons x 3.785 = liters

(1) Flights scheduled less than daily were assumed to fly daily to arrive at "busiest day" demand.
(2) Fuel loadings estimated from total fuel data provided by airline.
(3) Estimated.

Aircraft fuel capacities	
747-100	47 100 gal
747-200	51 400
DC10-10	26 100
DC10-40	36 000
L-1011	26 200

Table 18.—Daily International Schedule—ORD

(From: Reference 4)

Airline	Flight no.	A/C model	Origin
Widebody flights			
AA	265	D10	YYZ
UA	345	D10	YYZ
AA	104	D10	MEX
TW	771	747	LHR
KL	611	747	AMS
AF	031	747	YUL
LH	430	747	FRA
BA	569	747	LHR
SK	941	747	YUL
SR	164	D10	GVA
Narrow-body flights			
UA	483	727	YNG
UA	483	737	YNG
AC	721	D9S	YYZ
UA	221	727	YYZ
AC	731	72S	YUL
AA	623	72S	YYZ
AC	733	DC8	YUL
UA	633	737	YNG
AA	343	707	YYZ
MX	800	72S	MEX
AC	725	72S	YYZ
SK	945	D8S	CPH
NW	736	72S	YWG
OA	421	707	YUL
AC	735	D9S	YUL
PA	59	707	FRA
TW	849	B3F	CVG
AA	205	707	YYZ
IN	121	707	YUL
AC	727	D9S	YYZ
JM	053	72S	MBJ
AC	729	72S	YYZ
LL	801	D8S	KEF
AA	170	707	ACA
UA	685	727	YYZ
AA	611	727	YYZ
JM	051	D9S	NASJ
JM	051	72S	NAS
MX	802	727	ACA
AC	737	D9S	YUL

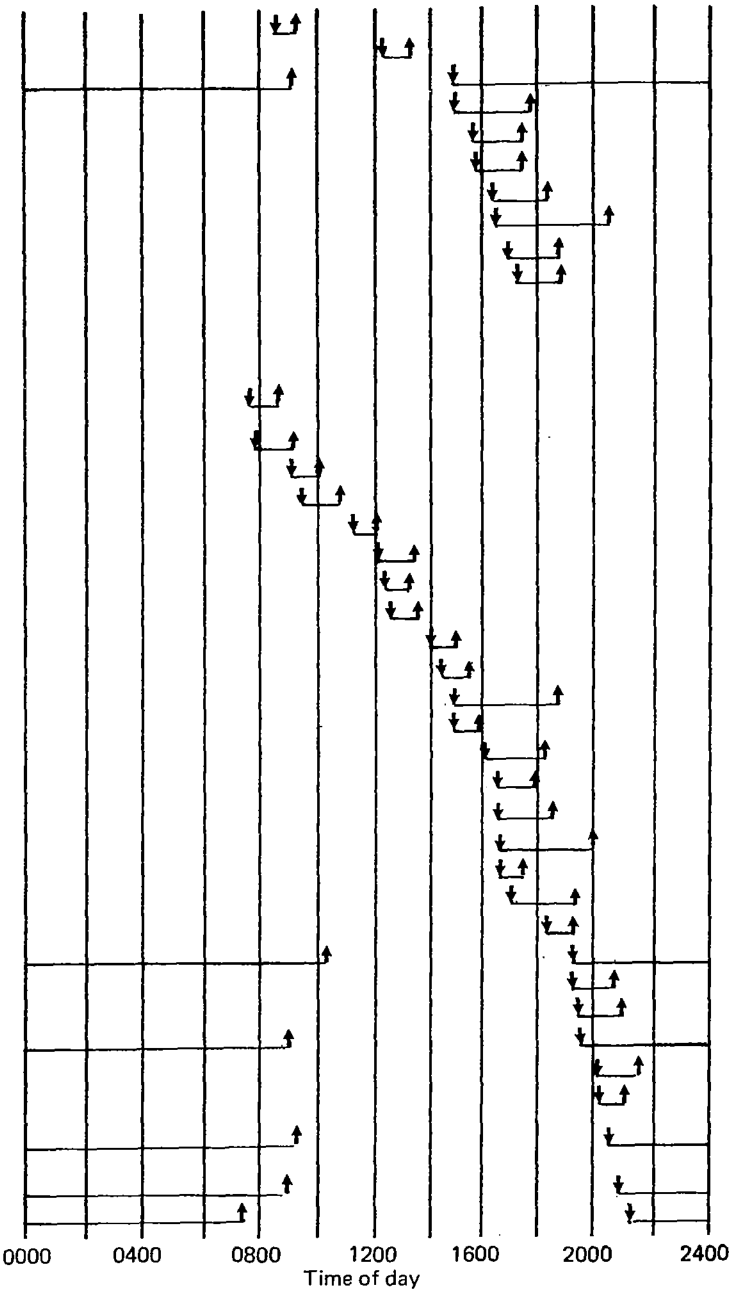


Table 19.—City/Airport Codes

(From: Reference 4)

ACA	Acapulco, Mex.	LHR	Heathrow—London
AMS	Amsterdam, Holland	MBJ	Montego Bay, Jamaica
ANC	Anchorage, Alaska	MCO	Orlando, Fla.
ATL	Atlanta, Ga.	MEX	Mexico City, Mex.
BDL	Hartford, Conn.	MIA	Miami, Fla.
BOS	Boston, Mass.	MSP	Minneapolis-St. Paul, Minn.
BUF	Buffalo, N.Y.	NAS	Nassau, Bahamas
CLE	Cleveland, Ohio	PDX	Portland, Ore.
CPH	Copenhagen, Denmark	PHL	Philadelphia, Pa.
CVG	Cincinnati, Ohio	PHX	Phoenix, Ariz.
DEN	Denver, Colo.	PIT	Pittsburgh, Pa.
DTW	Detroit, Mich.	SAN	San Diego, Calif.
EWR	Newark, N.J.	SEA	Seattle/Tacoma, Wa.
FRA	Frankfurt, Germany	SFO	San Francisco, Calif.
GVA	Geneva, Switzerland	SJU	San Juan, Puerto Rico
HNL	Honolulu, H.I.	SYR	Syracuse, N.Y.
ITO	Hilo, H.I.	TAP	Tampa, Fla.
JAX	Jacksonville, Fla.	YNG	Youngstown, Ohio
JFK	Kennedy—New York	YUL	Montreal, Que.
KEF	Keflavik, Iceland	YVR	Vancouver, B.C.
LAS	Las Vegas, Nev.	YWG	Winnipeg, Manitoba
LAX	Los Angeles, Calif.	YYZ	Toronto, Ontario
LGA	LaGuardia—New York		

