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PROPELLANT TRANSFER - TETHERED DEPOT

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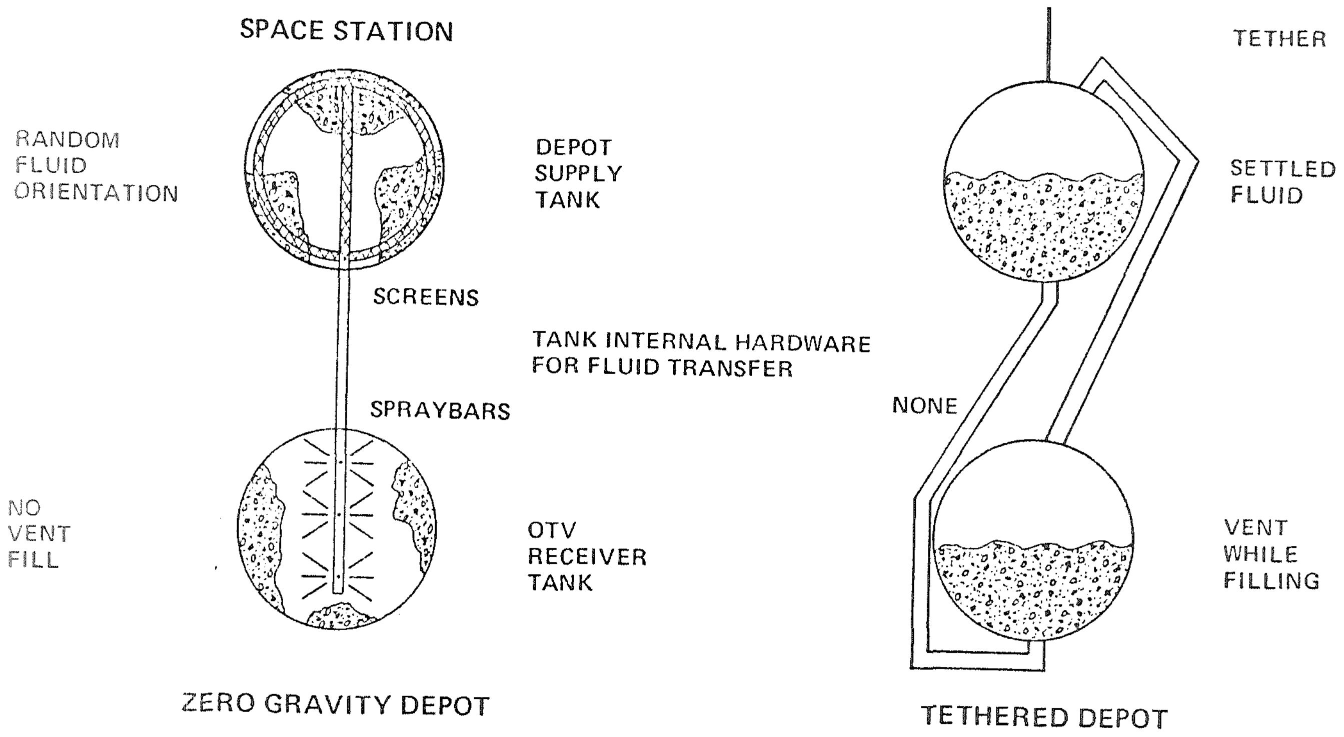
Spacebasing of orbital transfer vehicles at a space station will require a depot that will safely and efficiently store and transfer the resupply propellants. In order to transfer propellants, a method to effectively acquire only liquid and vent only gas must exist. Unfortunately, the current methods of transferring propellant, under the zero 'G' condition of random liquid orientation, have several weaknesses. A method that produces a low gravity to settle propellants would bypass these weaknesses, while allowing ground-like operations. This low gravity can be passively produced using gravity gradient techniques. A satellite with a large length to diameter ratio, such as a depot attached to a space station with a tether, will stabilize along an earth radial because of an outward acceleration proportional to the distance from the satellite's center of gravity. Analysis indicates that liquid can be settled with relatively short tether lengths. However, longer tether lengths may be required to prevent excessive residuals due to suction dip, to allow transfer using gravity feed, and to allow slosh control.

