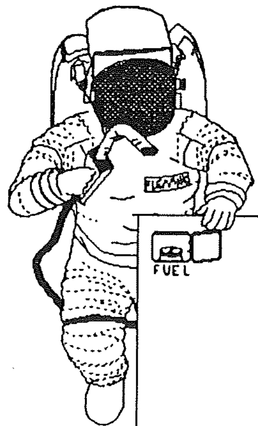

STV Fueling Options

Space Station Evolution
Beyond the Baseline Conference

August 7, 1991

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Outline

- ❑ Introduction
- ❑ Operations Concepts for On-Orbit Propellant Management
- ❑ Lunar Vehicle Processing Times
- ❑ Assembly of Propellant Management Facility Concepts
- ❑ Maintenance of Propellant Management Facility Concepts
- ❑ Analysis of Early Shuttle ET Mating Problems
- ❑ Conclusions

Introduction

Lunar vehicles that will be space-based and reusable will require resupply of propellants in orbit. Approximately 75% of the total mass delivered to low earth orbit will be propellants. Consequently, the propellant management techniques selected for Space Exploration Initiative (SEI) orbital operations will have a major influence on the overall SEI architecture.

Introduction

- Approximately 3/4 of the total mass to low-earth orbit for lunar missions will be propellant.

- Propellant management techniques selected will have a major impact on the overall SEI architecture.

- There are two primary options for propellant resupply of Space Transfer Vehicles:
  - Replacement of depleted propellant tanks
  - Replenishment of depleted tanks

- Data presented was culled from three studies:
  - Fuel Systems Architecture Study
  - On-Orbit Assembly/Servicing Study
  - Aerobraked Lunar Vehicle Cost & Operations Assessment

Key Technology Development Required

There are several technologies that will require further development to enable successful propellant management operations on orbit. These technologies are common to both drop tank installation and propellant transfer refueling options.

Key Technology Development Required

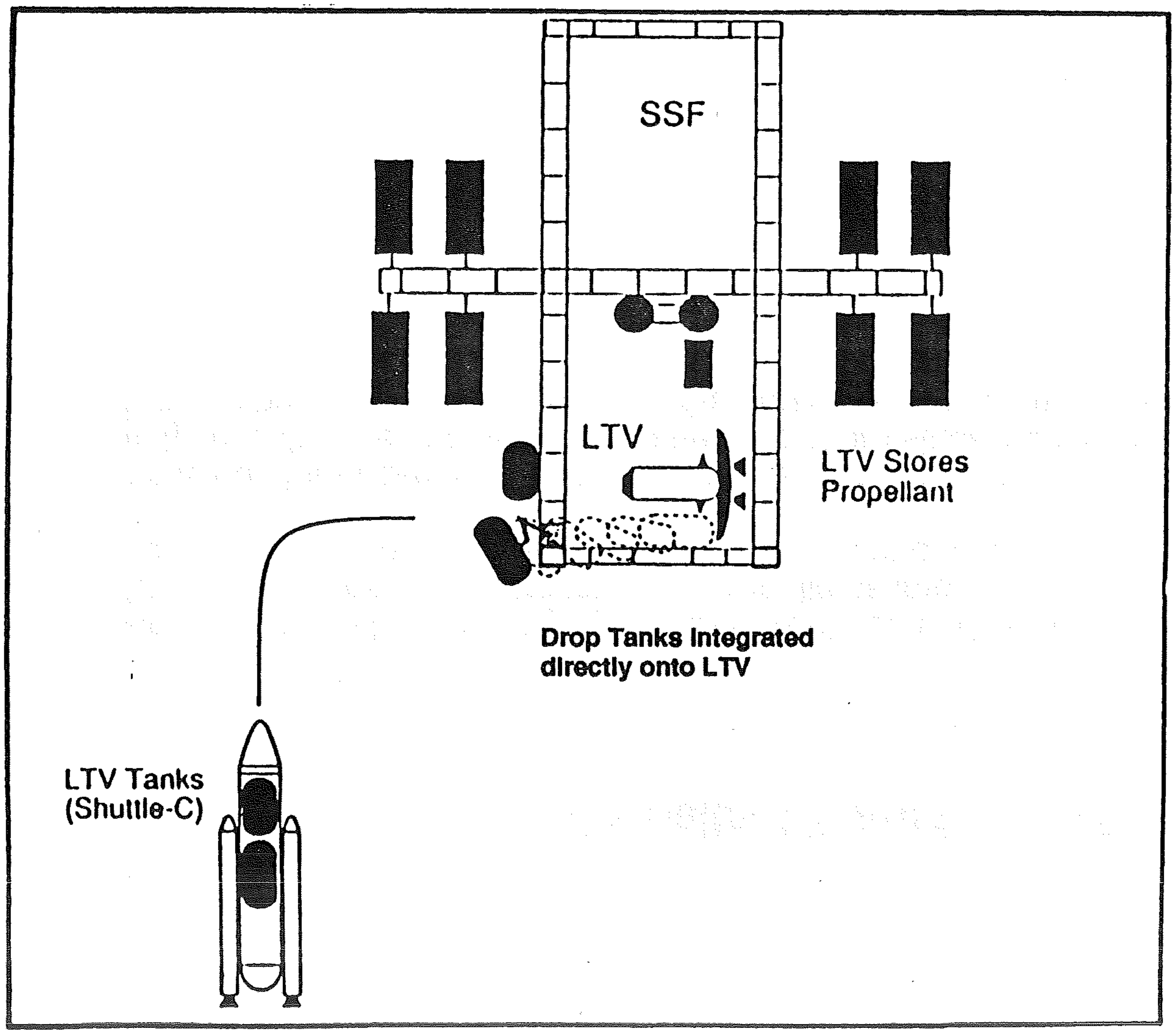
Technology	Propellant Management Concept	
	Drop Tank	Propellant Xfer
Fluid Transfer	√	√
Leak Detection	√	√
Mass Gauging	√	√
Liquid Acquisition	√	√
Fluid Dynamics (slosh, settling, etc.)	√	√
Boiloff Control (VCS, reliquefaction, refrigeration, TVS, etc.)	√	√
Reliable Quick-Disconnect Fluid Interfaces	√	√

- Key cryogenic technology developments are common to both methods of on-orbit propellant resupply.

Drop Tank Installation

The Drop Tank Installation operations concept calls for refueling of the Lunar Transfer Vehicles (LTV) by replacement of the empty propellant tanks that will be jettisoned during the mission. Three Shuttle-C launches would be needed to deliver the entire propellant load (contained in four fully-loaded drop tanks) to the LTV. The drop tanks would be installed on the LTV at the SSF Assembly/Servicing Facility during vehicle turnaround processing.

Drop Tank Installation



Propellant Operations

- LTV propellant drop tanks delivered to SSF via three Shuttle-C ETO launches.
- Drop tanks mated to LTV core immediately upon arrival at SSF.
- LTV core tanks resupplied from drop tanks prior to SSF departure.
- Two drop tanks jettisoned after TLI burn.
- LEV resupplied from LTV in low lunar orbit.
- Remaining two drop tanks jettisoned prior to TEI burn.
- Residual propellant boiloff control upon return to SSF.

Propellant Transfer at SSF

Another method of resupplying the LTV would be to deliver the propellant to the Space Station in a tanker, then transfer the propellants into the LTV. In this operations concept the tankers are designed for short-term stays in orbit and are disposed of after use.

As is true for all propellant transfer from tankers concepts in this paper, the LTV tanks are fully reusable (i.e., not jettisoned after depletion) since launch of dry drop tanks increases the number of ETO launches, with the additional launch mass capability underutilized.