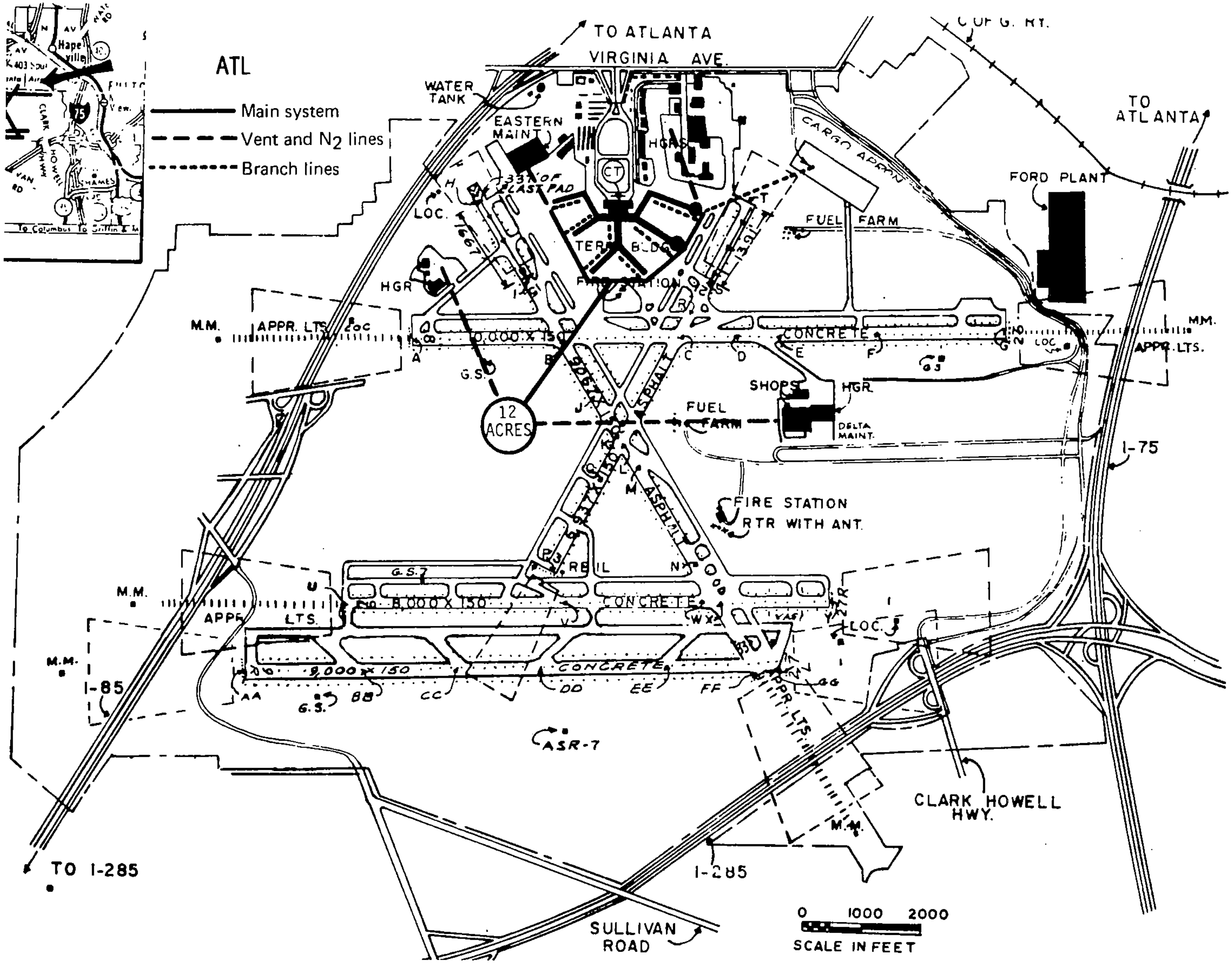


Figure 69.—Atlanta Airport

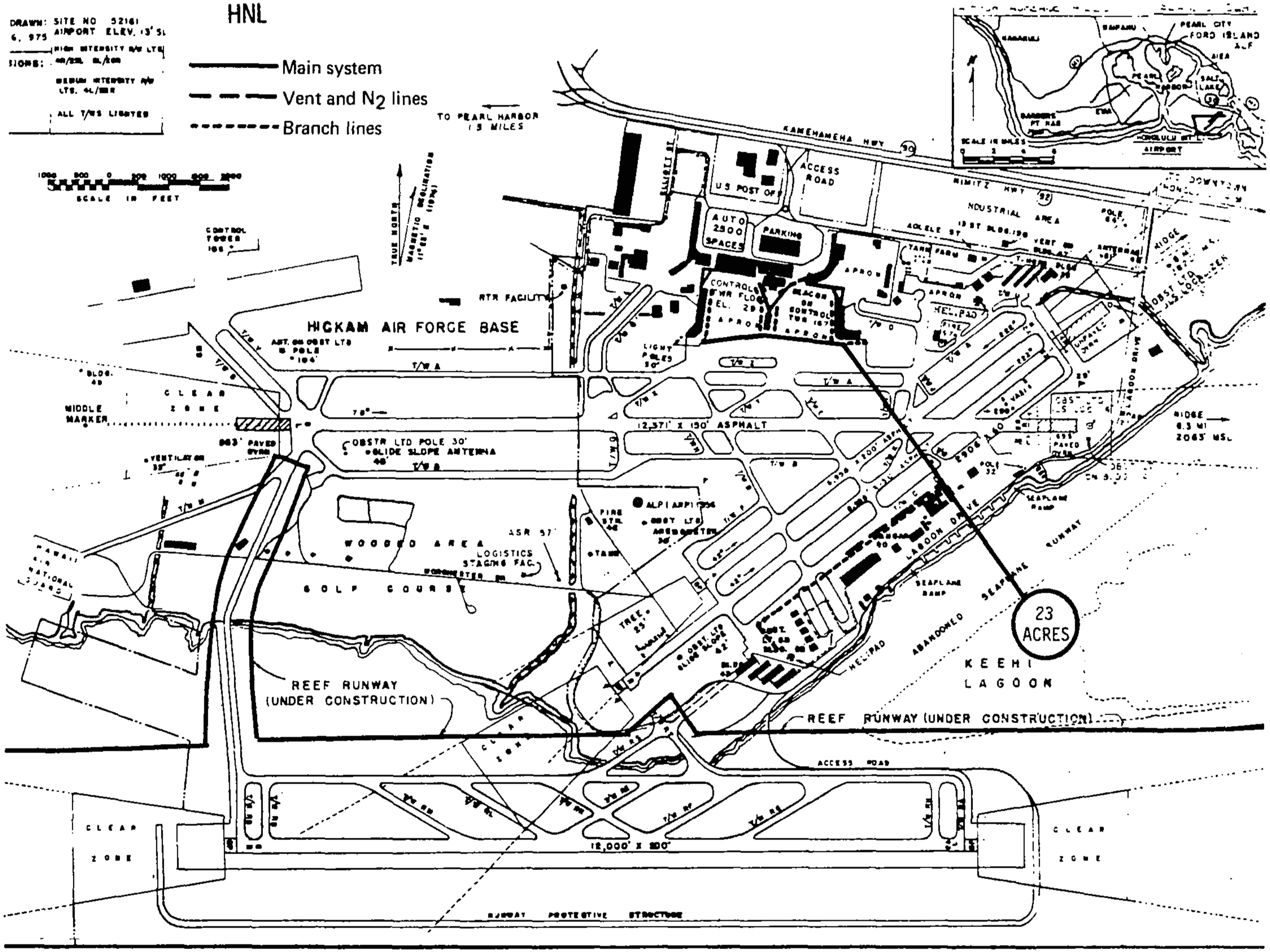


Figure 70.—Honolulu Airport

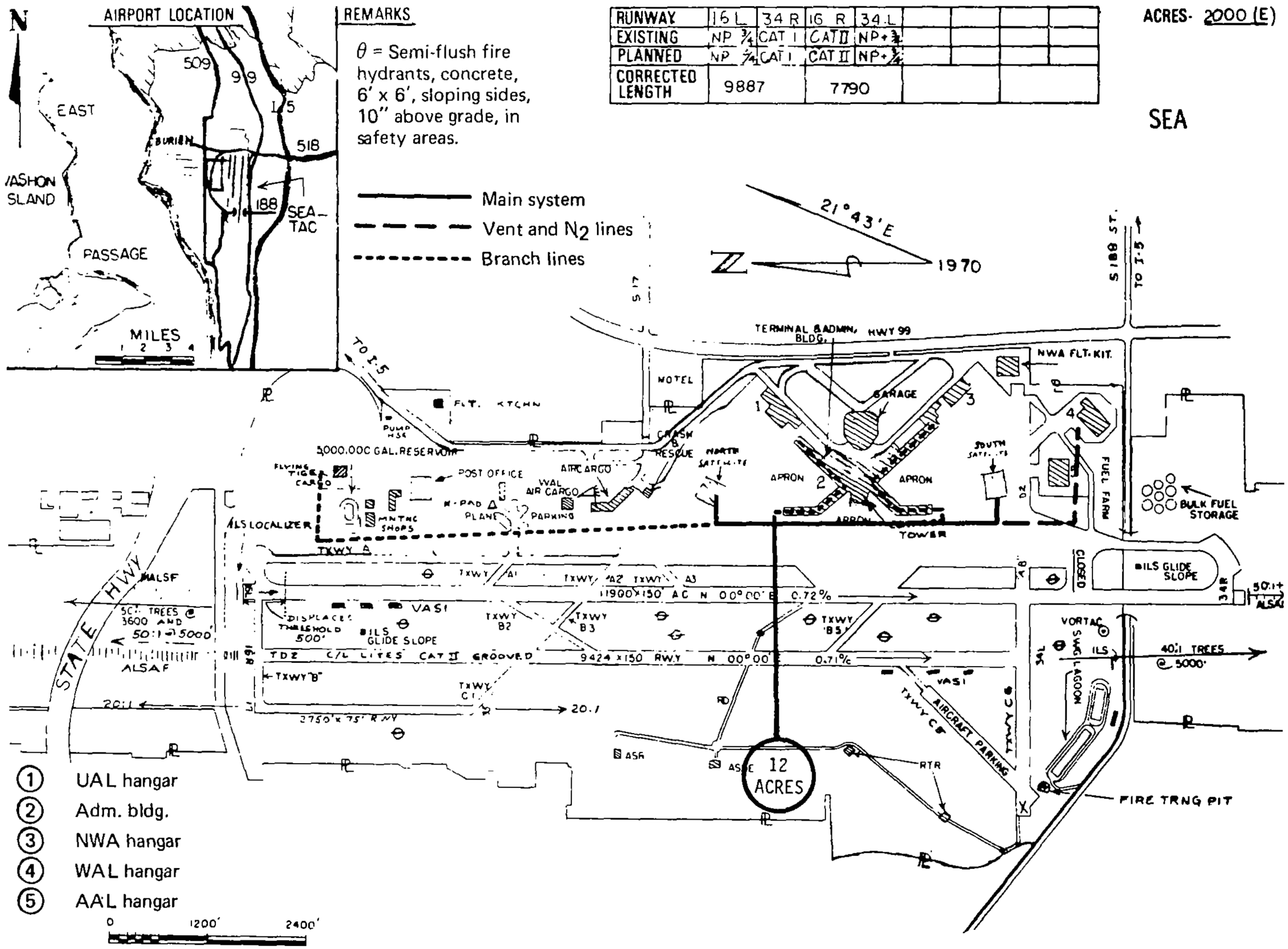


Figure 73.—Seattle/Tacoma Airport

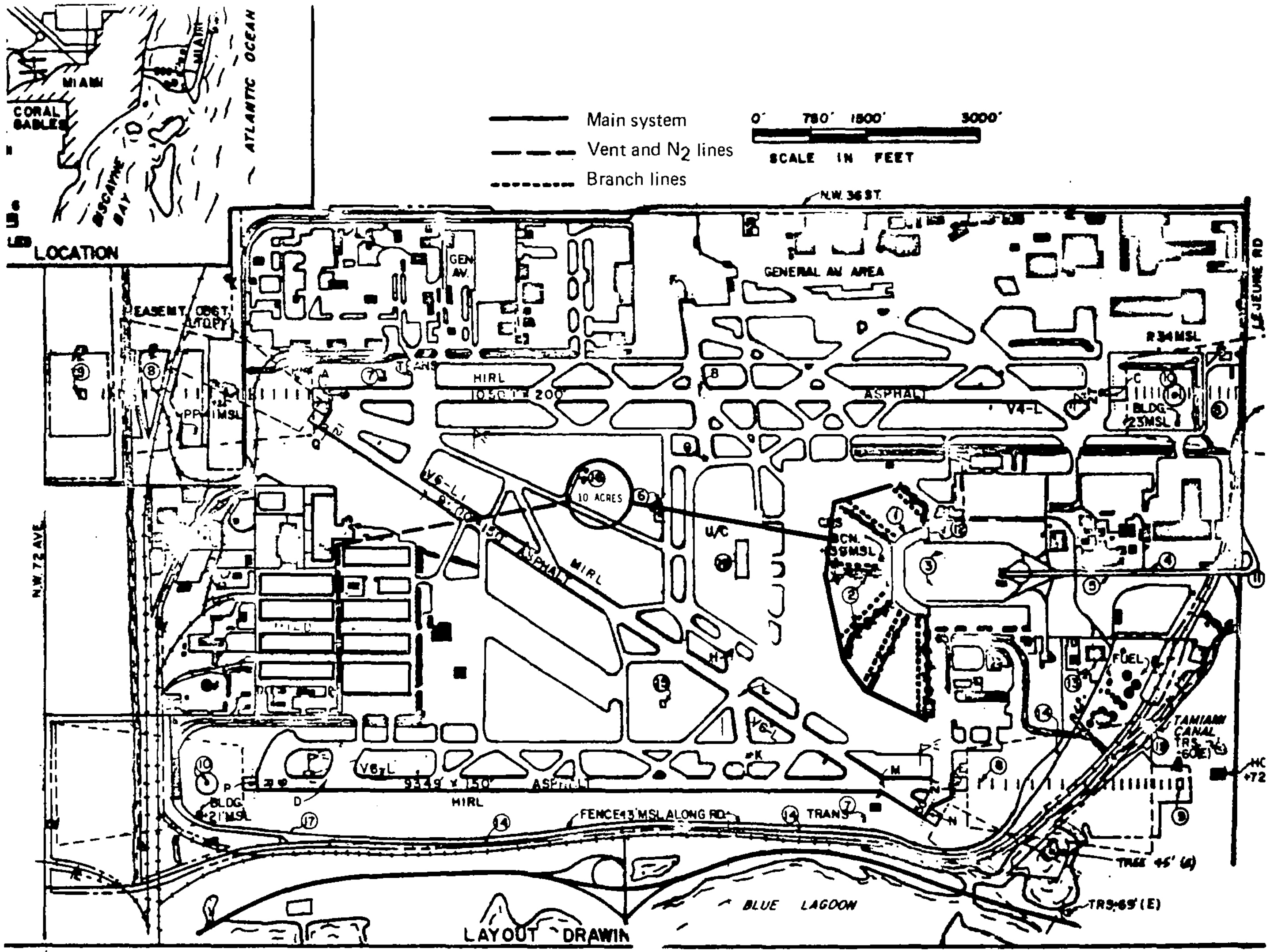


Figure 74.—Miami Airport

Table 20.—Relative LH_2 System Requirements—7 Airports

	ORD	JFK	LAX	ATL	HNL	SEA	MIA
Daily departures: total	112	90	112	47	43	35	33
$\geqslant$2000 nmi	8	58	40	2	43	8	6
1500 to 2000 nmi	37	13	31	6	0	7	0
$<$1500 nmi	67	19	41	39	0	20	27
Daily WTD miles (1000) total	147	213	211	50	129	54	40
(3000 x 1.0) for ranges $\geqslant$ 2000	24	174	120	6	129	24	18
(1750 x 1.05) for ranges 1500 to 2000	68	24	57	12	0	13	0
(750 x 1.10) for ranges $<$ 1500	55	15	34	32	0	17	22
WTD block fuel factor and WTD total fuel factor	1.00	1.45	1.44	0.34	0.88	0.37	0.27
Peak hydrant demand	12	15	20	8	8	4	6
Demand factor	1.00	1.25	1.67	0.67	0.67	0.33	0.50
LH_2 storage factor	1.00	1.45	1.44	0.34	0.88	0.37	0.27
LH_2 distribution system factors:							
Line size factor	1.00	1.12	1.29	0.82	0.82	0.57	0.71
Line length: main line	9200/1.00	12 000/1.30	13 000/1.41	6300/0.68	7300/0.79	6600/0.72	6500/0.71
branch line	9500/1.00	5200/0.55	3500/0.37	6000/0.63	7000/0.74	9100/0.96	4900/0.52
vent and N_2	17 000/1.00	8000/1.00	2000/0.12	8500/0.50	2000/0.12	3000/0.18	4700/0.28
Plant size, acres	25	32	32	12	23	12	10
Land acquisition	None	None	None	None	Fill	None	None