Currently the tethered refueling depot concept is being studied by Martin Marietta Aerospace under contract to NASA, Johnson Space Center. The objectives of this contract are to determine the feasibility, design requirements, and operational limitations of a tethered refueling depot with special emphasis on slosh control.

The purpose of this presentation is to introduce the tethered refueling depot concept to the orbital transfer vehicle community. This should allow the concept's effects on propellant resupply, space station, and orbital transfer vehicle to be given some consideration during preliminary design.

DEPOT COMPARISON



ZERO GRAVITY DEPOT

TETHERED DEPOT

Figure 1

A zero gravity depot is attached directly to the space station. Because of the random orientation of fluid phases this depot needs hardware internal to the tanks for acquiring liquid from the supply tank and filling the receiver tank without venting. The tethered depot is connected by a tether to the space station. Because of the settled condition of the fluid, the tethered depot can acquire liquid from the supply tank and vent gas during fill of the receiver tank without internal hardware. The supply and receiver tank ullages can be interconnected to equalize the pressure in both tanks or autogenously pressurize the receiver tank, which will also reduce the venting of propellant into space.

CURRENT TECHNIQUES TO SEPARATE FLUID PHASES ON-ORBIT

- TYPES
  - PHYSICAL BARRIERS (BLADDERS AND DIAPHRAGMS)
  - SURFACE TENSION DEVICES (VANES AND SCREENS)
  - ACTIVE PROPELLANT SETTLING (PROPULSIVE AND ROTATIONAL)
- PROBLEMS
  - COMPLEX HARDWARE
  - SUBJECT TO FATIGUE WITH REUSE
  - COMPATIBILITY PROBLEMS WITH PROPELLANT
  - SENSITIVE TO GAS FORMATION WITH CRYOGENS
  - COMPLEX VENTING AND VAPOR COLLAPSE TECHNIQUES
  - ACTIVE SETTLING INCOMPATIBLE WITH SPACE STATION CONTROL
- BASIC PROBLEM: RANDOM ORIENTATION OF LIQUID IN ON-ORBIT 'ZERO-GRAVITY' ENVIRONMENT

Figure 2

Currently two types of techniques, passive and active, are used to separate fluid phases on-orbit. Passive techniques include physical barriers, such as bladders and diaphragms, and surface tension devices, such as vanes and screens. These devices are internal to the propellant tanks which can present problems for long term reusability on a space station depot. They are complex to design, fabricate, and install; subject to fatigue with reuse; and difficult to repair and replace. Hardware material selection will be limited because of incompatibility with oxidizers and cryogens. Hardware will increase sensitivity to gas formation in cryogens which will increase the problem of separating the fluid phases. Surface tension devices are meant to insure that liquid is acquired, but they can't insure the gas position for venting; therefore, complex venting and vapor collapse techniques are required. Alternatively, active propellant settling, propulsive thrusting or rotation of a vehicle with offset propellant tanks, can force the denser liquid in the direction of the acceleration. Active propellant settling is incompatible with the space station requirement for control of attitude and orbital position.

ARTIFICIAL GRAVITY AT TETHERED SATELLITES

- BODY FORCES CANCEL AT CENTER OF GRAVITY (C.G.)
  - "ZERO GRAVITY"
- NET BODY FORCE OFF THE C.G.
  - GRAVITY FORCE INCREASES TOWARD EARTH
  - CENTRIFUGAL FORCE INCREASES AWAY FROM EARTH
  - CENTRIFUGAL AND GRAVITY FORCES IN OPPOSITE DIRECTION
  - BODY FORCE POINTS AWAY FROM C.G.
- TENSION IN STRUCTURE REACTS AGAINST BODY FORCE
  - "ARTIFICIAL GRAVITY"