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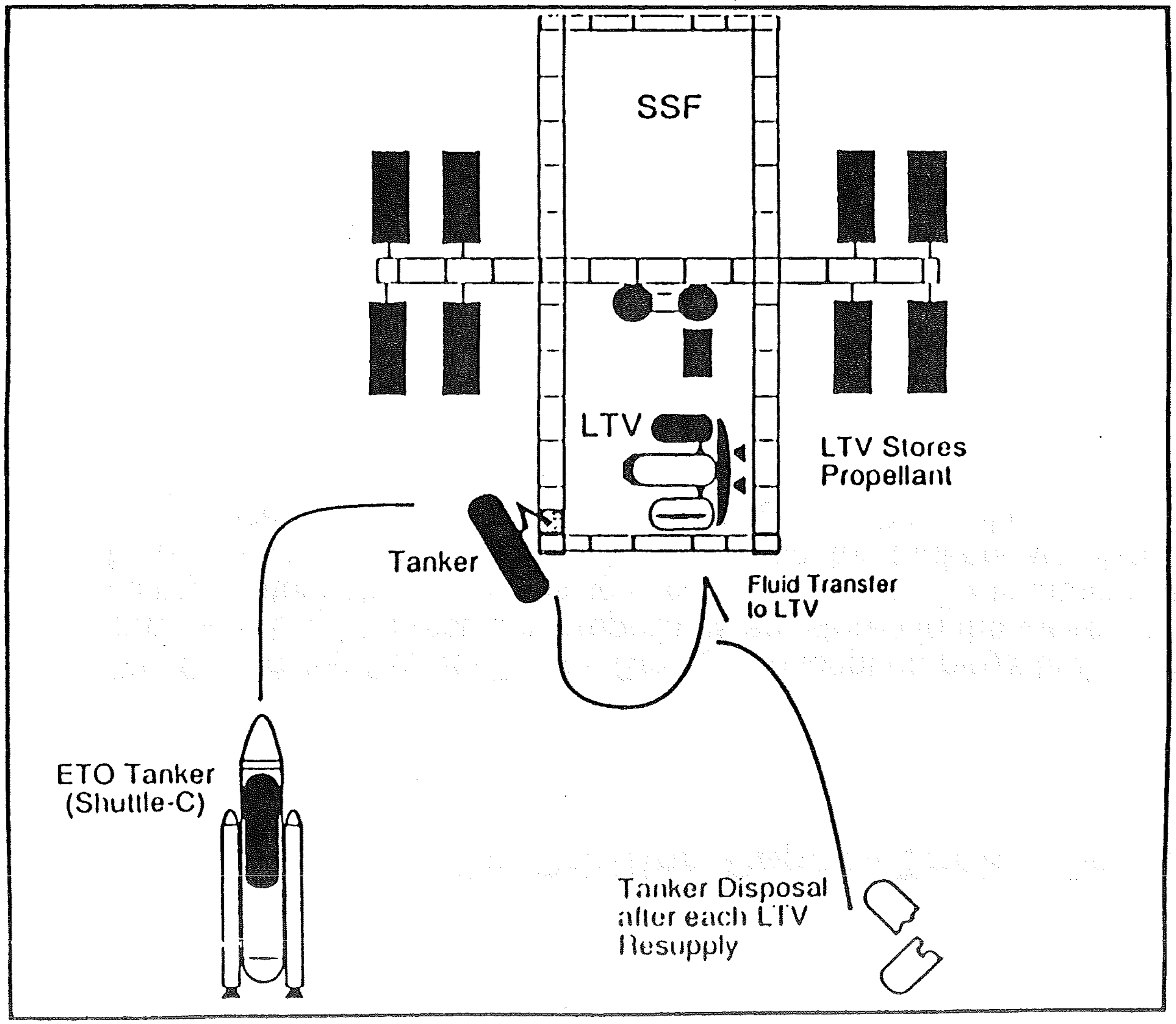
Propellant Transfer at SSF



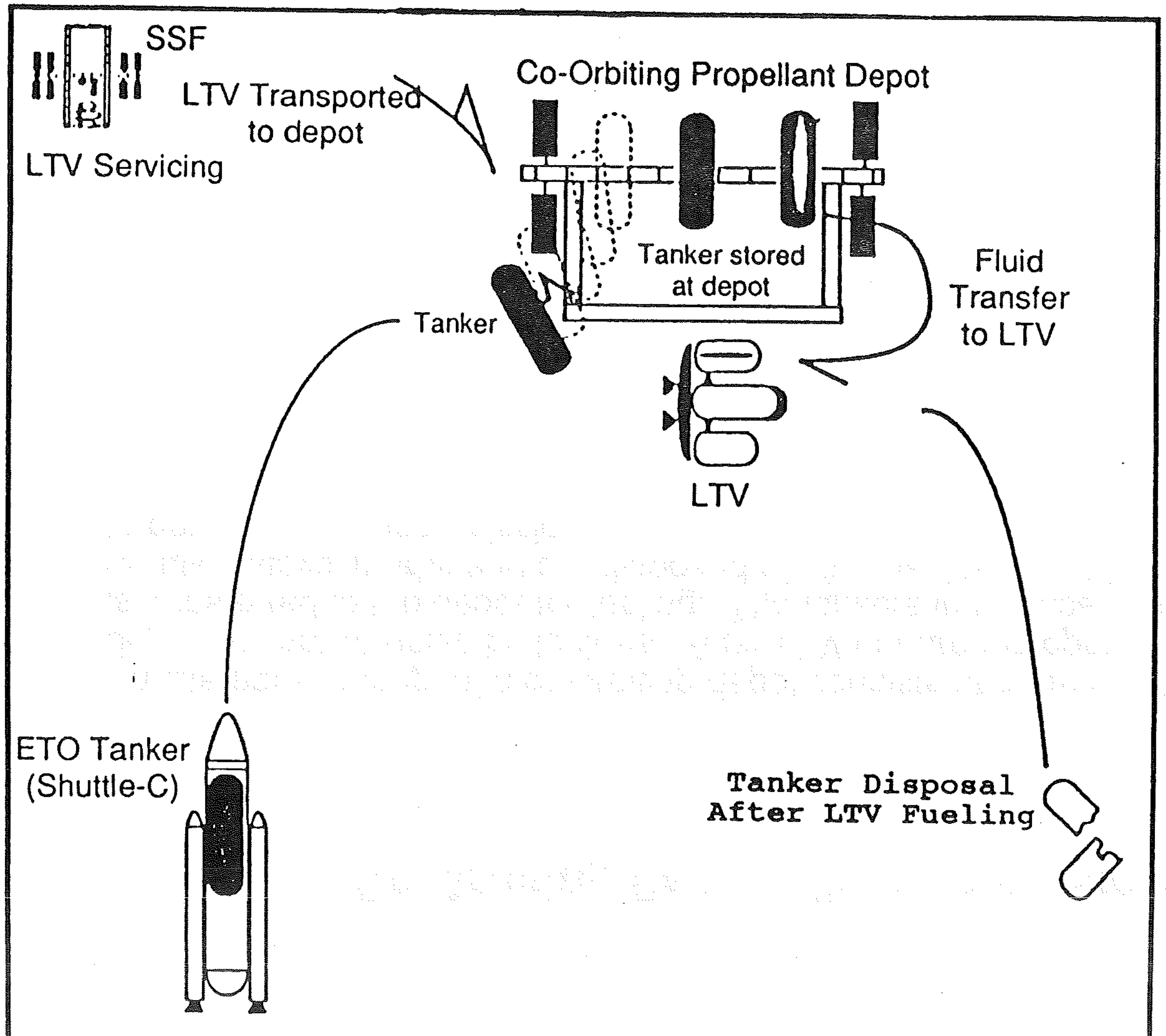
Propellant Operations

- LTV umbilicals mated during vehicle checkout at SSF.
- Propellants delivered to SSF in three tankers via Shuttle-C ETO launches (one tanker per launch).
- Propellants transferred from tankers to LTV tanks upon arrival.
- Tankers deorbited after depletion.
- No jettison of LTV propellant tanks during mission.
- LEV propellants resupplied from LTV in low lunar orbit.
- Residual propellant boiloff control upon LTV return to SSF.

Co-Orbiting Depot - Tanker Storage

The Co-Orbitng Depot - Tanker Storage concept employs tankers designed for long-term stays in orbit. The resupply propellants are stored in the tankers at a separate, co-orbiting facility. After vehicle processing is completed, the LTV is transferred to the depot and fueled. After vehicle departure for the moon, the tankers are disposed of in the atmosphere. This concept is most conducive to utilizing reusable tankers.