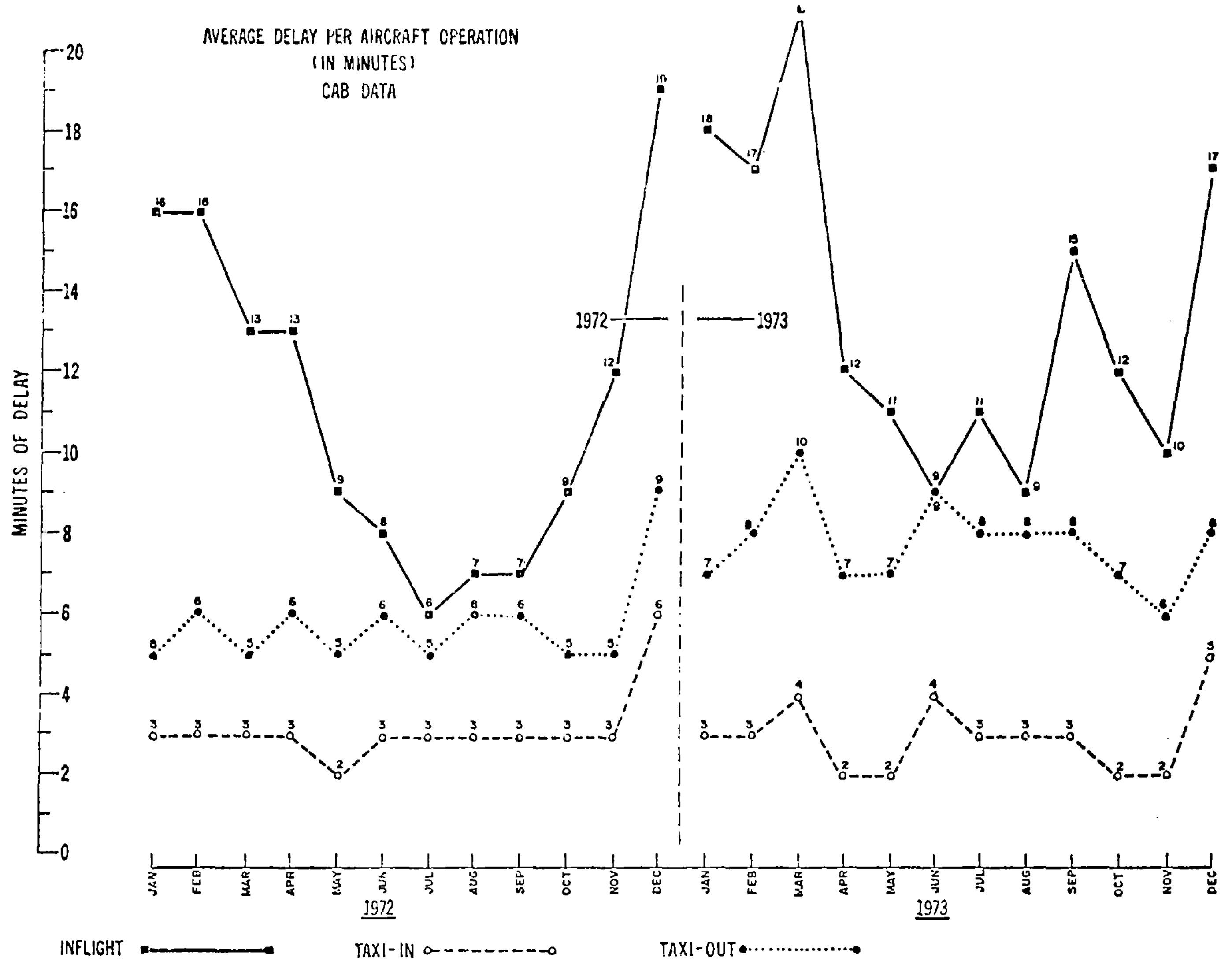


Figure 75.—In-flight and Taxi Delays—ORD

APPENDIX B
REGULATIONS

Airport-related regulations, explained and illustrated below, governed or influenced the installation of LH_2 facilities.

AIRSPACE PROTECTION

The Federal Aviation Regulations, Part 77 (reference 5) define the "imaginary surfaces" which protect the airways from encroachment of obstacles to air navigation. Figure 76, excerpted from reference 5, illustrates these surfaces. For the purposes of this study, no parked aircraft or building shall extend above the following imaginary surfaces:

Primary Surface
A surface longitudinally centered on a runway. This surface is as long as the associated runway plus 200 ft* on each end; 1000 ft wide (500 ft each way from centerline); elevation of any point on the surface is the same as the nearest point on the runway centerline.

Transitional Surface
A surface which extends outward and upward at right angles to the runway centerline, and the runway centerline extended, at a slope of 7 horizontal to 1 vertical from the sides of the primary surface.

Approach Surface
A surface longitudinally centered on the extended runway centerline and extending outward and upward from the end of the primary surface at a slope of 1 vertical to 50 horizontal.

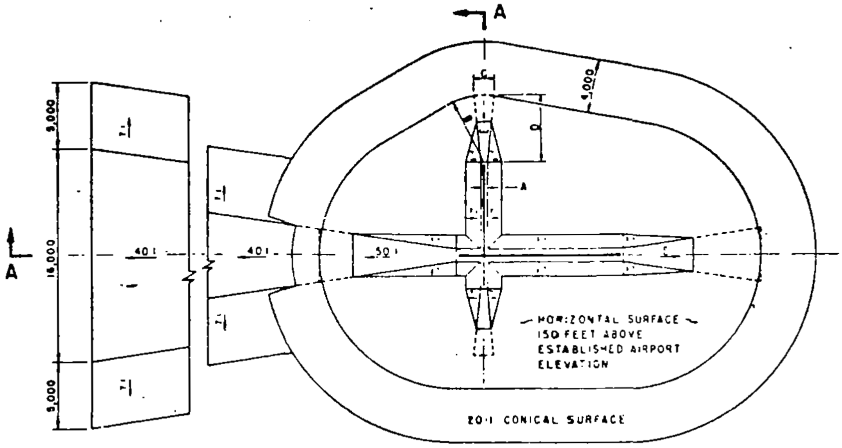
The ORD airport layout plan has chosen to interpret these descriptions to locate the "Building Limit Line" (BLL) parallel to and 750 ft from the runway centerline and/or 180 ft from taxiways. No building should be located on the runway side of such lines. In addition, no parked airplane should penetrate the imaginary surfaces. In effect this requirement places the parked airplane tail fin not closer to the runway centerline than:

Model	Tail height	Distance to runway centerline
Lockheed LH_2 (Internal Tank)	59.5 ft	920 ft
Boeing 707-320	42 ft	794 ft
Douglas DC-8-63	43 ft	801 ft
Beech B80 "Queen Air"	14.8 ft	605 ft

TERMINAL TAXI-LANE

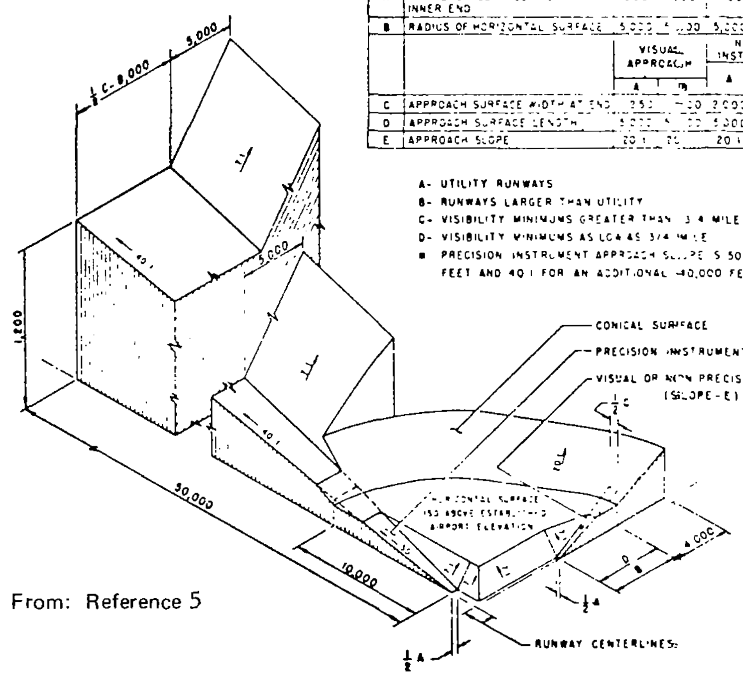
Airplanes approaching a location of high traffic congestion such as adjacent to the passenger loading apron will be taxiing at relatively low speed, yet still require a cleared path wider than their wingspans. Data from reference 8, shown in table 21,

* 1 ft = 0.3048 m.



DIM	ITEM	DIMENSIONAL STANDARDS (FEET)					
		VISUAL RUNWAY		NON-PRECISION INSTRUMENT RUNWAY			PRECISION INSTRUMENT RUNWAY
		A	B	A	B		
					C	D	
A	WIDTH OF PRIMARY SURFACE AND APPROACH SURFACE WIDTH AT INNER END	250	500	500	500	1,000	1,000
B	RADIUS OF HORIZONTAL SURFACE	5,000	[illegible]	5,000	10,000	10,000	10,000
		VISUAL APPROACH		NON-PRECISION INSTRUMENT APPROACH			PRECISION INSTRUMENT APPROACH
		A	B	A	B		
					C	D	
C	APPROACH SURFACE WIDTH AT END	[illegible]	[illegible]	2,000	3,500	4,000	16,000
D	APPROACH SURFACE LENGTH	5,000	[illegible]	5,000	10,000	10,000	*
E	APPROACH SLOPE	20:1	20:1	20:1	34:1	34:1	*

A- UTILITY RUNWAYS
B- RUNWAYS LARGER THAN UTILITY
C- VISIBILITY MINIMUMS GREATER THAN 3/4 MILE
D- VISIBILITY MINIMUMS AS LOW AS 3/4 MILE
* PRECISION INSTRUMENT APPROACH SLOPE IS 50:1 FOR INNER 10,000 FEET AND 40:1 FOR AN ADDITIONAL 40,000 FEET