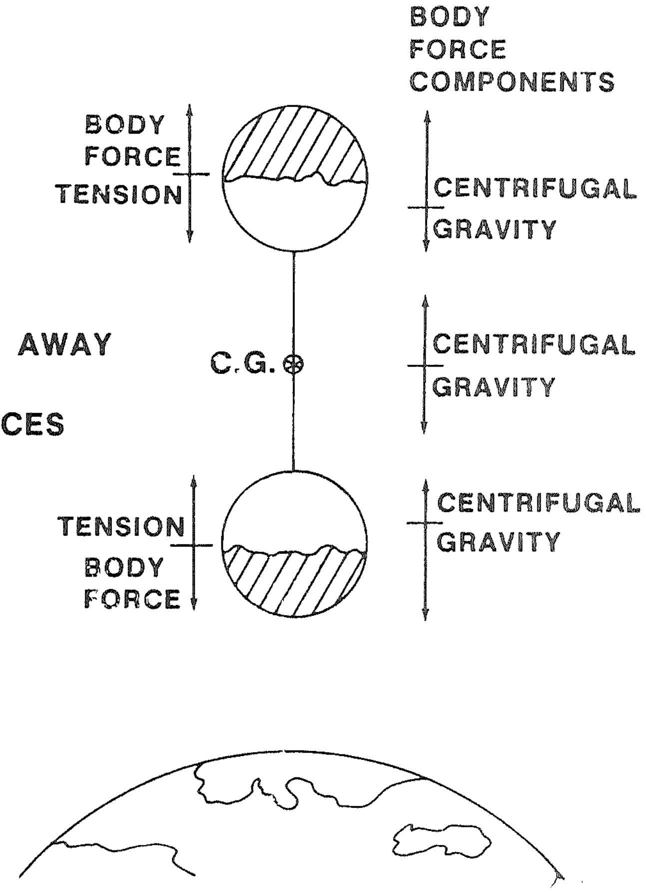


Figure 3

The cancelling of the centrifugal and gravity body forces for a tethered satellite in a circular orbit, "zero gravity", occurs only at the center of gravity. The gravity force is stronger toward the earth, while the centrifugal force is stronger away from the earth. The net body force, when not at the center of gravity, points away from the satellite's center of gravity along an earth radial to be reacted against by tension in the depot structure and tether resulting in "artificial gravity". This artificial gravity will stabilize a large length to width object, such as a tethered satellite, pointing at the earth. This stabilization is called "gravity gradient stabilization".

ARTIFICIAL GRAVITY FOR STATIC TETHER

ARTIFICIAL GRAVITY AT TETHER END

$$\frac{A}{G_O} = \frac{3^{*}\ TL\ {}^{*}R_O{}^{**}2}{K^{*}\ R_C{}^{**}3}$$

- APPARENT ACCELERATION

$$A = C\text{-}G$$

- CENTRIFUGAL ACCELERATION

$$C = V^{**}2/R$$

- VELOCITY OF ANY POINT ON TETHER

$$V = V_C{}^{*}R/R_C$$

- GRAVITATIONAL ACCELERATION

$$G = G_O\ (R_O/R)^{**}2$$

- SATELLITE VELOCITY

$$V_C = \sqrt{G_C{}^{*}R_C}$$

SUBSCRIPTS
O = EARTH'S SURFACE
C = SATELLITE CENTER OF GRAVITY

PARAMETERS
R = RADIUS FROM EARTH'S CENTER
TL = TETHER LENGTH FROM C.G.
K = 6076 FT/NM

Figure 4

The apparent acceleration that a point in orbit sees is the differance between the centrifugal acceleration, which is a function of velocity and radius from the earth's center, and the gravitational acceleration, which is a function of the distance from the earth's center. For a static tether, the velocity for any point on the tether can be found as a function of its distance from the earth's center, which can be related to the tether length from the satellite's center of gravity which is a known distance from the earth's center. The artificial gravity, the ratio of apparent acceleration to the earth's surface gravity, is found to be a direct function of the tether length.