Co-Orbiting Depot - Tanker Storage



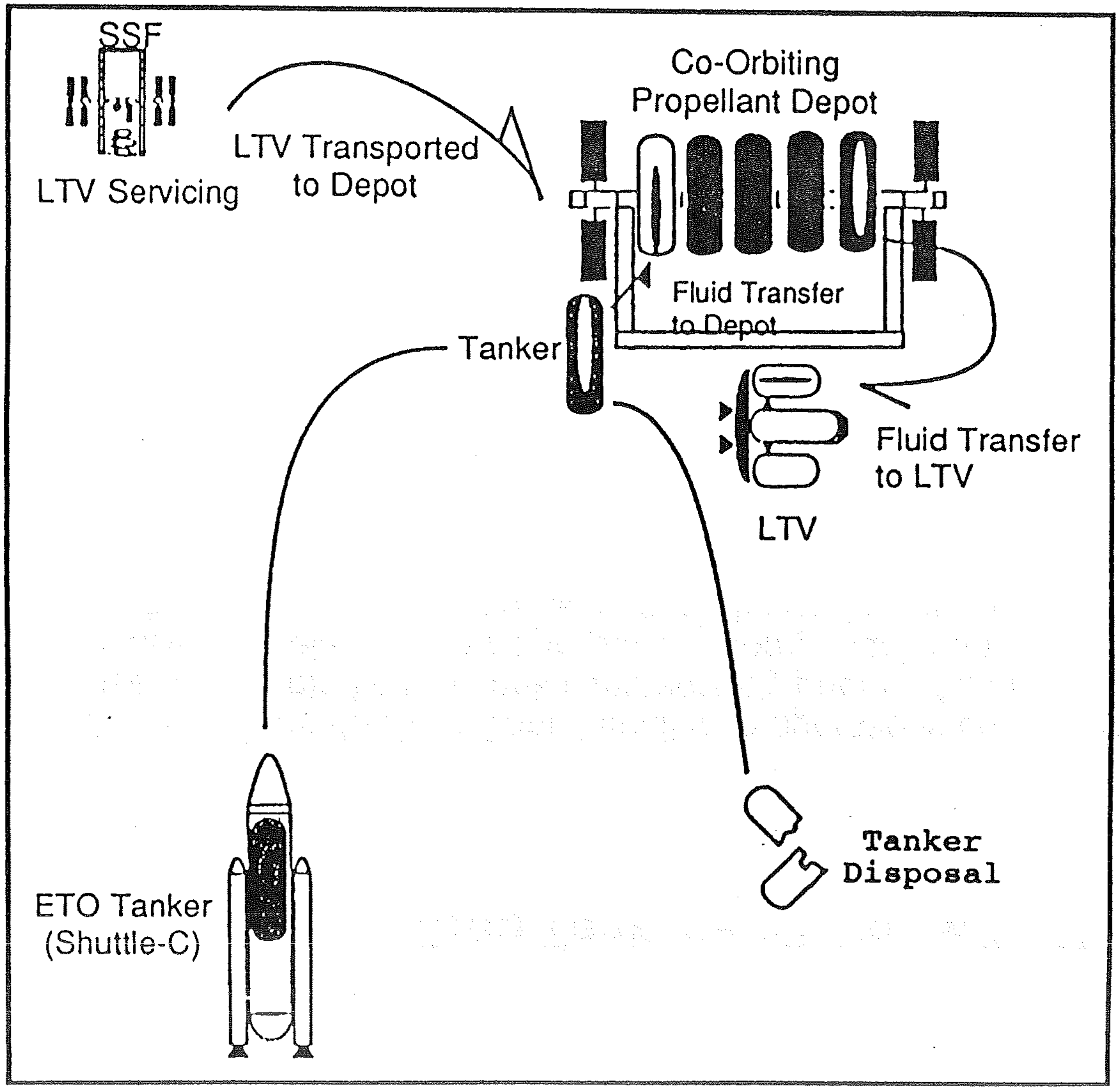
Propellant Operations

- Propellants delivered to co-orbiting depot in three tankers via Shuttle-C ETO launches (one tanker per launch).
- Propellants stored at depot in tankers.
- LTV rendezvous and dock with depot after processing at SSF completed.
- Umbilicals mated and propellants transferred from tankers to LTV.
- Tankers deorbited after depletion.
- No jettison of LTV propellant tanks during mission.
- LEV resupplied from LTV in low lunar orbit.
- Residual propellant boiloff control upon LTV return to SSF.

Co-Orbiting Depot - Permanent Storage Tank

An alternate concept of a co-orbiting depot consists of permanent storage tanks on the depot that are refueled by tankers. After LTV turnaround operations are finished, the vehicle is transferred to the depot for fueling. The tankers in this scenario are designed for short duration stays in orbit and are disposed of after depletion. This concept is the most tolerant to delays of the lunar mission.

Co-Orbiting Depot - Permanent Storage Tank



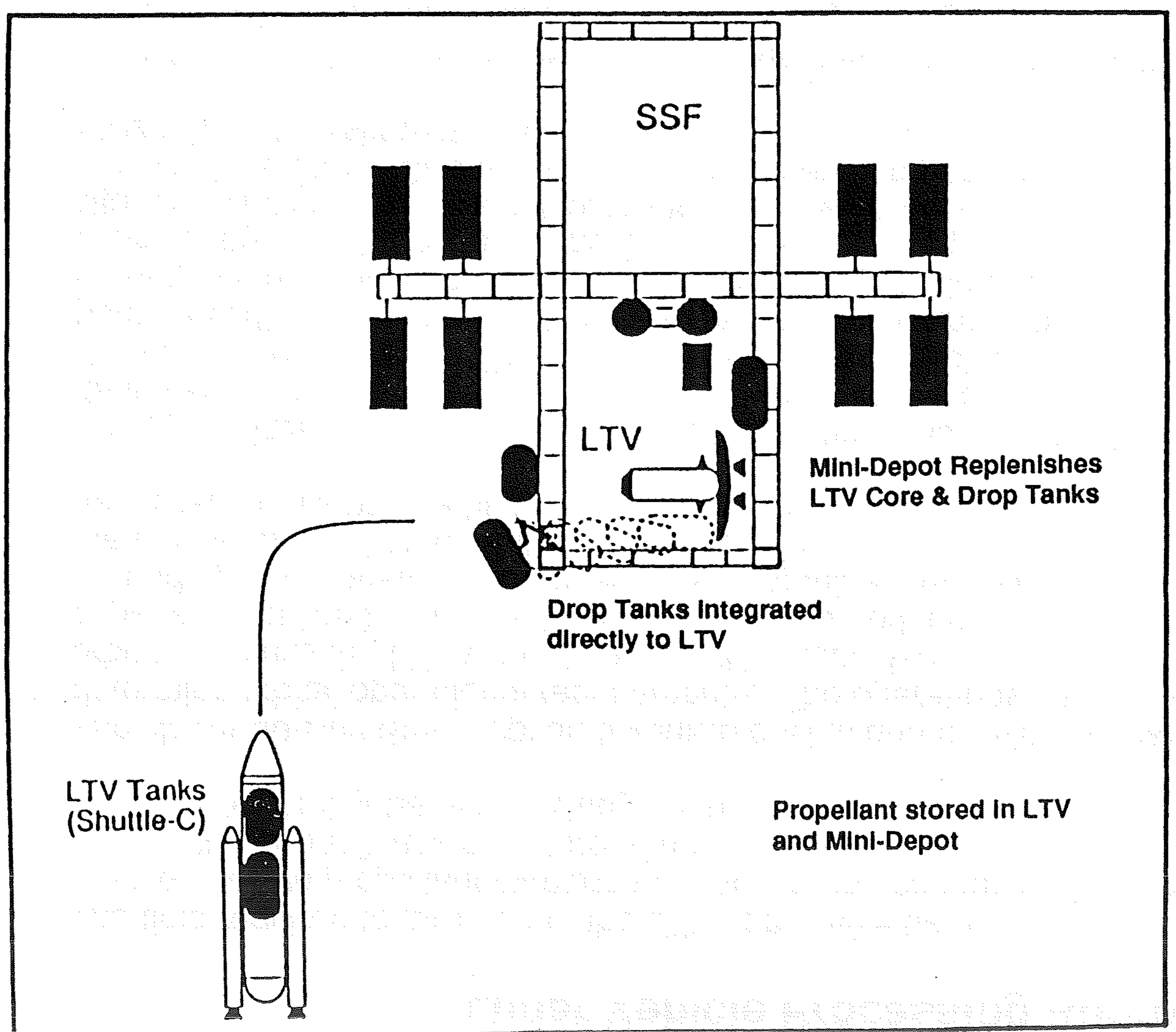
Propellant Operations

- Propellants delivered to co-orbiting depot in three tankers via Shuttle-C.
- Propellants transferred from tankers to depot storage tanks upon arrival.
- Tankers deorbited after depletion.
- LTV rendezvous and dock with depot after processing at SSF completed.
- Umbilicals mated and propellants transferred from depot to LTV.
- No jettison of LTV propellant tanks during mission.
- LEV resupplied from LTV in low lunar orbit.
- Residual propellant boiloff control upon return to SSF.

Drop Tank Installation with Mini-Depot

A variation on the Drop Tank Installation operations concept includes a "Mini-Depot" that is used to top-off the LTV tanks immediately prior to departure for the moon. The Mini-Depot consists of relatively small propellant storage tanks and transfer equipment that are used to fill the LTV core tanks and replace the boiloff losses experienced by the drop tanks.