From: Reference 5

Isometric View of Section A-A

77.25 Airport Imaginary Surfaces

Trans. 8 (Amdt. 77–9, Eff. 5/16/71)

Figure 76.—Objects Affecting Navigable Airspace

Table 21.—Taxiway Dimensional Criteria
(From: Reference 8)

	DESIGN ITEM	SYMBOL	DIMENSIONAL CRITERIA (FEET) AIRPLANE TAXIWAY DESIGN GROUP 1/			
			I	II	III	IV
1.	Taxiway Structural Pavement Width on Tangents	W_T	50	75	100	125
2.	Taxiway Structural Pavement Width on Turns	W_C	65	90	115	140
3.	Taxiway Shoulder Width	--	20	25	35	40
4.	Safety Area Width	--	110	165	220	310
5.	Taxiway and Apron Taxiway Obstacle Free Area Width	--	210	285	365	470
6.	Terminal Taxilane Obstacle Free Area Width	--	160	225	295	390
7.	Separation Distance from Taxiway C_L to Taxiway C_L	S_T	200	300	300	400
8.	Separation Distance from Taxiway C_L to Runway C_L 2/	S_R	400	400	600	1000
9.	Radius of Taxiway C_L Turns	R	100	150	150	200

1/ Determine Airplane/Taxiway Design Group from Figure 4 or 5.
2/ Where CAT II operations are anticipated, use at least 600 feet.

specifies minimum widths for terminal taxilanes, related to the size of the largest airplane for which it is designed. The LH_2 airplane would be classed in Group 3, requiring a 295-ft wide taxilane. This width would provide 61-ft clearance on each wingtip.

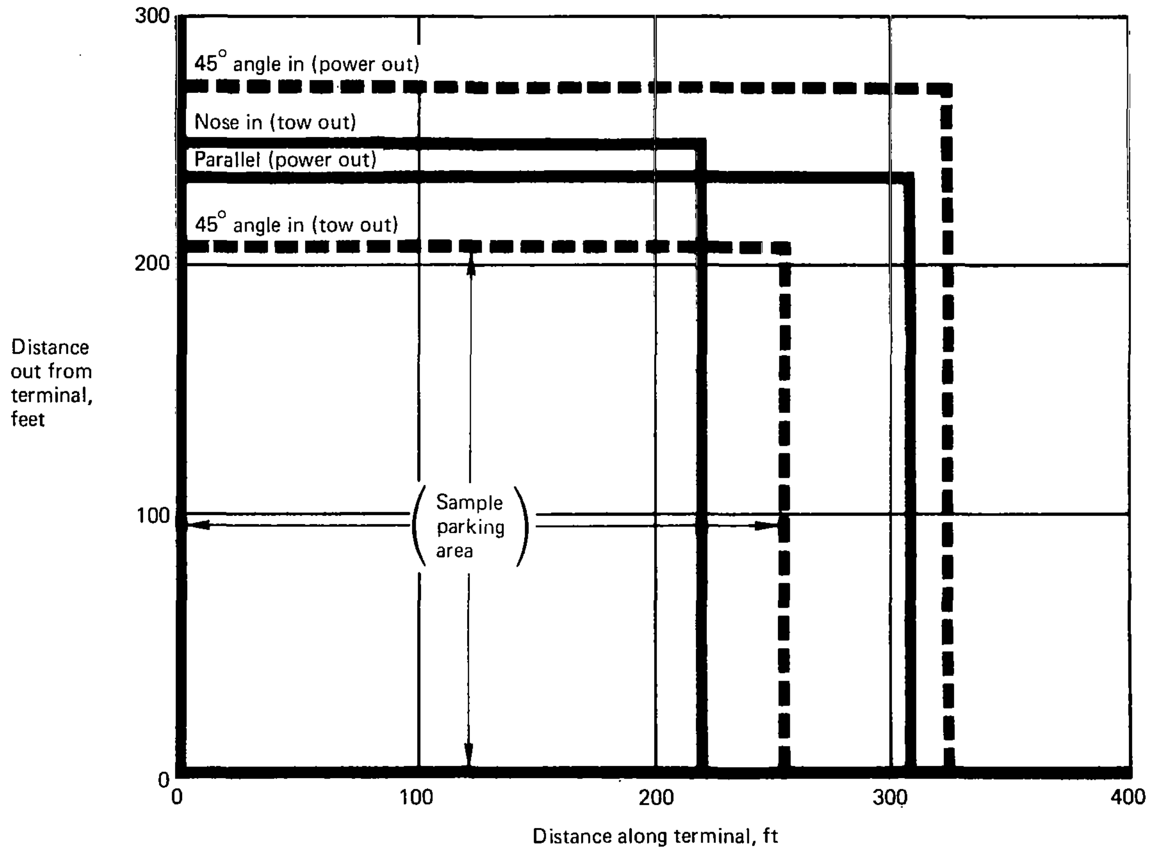
TERMINAL AIRPLANE PARKING

When approaching and maneuvering into its assigned parking space on the passenger loading apron, airplane speed is reduced even further than on the terminal taxilane. With reduced speed, airplanes can be parked very close to each other. Industry agreement, as documented in reference 9, defines the conditions and relationships of parked airplanes to the terminal building. Figure 77, excerpted from reference 9, spells out those conditions.

PASSENGER ACCOMMODATION SPACE IN TERMINAL

It is recognized that rational passenger terminal design must allow adequate space for airport functions, plus that required for passenger waiting, circulation and convenience. However, it is difficult to obtain agreement among architects as to what factor can be considered adequate: adequate space in a given terminal situation may be lavish for another and yet inadequate for a third. The FAA selected a factor of 242 ft^2 per typical peak hour passenger for estimating terminal space requirements for long-range planning (see table 22). That is probably a good factor since architects Landrum and Brown found the present ORD terminal "over utilized" in 1967 with a calculated factor of 212 ft^2/TPHP.

Our situation here is different: all of our airport functions requirement is already fulfilled in the existing terminal. Therefore, all that is required is boarding lounge space. Reference 10 suggests an allowance for terminal boarding lounges of 11 ft^2 per passenger seat in the airplanes accommodated.



- 70° nose wheel steering (power out)
- 10-ft travel with nose wheel straight ahead before and after parked position
- 15-ft building clearance for nose-in parking
- 25-ft building clearance for other parking positions
- 25-ft aircraft-to-aircraft clearance during parking maneuvers
- Coordinate with using airline for specific planned operating procedure

From: Reference 9

Figure 77.—Minimum Parking Space Requirements

Table 22.—Terminal Building Area Requirements
(From: Reference 7)

Backup Sheet for Terminal Building, Air Carrier, Passenger

1. Derivation, Unit Area Per TPHP, Domestic

Using the data in "Airport Terminal Buildings" as bases for determining unit square foot areas per typical peak hour passengers (TPHP), and assuming the values in the curves for 1,000 TPHP to be the norms for our present purpose, the following values are given:

Ticket Lobby	10 sq. feet	
Airline Oper.	48 sq. feet	
Baggage Claim	10 sq. feet	
Waiting Rooms	18 sq. feet	
Eating Fac.	16 sq. feet	
Kitchen & Stor.	16 sq. feet	
Other Concessions	5 sq. feet	
Rest Rooms	3 sq. feet	
Total	126 sq. feet	= 52*
Circulation, Mech. & Maint., Walls, Partitions	116 sq. feet	= 48*
Gross Area	242 sq. feet/TPHP	= 100%

* Factors used by Philadelphia Consultants, 1966

APPENDIX C
ALTERNATE RAMP SERVICE CONCEPTS

C1–FUELING

Many methods and equipment designs were considered in servicing the LH_2 airplane on the ramp. The fueling operations were given a great deal of study for the optimum arrangements and concept designs for safety and reduction in ramp congestion. The selected fueling design is described in sections 5.6 and 5.7 of this report. Some of the alternate concepts reviewed are described in the following paragraphs.

LH_2 FUEL TRANSFER TRUCK CONCEPT

Figure 78 shows an LH_2 transfer truck system to transfer and meter the LH_2 from an underground hydrant in the ramp to the airplane receptacles. As with the tanker truck concept, this truck connects to the airplane by a powered boom controlled by the driver. The LH_2 supply from the hydrant to the truck is also through vacuum insulated lines. The GH_2 vent recovery system will connect by an independent, flexible insulated hose from the airplane to the hydrant recovery system. The reason for the separate vent recovery line is to keep the recovery system connected to the airplane at all times and allow the LH_2 transfer truck to move to other airplanes. The LH_2 fuel transfer truck includes a hydrogen leak detection system and a fire control system.