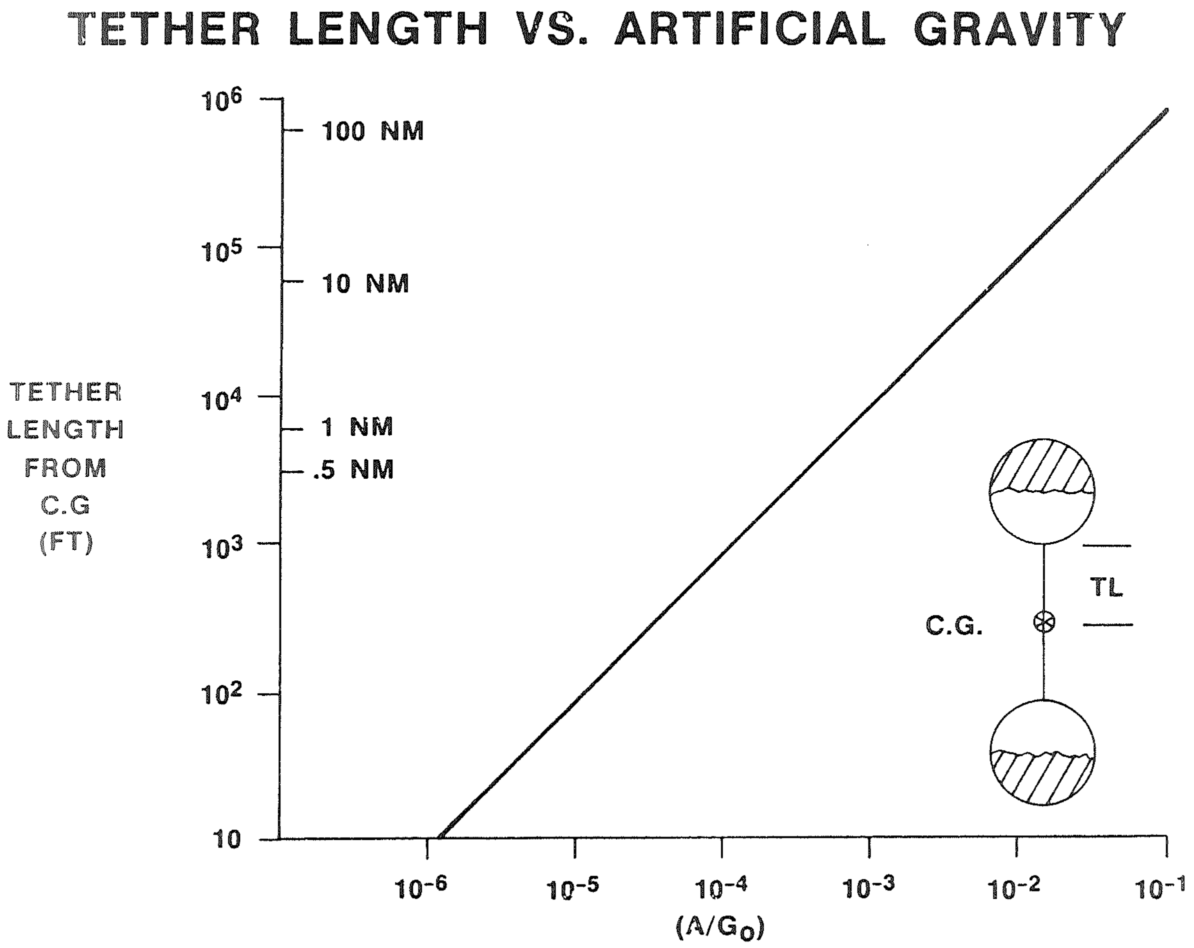


Figure 5

For a static vertical tether the artificial gravity is $7.06*10^{-4}$ g/nm or $1.16*10^{-7}$ g/ft of tether length from the satellite center of gravity.