Drop Tank Installation with Mini-Depot



Propellant Operations

- LTV propellant drop tanks delivered to SSF via three Shuttle-C launches.
- Drop tanks mated to LTV core immediately upon arrival at SSF.
- Mini-Depot resupplied.
- LTV core and drop tanks replenished by Mini-Depot prior to SSF departure.
- Two drop tanks jettisoned after TLI burn.
- LEV resupplied from LTV in low lunar orbit.
- Remaining two drop tanks jettisoned prior to TEI burn.
- Residual propellant boiloff control upon return to SSF.

Lunar Vehicle Processing Approach

The time required to turnaround the LTV at the ASF between lunar missions was estimated for each of the five propellant management operations concepts. The estimates were based on the work of the Lunar Transfer Vehicle On-Orbit Processing Study performed by the MDSSC-KSC On-Orbit Assembly/Servicing Study Team.

The NASA 90-Day Study Option 5 vehicle design and mission scenario were first analyzed to determine orbital operational requirements. The operations that are expected to be required on orbit to process the LTV were determined by considering current and past vehicle processing experience at KSC. Many of the lunar vehicle on-orbit operations will be similar to current Shuttle ground ops. An operations concepts that organized the required tasks into a logical sequence was then developed. Only operations considered essential to process the LTV with the minimum effort necessary to maintain a high probability of mission success were included.

An appropriate analogy for each on-orbit operation was selected from the KSC ground operations database of procedures and schedules drawn from the Shuttle, Spacelab, Delta, Centaur, and Saturn/Apollo programs. The actual ground time of each analogy was determined, including only personnel directly involved with physically performing the task. A time estimate for the corresponding orbital operation was derived by "transitioning" the ground time to space, considering the differences of the SEI vehicle and manpower and resource limitations of the Space Station. The on-orbit time estimates for the operations were then compiled into a processing timeline flow chart. Operations were incorporated in parallel in the timelines when logical to fully utilize the refurbishment crew.

Adjustments to the timelines were then made based on EVA quantifiable analogies from Shuttle EVA and RMS operations and neutral buoyancy testing. Advanced automation capabilities were also considered and appropriate timeline modifications incorporated.

The final processing flow timeline was then modified for each of the five propellant management concepts in order to compare the impact on LTV processing times.

Lunar Vehicle Processing Approach

Analyze Vehicle and Mission Scenario

↓

Develop Operations Concept

↓

Select & Quantify KSC Processing Analogies

↓

Transition Ground Tasks to On-Orbit Operations

↓

Assemble On-Orbit Processing Flows

↓

Incorporate EVA and Robotic Enhancements

↓

Modify Flows per PMF Concept

Lunar Vehicle Processing Times

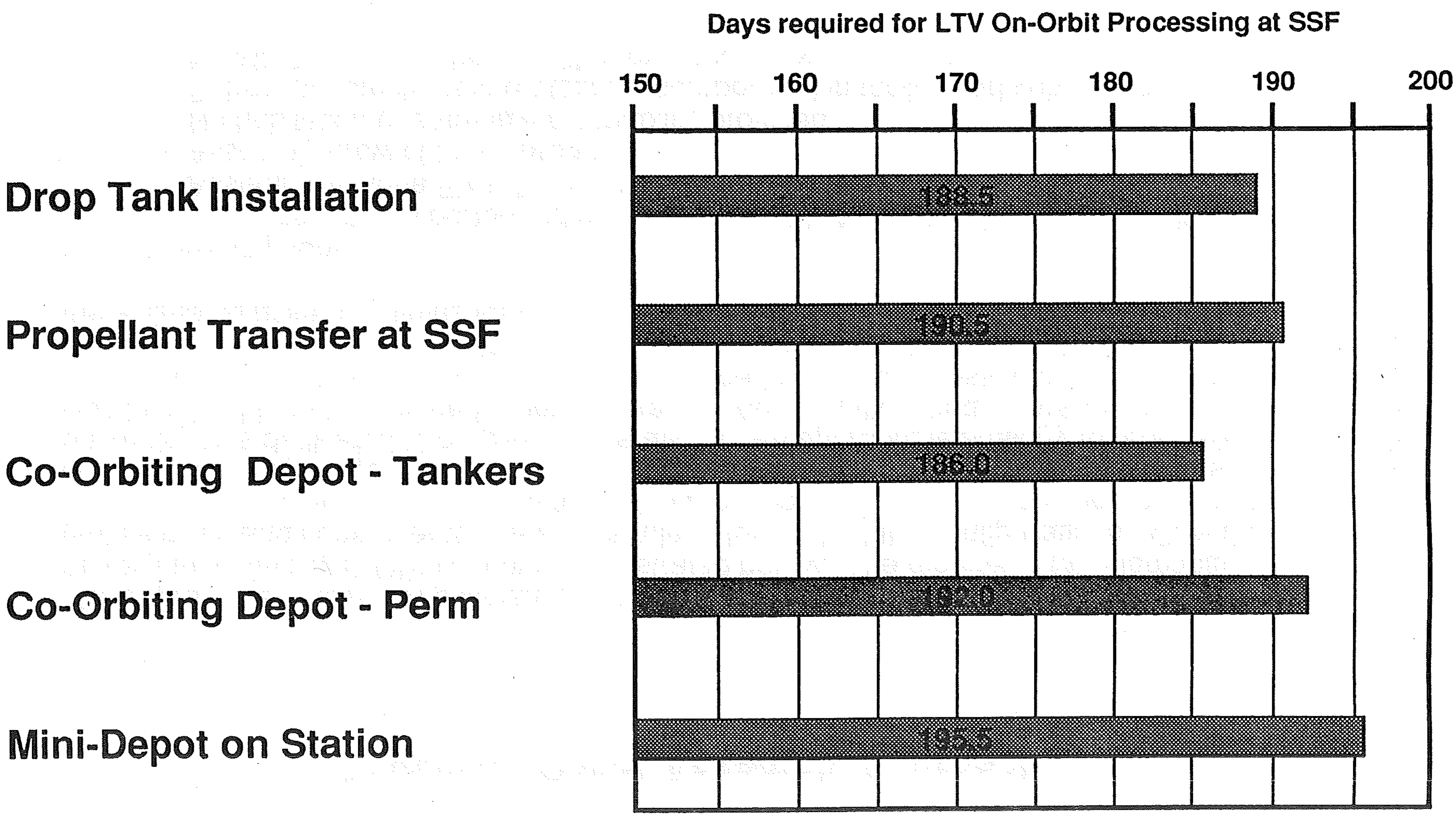
The comparison of the estimated LTV orbital turnaround processing times shows that there is no significant difference between the five propellant management architectures. The Drop Tank Installation method will require an estimated 188.5 shifts, with the other methods varying less than 4% from that baseline.

The propellant handling-specific operations constitute only 10 to 14% of the total LTV processing time. Based on the KSC analogies of Shuttle External Tank (ET) mate and ET propellant load, installation of drop tanks and propellant transfer from a tanker were both estimated to be two-shift operations. Also included in the timelines are tanker deorbit operations and Advanced Orbital Maneuvering Vehicle (AOMV) servicing.

Primary assumptions:

- LTV is the Option 5 vehicle from the NASA 90-Day Study
- SSF Assembly/Servicing Facility (ASF) is fully operational
- steady-state lunar missions
- AOMV operational and SSF-based
- dedicated orbital processing crew of four personnel
- Shuttle-C is the the Earth-to-orbit (ETO) carrier

Lunar Vehicle Processing Times



- There is no significant difference between propellant management architectures for lunar vehicle processing time.