The fuel transfer truck concept is a practical way to service the airplane if the terminal boom concept cannot be adopted. The transfer truck-hydrant system offers the most in versatility in that one truck could supply and meter LH_2 fuel to many airplanes. It will add to the congestion of the ramp.

GASEOUS HYDROGEN RECOVERY LINE TRUCK–CONCEPT

Figure 79 shows a truck to supply and connect the airplane GH_2 vent lines to the recovery system in the ramp mounted hydrants. These vent hoses are used in conjunction with the fuel transfer truck system previously discussed and are connected to the airplane at all times the airplane is parked. The GH_2 flexible hoses are insulated flexible sections which have self-closing poppet valves at each end to prevent entrance of contaminating atmospheres or materials, eliminating the need for purging the lines before each use of the hose. Each hose section also has a pressure bleed-off system to capture the GH_2 given off from the hose as it warms up in storage.

The vent recovery lines are required where the LH_2 transfer truck fueling system is used and also at remote locations where fueled airplanes are on standby. The use of this system at each parked airplane is necessary. The hanging flexible lines are not a safe arrangement and further research would be necessary to properly design a vent recovery system of this type.

FIXED RAMP BOOM CONCEPT

Figure 80 shows a concept for transferring LH_2 and GH_2 recovery from an underground supply system. The booms as shown are controlled remotely by an operator nearby.

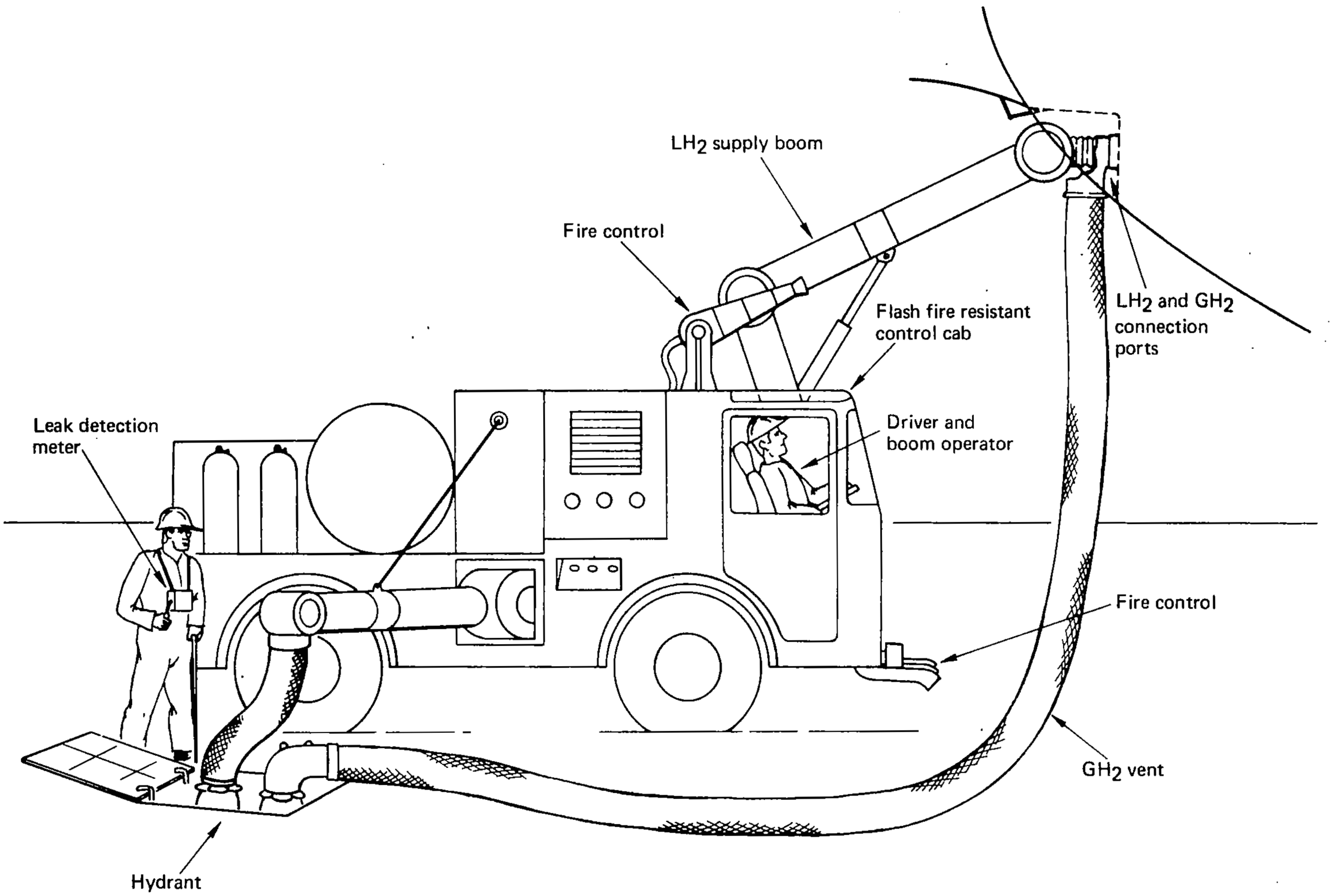


Figure 78.—Liquid Hydrogen Fueling—Remote Control Boom Truck

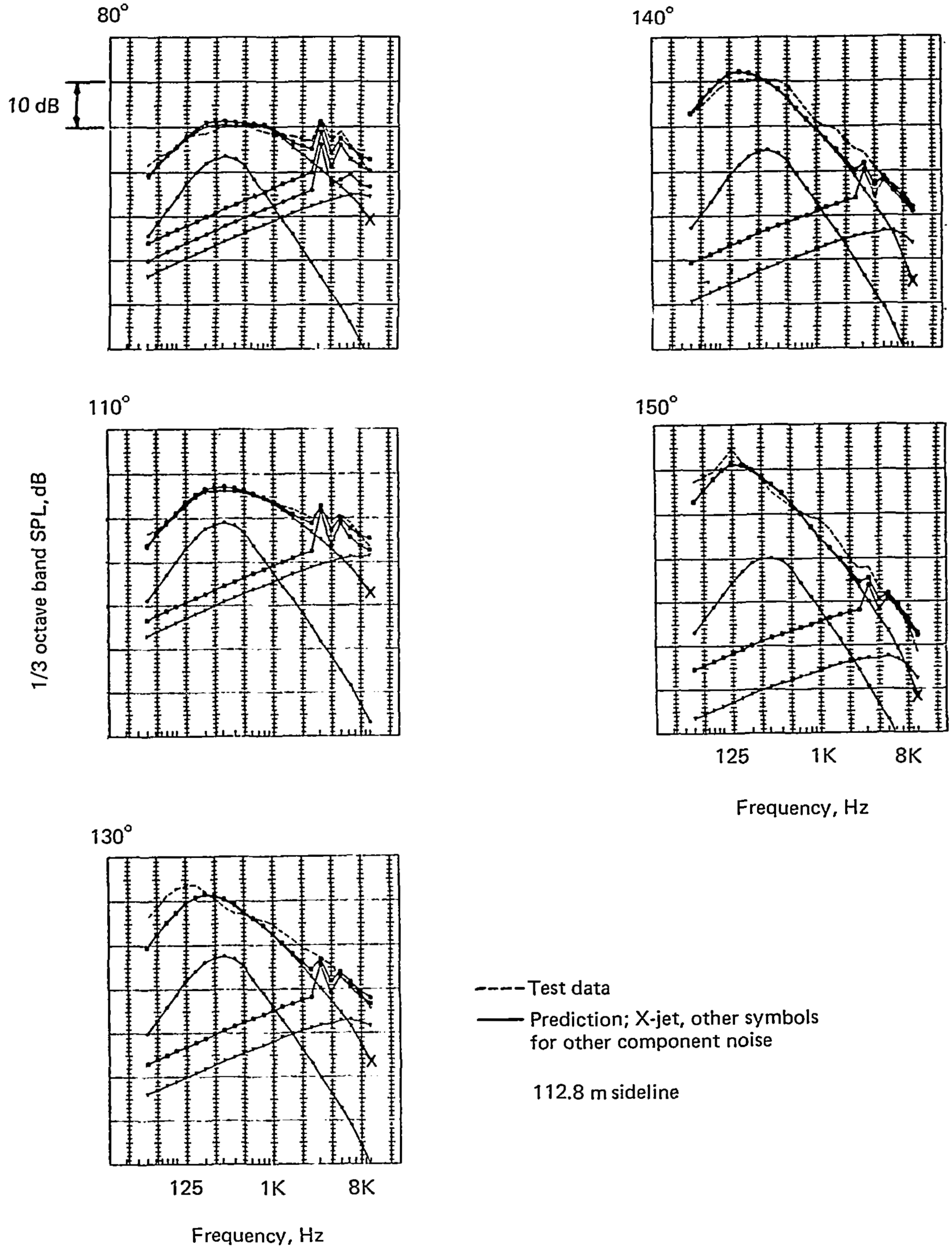


Figure 93.— Comparisons of Predicted Noise and Test Data, Total Noise and Noise Components