A/Go	TL
10^{-6}	8.6 ft
10^{-5}	86 ft
10^{-4}	860 ft
10^{-3}	1.4 nm
10^{-2}	14 nm
10^{-1}	140 nm

CRITERIA FOR FLUID SETTLING

- DESCRIPTION OF FLUID SETTLING PARAMETER

$$\text{BOND NUMBER (Bo)} = \frac{\text{ACCELERATION FORCE}}{\text{SURFACE TENSION FORCE}} = \frac{\rho*A*D**2}{4*G_C*\sigma}$$

ρ = FLUID DENSITY (LBM/FT**3)
A = ACCELERATION (FT/SEC**2)
D = EFFECTIVE TANK DIAMETER (FT)
G_C = 32.174 LBM *FT/LBF/SEC**2
σ = SURFACE TENSION (LBF/FT)

- BOND NUMBER CRITERIA

$Bo < 1$	SURFACE TENSION DOMINATES ACCELERATION, THEREFORE NO FLUID SETTLING
$1 < Bo < 10$	TRANSITION ZONE
$Bo > 10$	ACCELERATION DOMINATES SURFACE TENSION, THEREFORE FLUID SETTLES
$Bo = 50$	ALLOWS RELATIVELY FLAT FLUID PHASE INTERFACE (CHOSEN AS MINIMUM BOND NUMBER FOR ANALYSIS)

Figure 6

Fluid settling is the basic requirment on a tethered depot to position liquid over the outlet so only liquid will be transfered and only gas vented. The fluid settling parameter is the Bond number which is the ratio of the acceleration force to the surface tension force. The Bond number is primarily a function of the fluid properties, the effective tank diameter, and the acceleration. The Bond number can be used to divide the fluid behavior into a number of zones with a value greater than ten required to settle fluid. A value of fifty was chosen as the minimum for analysis for conservatism while allowing a relatively flat interface.