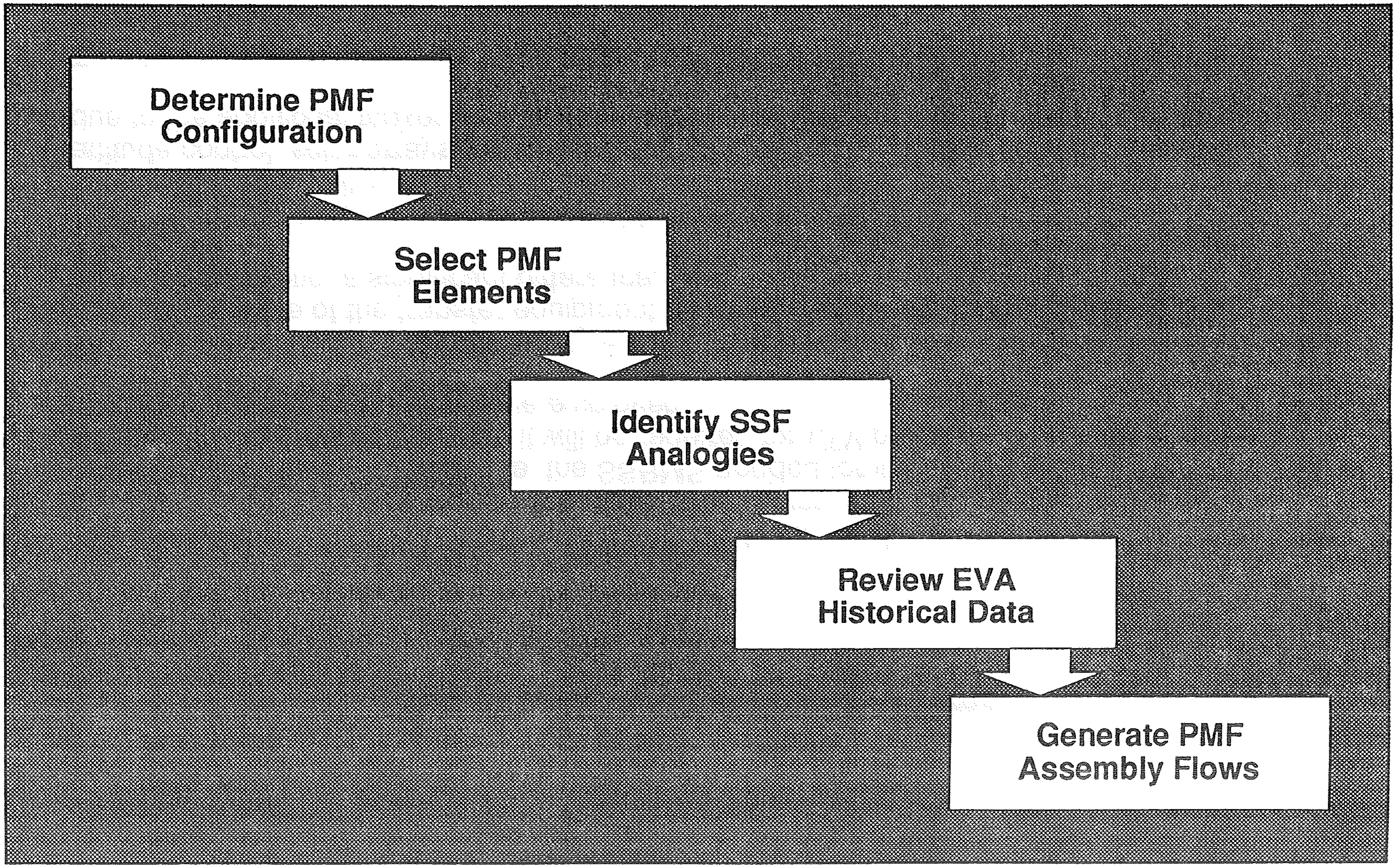
Propellant Depot Assembly Approach

The approach employed to estimate the on-orbit assembly times for each of the propellant management facility (PMF) concepts is illustrated below. The required PMF elements (subsystems and components) were determined for each of the configurations. Only the orbital support equipment (OSE) dedicated to propellant handling was considered, however, all co-orbiting depot systems (i.e. support truss, attitude control, etc.) were included since the entire depot is dedicated to propellant operations. An appropriate analogy for each element was identified from the Space Station program. Additionally, Shuttle EVA experience such as the Solar Max repair and the Ease/Access experiment was investigated. The assembly time estimates for the Space Station and the EVA historical data were both used to generate the estimated assembly times for the five PMF concepts.

Primary assumptions:

- PMF assembly is performed at the growth SSF Assembly/Servicing Facility
- Assembly is done EVA, SSF-style (little or no automation)
- Assembly crew of four astronauts
- No habitation or safe-haven capability provided
- Debris/micrometeoroid protection incorporated in facility and vehicle designs
- No MSC/RMS required for PMF operations except drop tank installation

Propellant Depot Assembly Approach



Propellant Depot Assembly Times

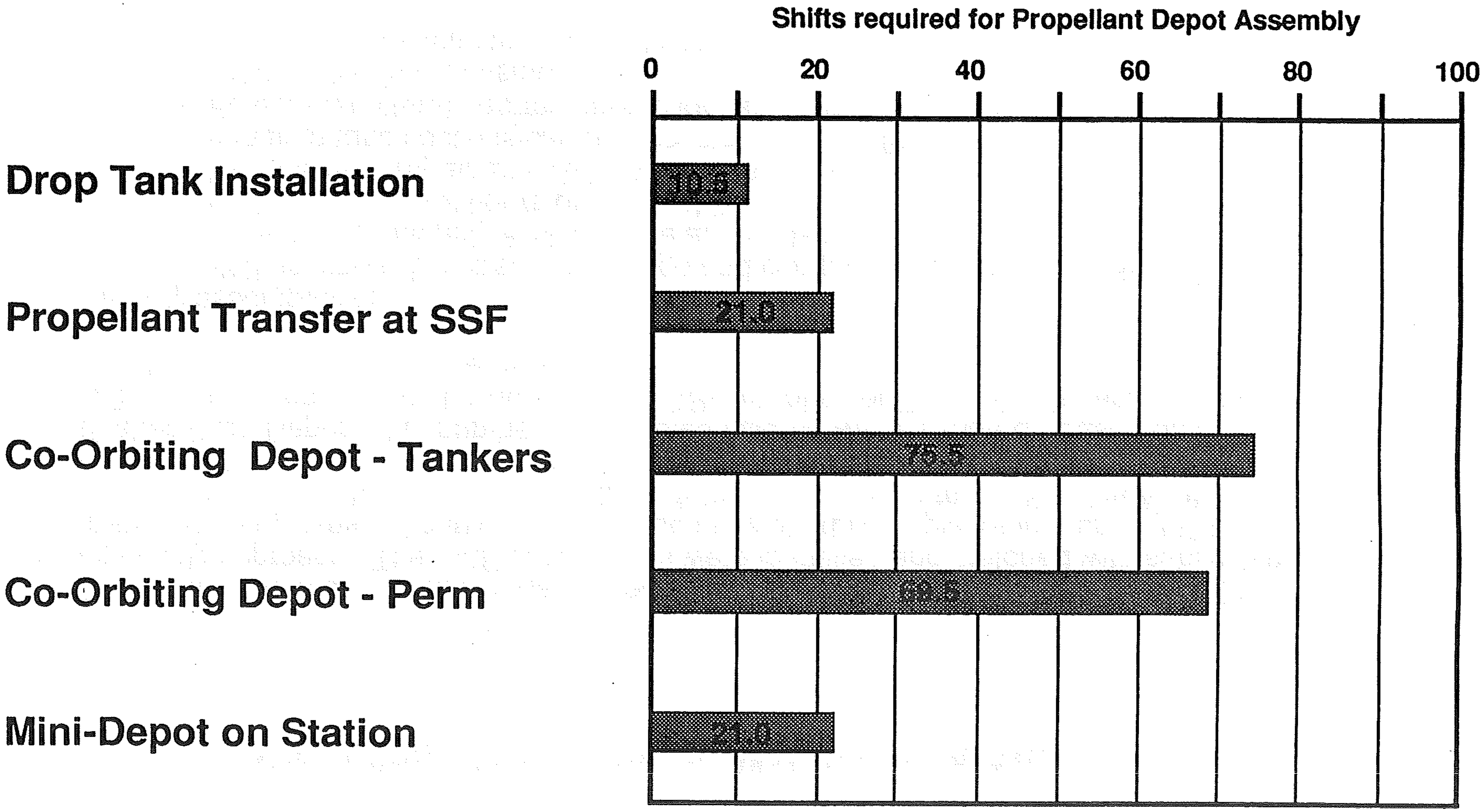
The comparison of the PMF estimated assembly times yielded expected results. Drop Tank Installation was the clear winner since it will require very little OSE that is dedicated to propellant handling. For instance, the SSRMS needed for installing the Drop Tanks was not included in the timeline because it will be required for LTV processing regardless of the propellant management technique employed.

The Propellant Transfer at SSF facility will take twice as long to assemble as the Drop Tank concept because of the transfer equipment needed. Relative to LTV processing time, however, this is not a significant difference.

Co-orbiting depots will require considerably more assembly time than the SSF-attached concepts, as they will need all the systems of a self-sufficient orbital node (support truss, attitude control, solar arrays, etc). Assembly of the Tanker Storage concept is slightly longer due to the additional tanker docking ports and associated transfer equipment.

The PMF assembly times are rough estimates and should be used only for comparison of the concepts.

Propellant Depot Assembly Times



- Co-orbiting propellant depots require 200 - 600% more assembly shifts.
- Propellant Transfer depots require twice as many assy shifts as Drop Tank.