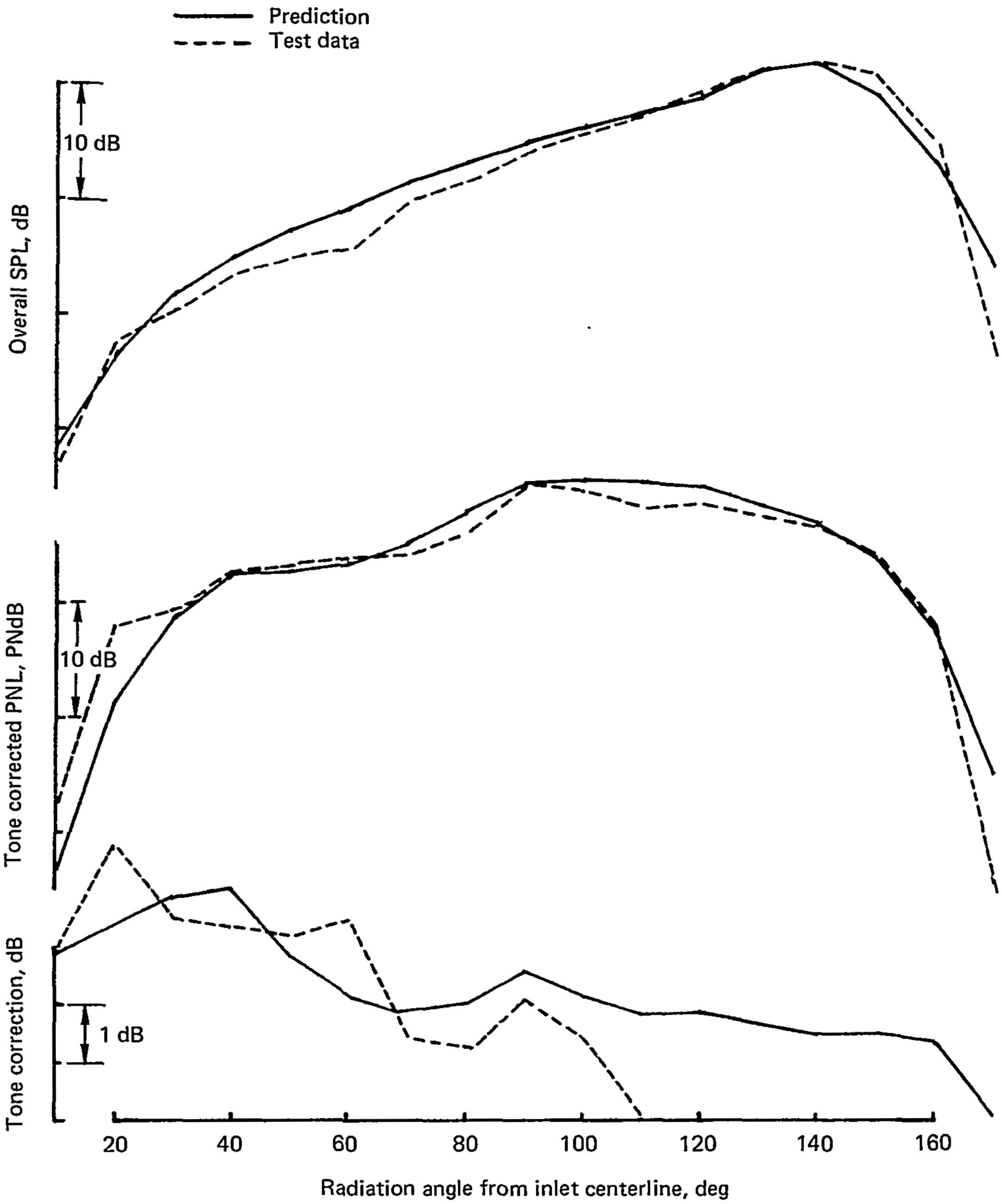


Figure 94.— Comparison Between Prediction and Test Data; Overall Sound Pressure and Tone Corrected Perceived Noise Levels and Tone Correction,Ground Static

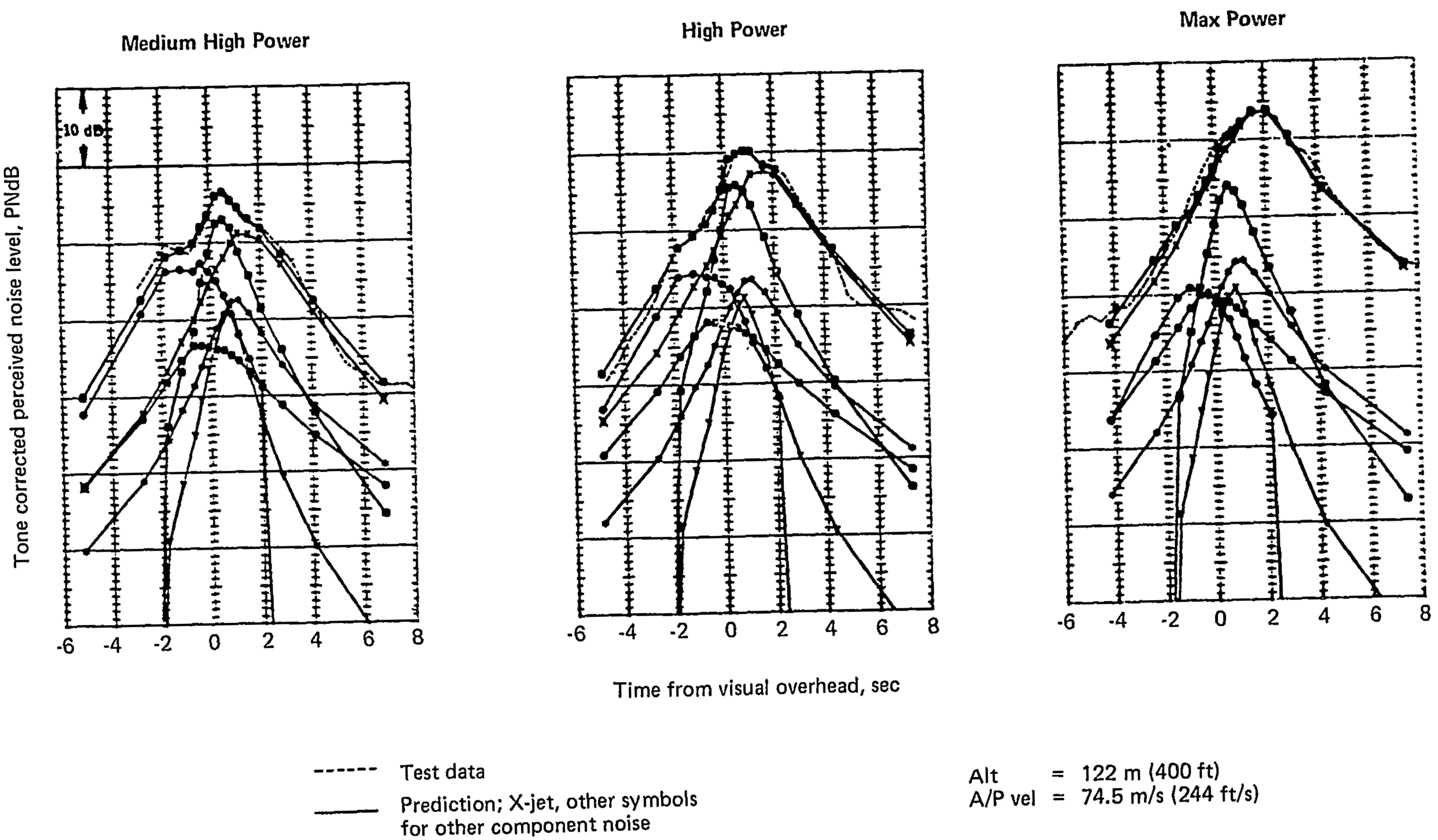


Figure 95.—Comparisons Between Predicted Tone Corrected Perceived Noise Level and Test Data (Level Flight)