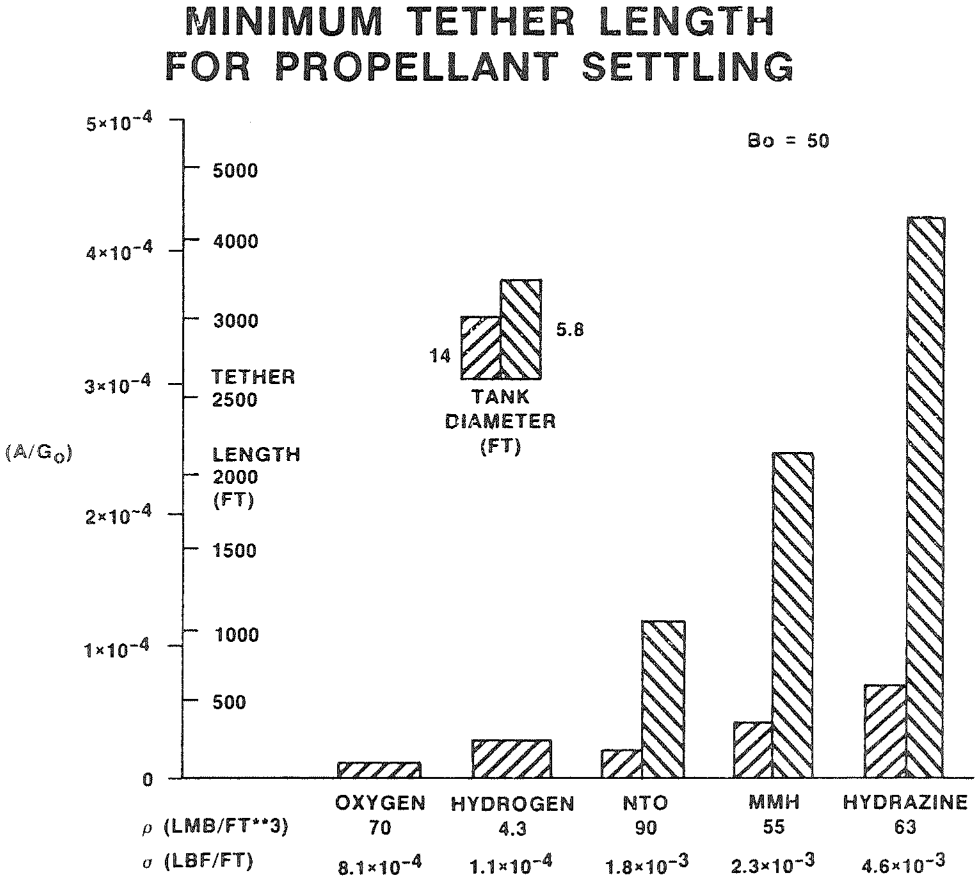


Figure 7

The tether length required for fluid settling is affected by fluid properties and effective tank diameter. Longer tethers are required for having higher surface tension or smaller liquid density. Decreasing the effective tank diameter also requires a longer tether. This is a consideration when looking at baffles for slosh control because because they can change the effective tank diameter. With no baffles the cryogenics would require 230 feet of tether length with 14 foot diameter tanks, the bipropellant storables would require 2180 feet with 5.8 foot tanks, and hydrazine would require 3750 feet with 5.8 foot tanks to settle propellant.

PROPELLANT SLOSHING

- ISSUE
  - SLOSHING SHOULD NOT INTERRUPT FLUID TRANSFER
    - DO NOT UNCOVER SUPPLY TANK OUTLET
    - DO NOT COVER RECEIVER TANK VENT
- POTENTIAL SOLUTIONS
  - INCREASE ACCELERATION LEVEL TO REDUCE SLOSH HEIGHT
  - INTERNALLY DAMP SLOSHING WITH BAFFLES
    - DECREASE IN EFFECTIVE DIAMETER WILL INCREASE REQUIRED ACCELERATION FOR SETTLING
  - EXTERNALLY DAMP SLOSHING
    - MAY NOT BE EFFICIENT
- SLOSHING WILL BE STUDIED BY MARTIN MARIETTA UNDER CONTRACT TO NASA, JOHNSON SPACE CENTER

Figure 8

Even though a liquid will eventually settle it can still slosh when disturbed, changing the position of the liquid relative to the tank outlet and vent. This sloshing should not cause the fluid transfer to be interrupted by uncovering the the supply tank outlet or covering the receiver tank vent. Sloshing can be reduced by increasing the acceleration to limit the slosh height, internally dampening the sloshing with baffles, or externally dampening the sloshing with devices such as reaction wheels, dashpots, etc. Baffles may have a problem because they can reduce the effective diameter of the tank, thus requiring greater tether length to insure settled propellant. The external dampening methods may not be efficient. This problem will be further studied by Martin Marietta under contract to NASA, Johnson Space Center.

RESIDUAL DUE TO SUCTION DIP

- RESIDUAL IS REMAINING LIQUID WHEN SUCTION DIP REACHES OUTLET
- SUCTION DIP HEIGHT (H)

$$H = .51 * D_L \left[\left(\frac{D_T}{D_L} \right)^2 \left(\frac{V^2}{A*D_L} \right) \right]^{.143}$$