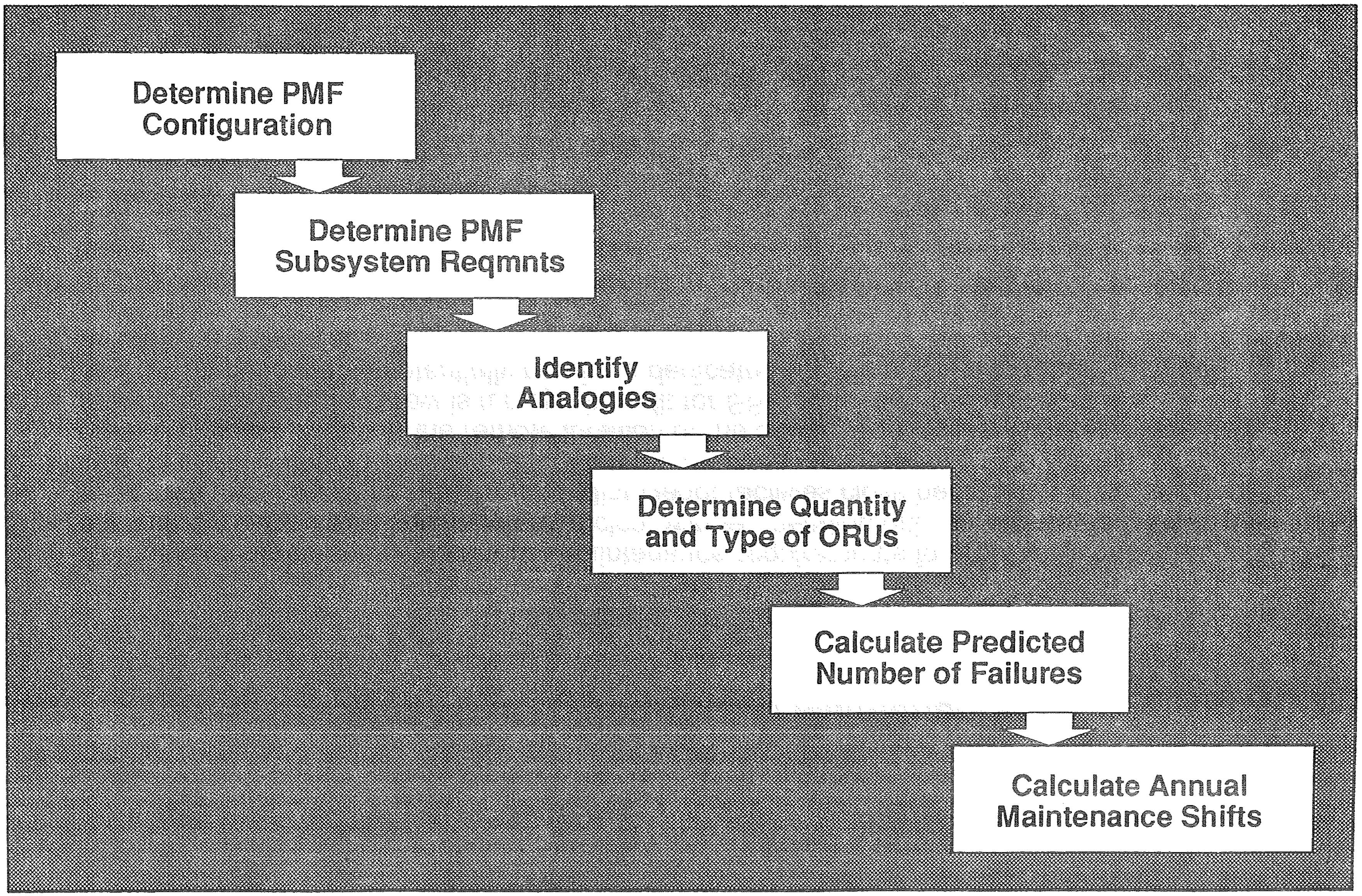
Propellant Depot Annual Maintenance Approach

The estimation of annual maintenance requirements for the PMF concepts was similar to the assembly approach. The PMF subsystems were identified and matched with subsystems from other programs, primarily SSF. The quantity of orbital replacement units (ORU) components for each subsystem was then determined. Using the In-Service Analysis method of the Space Station Freedom External Maintenance Task Team Final Report (Fisher-Price Report), the number of predicted failures was estimated. Based on an average ORU replacement time of 1.1 hours and 5 ORU repairs per EVA shift, the estimated annual maintenance shifts were determined.

Primary assumptions:

- PMF is similar in subsystem design and component reliability to SSF
- Repairs are primarily EVA remove and replace
- EVA overhead = 2 hours per EVA shift
- Mean time to repair an ORU = 1.1 hours
- 5 maintenance actions can be accomplished per EVA shift
- Passive structural, thermal protection, and debris shielding ORUs not included in assessment
- Only corrective maintenance actions considered

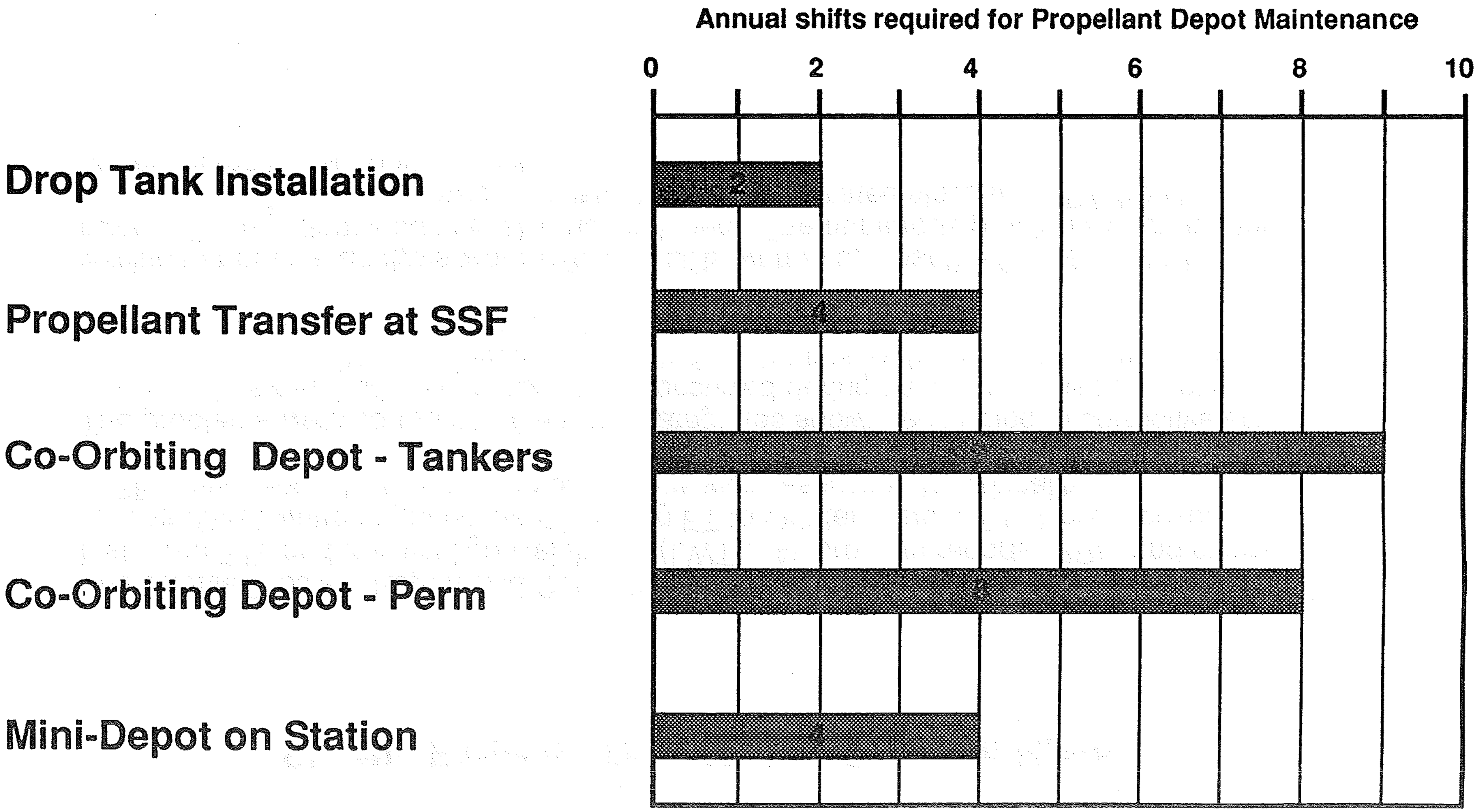
Propellant Depot Annual Maintenance Approach



Propellant Depot Annual Maintenance

Comparison of the estimated annual maintenance requirements for the PMF concepts showed the Drop Tank Installation as a clear winner, needing only an estimated 2 shifts per year, with the Propellant Transfer and Mini-Depot facilities close behind at 4 shifts per year. The co-orbiting depots, however, increase the maintenance needs by 100 - 350%, which is quite significant in light of the remote location of the depot. The logistics infrastructure and readily available repair crew is a major benefit for SSF-attached PMF architectures. A co-orbiting depot could potentially require a dedicated Shuttle mission to repair a critical failure.