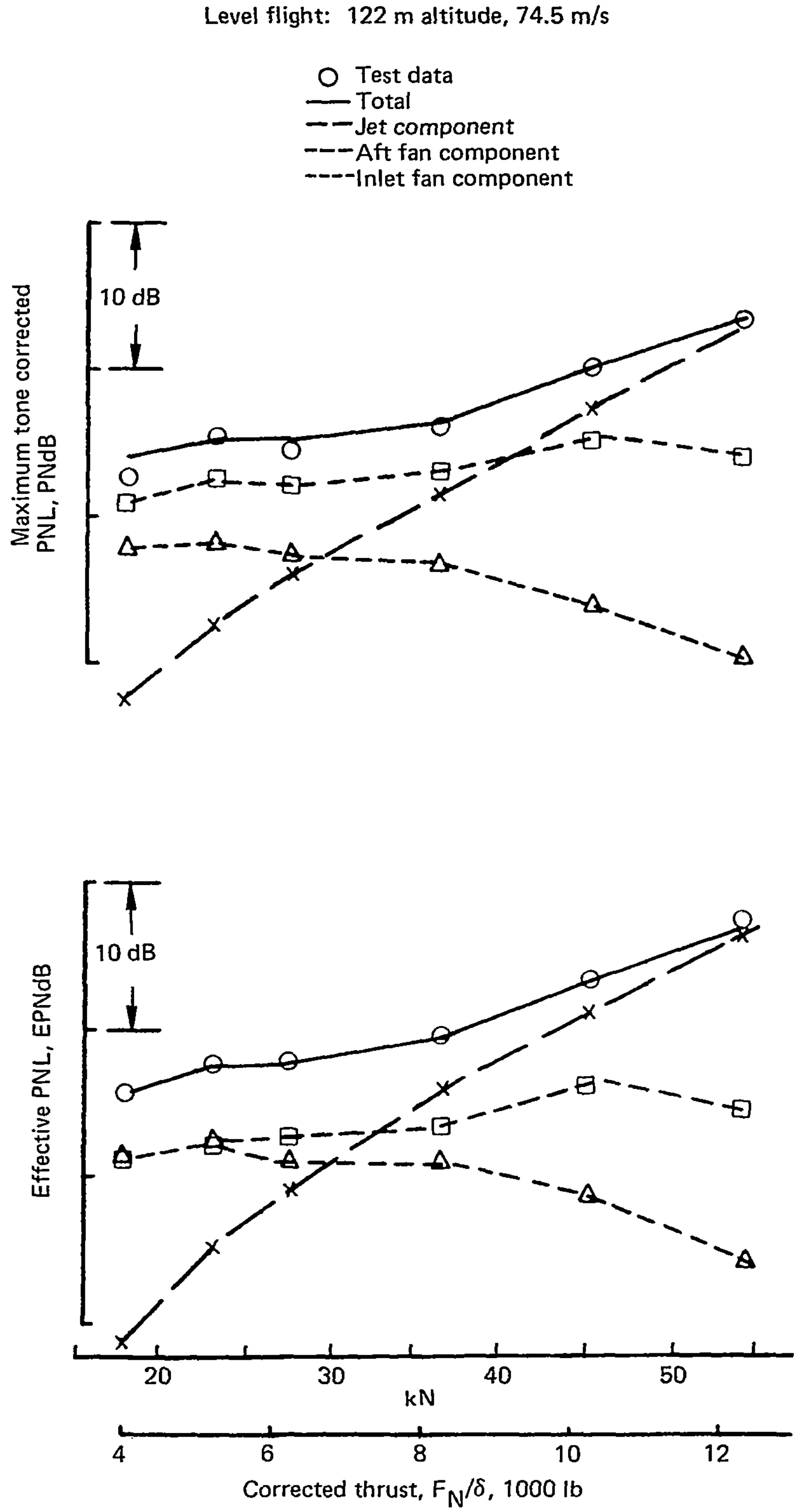


Figure 96.— Comparisons of Predicted Maximum Tone Corrected and Effective Perceived Noise Levels With Test Data

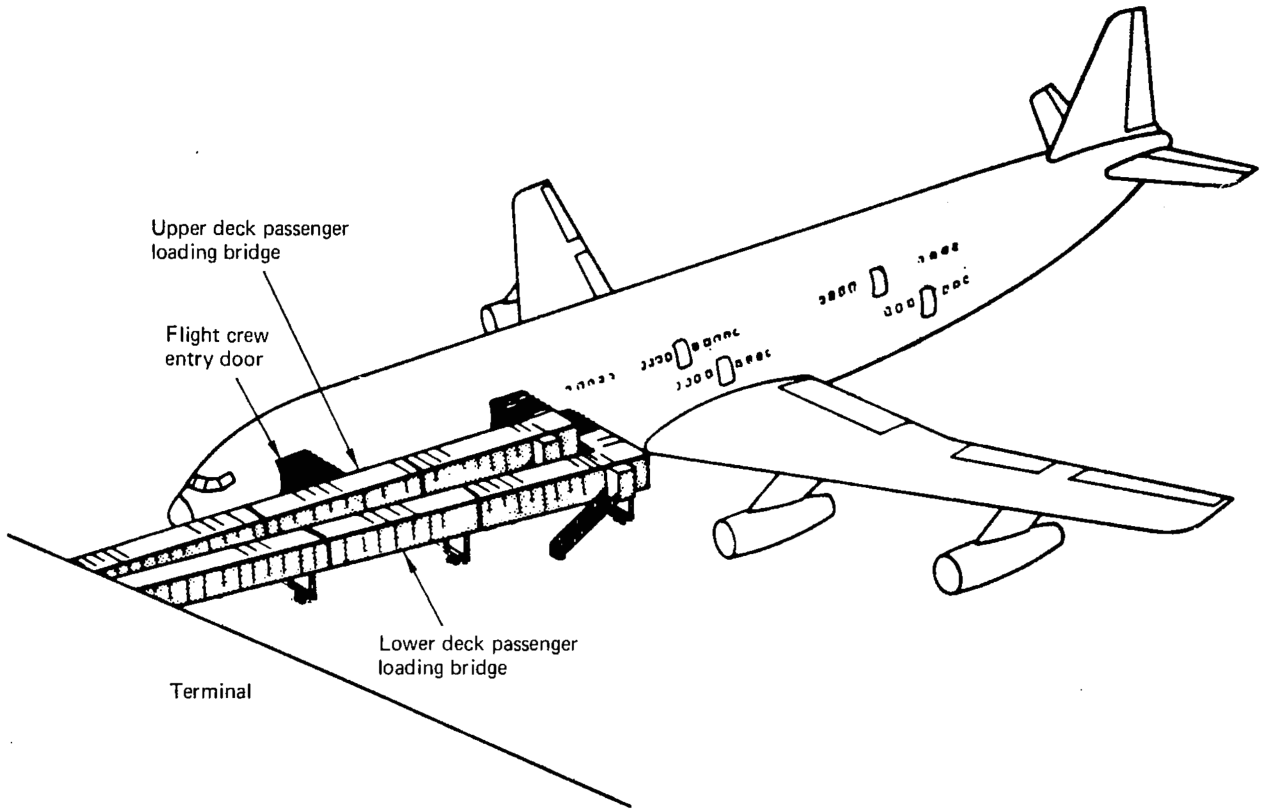


Figure 82.—Passenger Loading—Separate Bridges

passenger decks and an elevator between decks for in-flight transferring. The support system is described in section 5.6 of this report. Two other concepts are discussed as follows.

GALLEY INTEGRAL ELEVATOR SYSTEM

The galleys at each end of the cabin would include a built-in elevator. This elevator would be used to service the upper deck galleys from the lower deck. It also would be used during flight to transfer galley supplies.

The use of integral elevators to supply the upper deck galleys would reduce the need for outside lift platforms to reach the 8.22 m (27 ft) level. The elevator system could be used in the cabin service support to the upper deck, however, this method used in either galley or cabin support would be slower than an outside lift platform system.

GALLEYS ON LOWER DECK ONLY-CONCEPT

A third concept to be considered is to have all the galleys located on the lower deck and the upper deck served by elevators at each end of the passenger cabin. This arrangement would eliminate the need for outside lifting devices and upper deck storage areas.

This galley arrangement would be practical for quick ground service due to the need only for lower deck loading. It would not be the most convenient for meal service to the passengers.

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