Propellant Depot Annual Maintenance



- Co-orbiting propellant depots require 100 - 350% more annual maintenance.

Shuttle External Tank Mating Problem History

The Shuttle Problem Report and Corrective Action (PRACA) database was examined for the first three ETs and the first lightweight ET (LWT). All problem reports (PRs) and discrepancy reports (DRs) written against the ET during ET to Orbiter mate, ET to Solid Rocket Booster (SRB) mate, and interface testing operations were assessed for criticality.

The problems were sorted into the three categories shown, according to corrective action that would be required if the problem had occurred during an on-orbit assembly of drop tanks to the LTV. Problems were also sorted by the type of hardware system affected: electrical, fluids/pneumatics, or structures.

Excluded from the analysis were PRs and DRs written against the Orbiter and SRBs during mate. ET propellant load was also not included. The numerous problems documented against the ET thermal protection system were also omitted since the LTV drop tanks are not expected to use foam insulation.

Shuttle External Tank Mating Problem History

- Examined External Tank records from ET-1, 2, 3, and LWT ET-8 for ET-Orbiter-SRB mate problems

- Sorted all problem/discrepancy reports into three STV related categories:
  1 - Would require replacement hardware from earth
  2 - Repairable on-orbit, but with schedule impact
  3 - Not a significant on-orbit concern

- Sorted all problem/discrepancy reports into three system related categories:
  - Electrical
  - Fluids/Pneumatics
  - Structures

ET Mate Problem Categories

Examples of the types of problems in the three categories are shown.

ET Mate Problem Categories

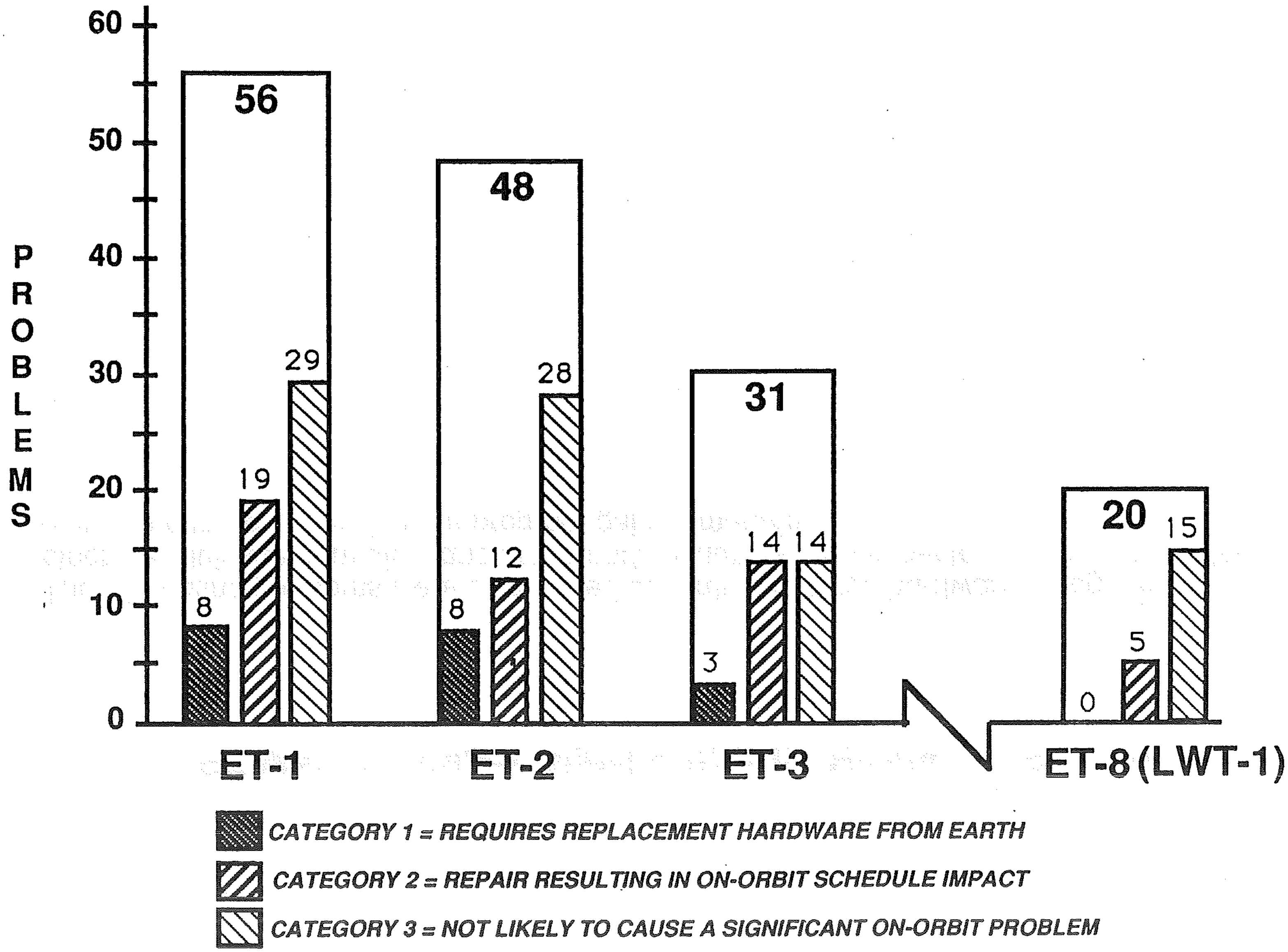
Category 1&2		Category 3
Broken/Crushed Wires	Missing Hardware	External Tank Unique Hardware
Electrical Shorts	Structural Interferences	Tasks Not Done On-Orbit
Cables To Short To Mate	Loose Fasteners	Procedural Errors
Broken Sensors	Damaged Fasteners	Cosmetic Defects
Loose Electrical Connections	Missing/Broken Safety Wire	Out-of Tolerance Readings
Leaking Fluid Lines	Incorrect Shimming	Incorrect Part Identification
Scratched Cryogenic Seals	Corrosion	
Bent Fluid Lines	Foreign Material/Debris	
Failed Valves	Misalignment of Hardware	

ET Mate Problem Distribution by Criticality

The problems documented during ET mate for the first three and the eighth (LWT-1) Shuttle flights were categorized according to criticality. There were a high number of problems associated with the early assembly operations. As expected, the number of problems decreased with each succeeding mission processing flow as hardware design, manufacturing, and operations matured.

ET mate is a complex assembly operation; drop tank installation is a similarly complex operation that will occur four times per mission. The alarming number of Category 1 problems experienced during the first three Shuttle ET mates would cause unacceptable delays in lunar missions if experienced in orbit.

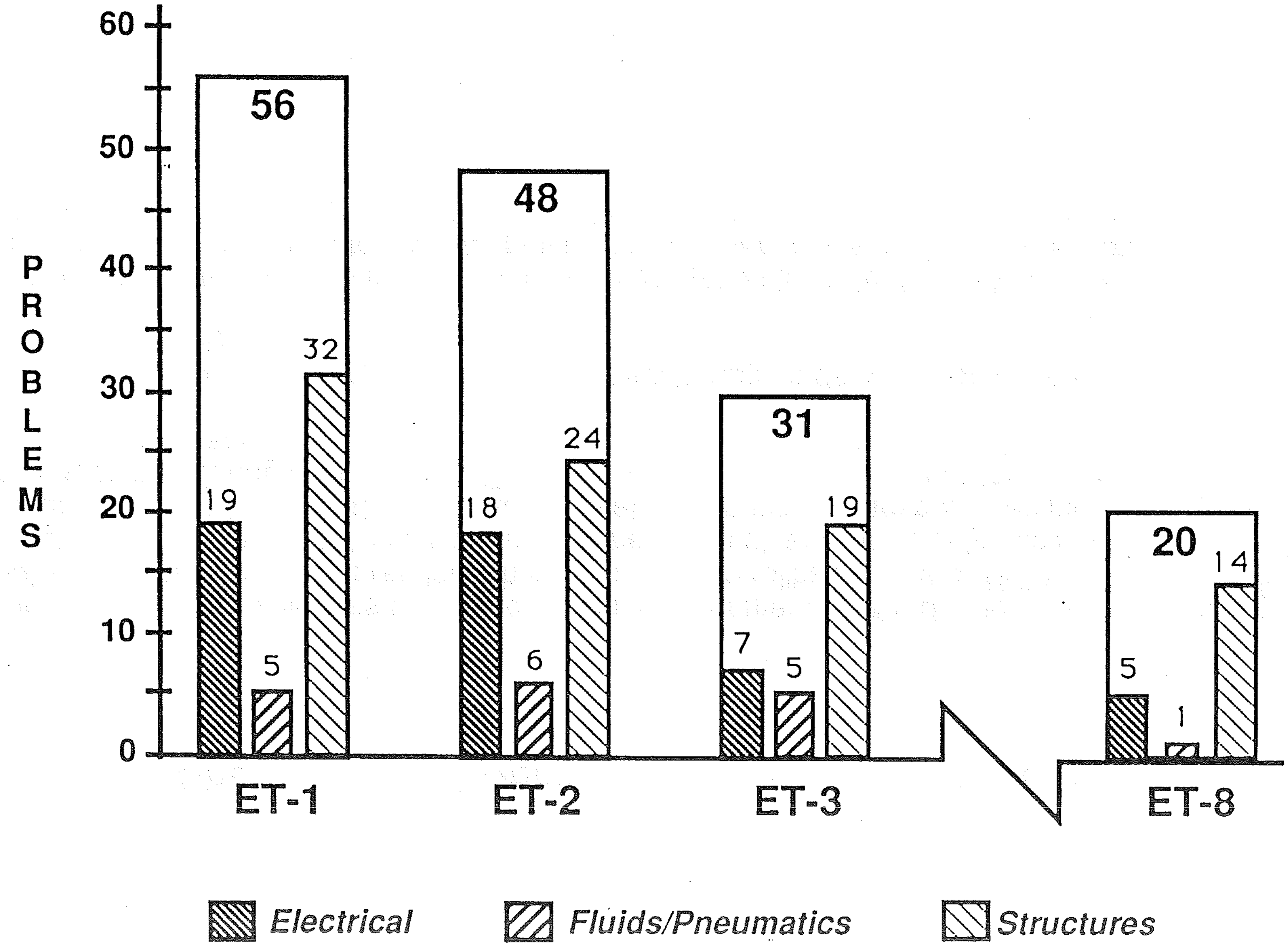
ET Mate Problem Distribution by Criticality



ET Mate Problem Distribution by Hardware System

The ET mating problems were also sorted according to three hardware categories: electrical, fluids/pneumatics, and structural/mechanical. As expected, all systems reflected a downward trend as the Shuttle program gained maturity.

ET Mate Problem Distribution by Hardware System



Shuttle ET Hydrogen Disconnect Leak Lessons

The Space Shuttle fleet was grounded during the summer of 1990 due to a series of hydrogen leaks. The leaks caused three launch scrubs and two rollbacks to the VAB for ET demate from the Orbiter. These "smart" leaks were extremely difficult to isolate, only occurring at cryogenic temperatures and with inert purges and insulation serving as transport mechanisms to give false readings during leak checks. Extensive disassembly and vendor testing were required to isolate the leak sources.

It is especially disconcerting that problems of such magnitude would be experienced on a mature launch system.

The main recommendations from the leak investigation team for future launch systems were: 1) make designs as leak tolerant as possible (redundant seals, built-in purges, etc.), 2) eliminate as many joints as possible, and 3) design built-in, automated leak check methods.

Shuttle ET Hydrogen Disconnect Leak Lessons

- Shuttle fleet grounded during summer of 1990 due to hydrogen leaks (3 launch scrubs and 2 rollbacks)
  - STS-35 (Columbia) delayed 5 months
  - STS-38 (Atlantis) delayed 4 months
- "Smart" leaks were extremely difficult to isolate.
  - Leaks occurred in cryogenic conditions only.
  - Extensive disassembly & vendor testing required to isolate leaks.
  - All leaks discovered on single-seal joints.
- Recommendations
  - Make designs as leak-tolerant as possible.
  - Eliminate joints as much as possible.
  - Design built-in, automated leak-check methods.

Comparison of Propellant Interface Disturbances

The increased mission risk inherent with the use of drop tanks is a significant concern. The in-flight jettison and subsequent installation of four drop tanks per mission over the course of a five mission vehicle lifetime will result in a minimum of 160 cryogenic propellant interface disturbances per vehicle. In comparison, a LTV utilizing permanent, reusable propellant tankage will experience only 40 such disturbances.

The use of drop tanks greatly increases the number of failure modes and critical items. Cryogenic quick-disconnect couplings have a history of leakage, and isolation and repair of cryogenic leaks at KSC have proven at times to be an operational nightmare. Complex assembly operations by their very nature incur problems requiring parts rework or replacement. Such problems may prove to be insurmountable to processing crews in space.

The question remains to be satisfactorily addressed: Is the mass savings gained by jettisoning depleted propellant tanks in flight justify the increase in mission risk?

Comparison of Propellant Interface Disturbances

Drop Tank Installation

$$4\ \frac{\text{Drop Tanks}}{\text{Vehicle}} \times 4\ \frac{\text{Prop Interfaces}}{\text{Drop Tank}} \times 2\ \frac{\text{Disturbances}}{\text{Mission}} \times 5\ \text{Missions}$$

$$= 160\ \frac{\text{Disturbances}}{\text{Vehicle Life Cycle}}$$

Propellant Transfer

$$1\ \frac{\text{Tankset}}{\text{Vehicle}} \times 4\ \frac{\text{Prop Interfaces}}{\text{Tankset}} \times 2\ \frac{\text{Disturbances}}{\text{Mission}} \times 5\ \text{Missions}$$

$$= 40\ \frac{\text{Disturbances}}{\text{Vehicle Life Cycle}}$$

- Use of Drop Tanks significantly increases number of critical propellant interface disturbances.
- An open question: Does the mass saved by jettisoning depleted propellant tanks justify the increase in mission risk?

Conclusions

Five proposed propellant management facility (PMF) concepts were analyzed and compared in order to determine the best method of resupplying reusable, space-based Lunar Transfer Vehicles (LTVs).

LTV Processing - The processing time needed at the Space Station to prepare an LTV for its next lunar mission was estimated for each of the PMF concepts. The somewhat surprising result was that there is little difference in the estimated processing timelines among the concepts. The estimates vary less than 4% from the Drop Tank baseline of 188.5 shifts. The shortest estimate of 186.0 shifts was for the Co-Orbiting Depot - Tanker Storage facility.

PMF Assembly - The estimated times required to assemble and maintain the different PMF concepts were also compared. The distinguishing factor between the concepts is the orbital location of the facility. Co-orbiting depots will require significantly more time (200-600%) to assemble than the SSF-attached architectures. However, even the longest assembly time (75.5 shifts for the Co-Orbiting Depot - Tanker Storage) constitutes less than 10% of the total processing time for one LTV's life cycle of five missions.

PMF Maintenance - The results of the maintenance analysis were similar, with co-orbiting depots needing 100-350% more annual maintenance. The Drop Tank and Mini-Depot concepts were estimated to need only 2 shifts per year, whereas the co-orbiting depots required 8-9 shifts. This is quite significant in light of the remote location of a co-orbiting depot. The logistics infrastructure and readily available repair crew is a major benefit for SSF-attached PMF architectures. A co-orbiting depot could potentially require a dedicated Shuttle mission to repair a critical failure.

Shuttle ET Mating History - The first few ET mating operations at KSC encountered numerous problems that would, if experienced on orbit during Drop Tank Installation, cause serious lunar mission schedule delays. The grounding of the Shuttle fleet in the summer of 1990 due to hydrogen leaks at the ET disconnect is especially disturbing in that it occurred on a mature launch system. Ground processing methods to prevent such flight hardware problems must be developed to enable space-basing of LTVs.

The Problem with Drop Tank Installation - The use of Drop Tanks on lunar vehicles increases by a factor of four the number of critical propellant interface disturbances. The increased mission risk (many more failure modes and critical items, as well as the lkelihood of interface damage and requisite repair) must be satisfactorily addressed before being baselined into LTV designs.

Key Technologies - The key cryogenic propellant management technologies that require further development are common to all proposed architectures, and therefore are not a discriminator between the concepts. The development of these enabling technologies should be pursued aggressively.

Conclusions

- There is no significant difference between PMF concepts for LTV on-orbit processing times.
- Orbital location is the cost and schedule driver for PMF assembly and maintenance.
- Shuttle - ET mating history shows an alarming number of problems that would cause LTV mission delays if encountered on orbit.
- Drop Tanks Installation requires four times as many critical propellant interface disturbances.
- Development of key orbital cryogenic propellant management technologies is required for all PMF concepts.