V = FLUID VELOCITY IN LINE
A = APPARENT ACCELERATION
D_L = LINE DIAMETER
D_T = TANK DIAMETER

- PRIMARY VARIABLE AFFECTING RESIDUALS
  - MASS FLOW
  - LINE DIAMETER
  - ACCELERATION LEVEL

DRAINING TANK

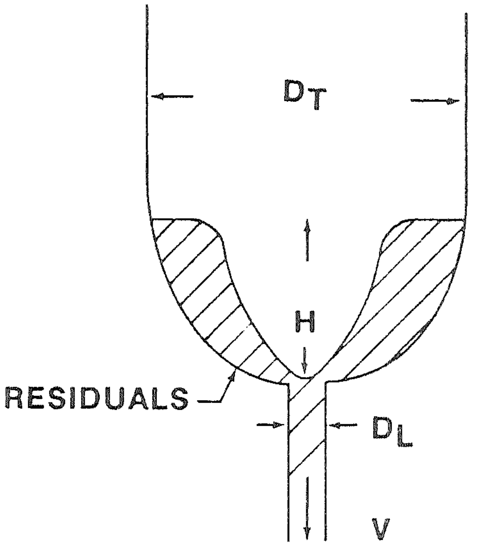
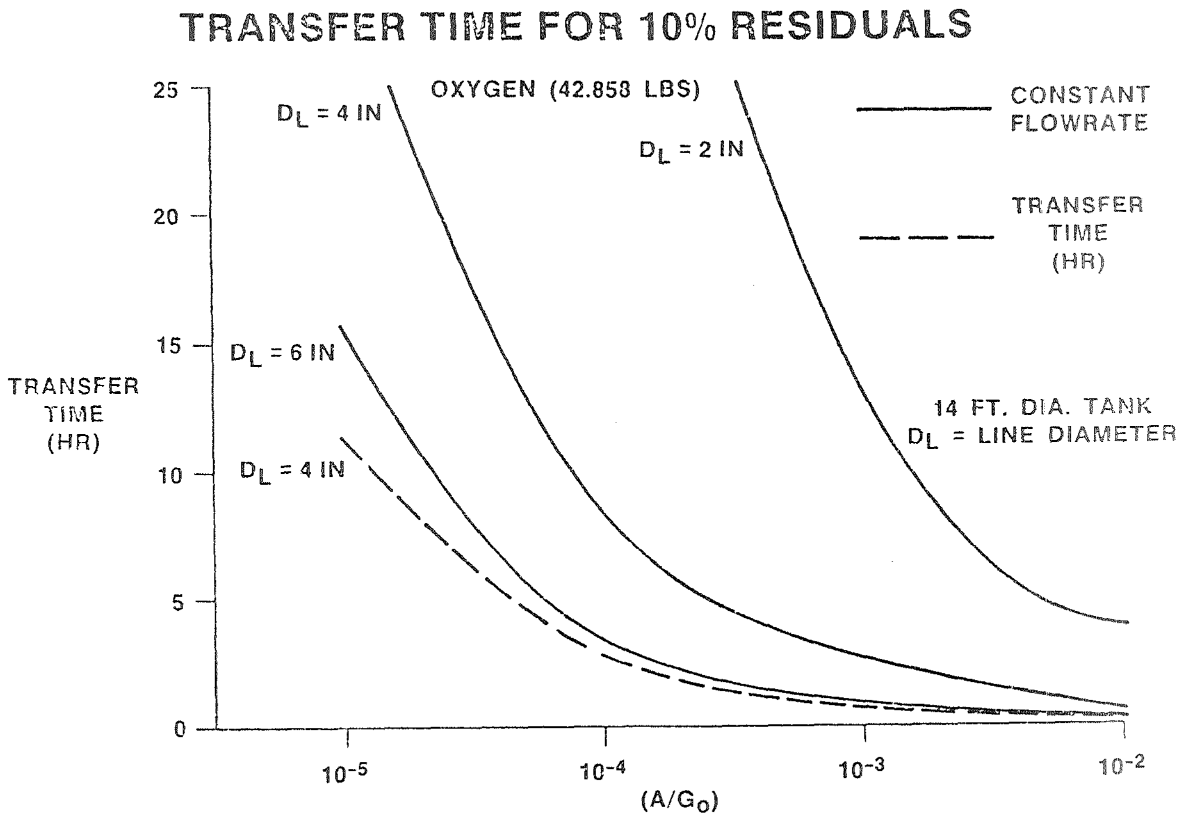


Figure 9

A problem that a tethered depot does have that a zero gravity depot does not have is preventing the vapor from dipping into the outlet due to suction from propellant outflow. This is called "suction dip". For the tethered tank, outflow must be stopped when vapor reaches the outlet, which can result in substantial residual propellant in the tank. The suction dip is primarily a function of mass flow, line diameter, and the acceleration level; therefore, if the steady state mass flowrate during a transfer is decreased to reduce residuals longer transfer times will result. Special outlet provisions such as outlet contouring and screens can limit the affect of the suction dip. However, if no special outlet provisions are used, varying the flowrate, increasing line diameter, and increasing the acceleration levels will be required to minimize transfer times and residuals.



TRANSFER TIME FOR 10% RESIDUALS

Figure 10

Each plotted point is transfer time assuming a constant flowrate during the transfer; therefore, along the lines of constant diameter shown, the mass flowrate varies continuously. The exception is the two flowrate case shown where high initial flowrate was assumed until the suction dip from that flowrate reaches the outlet. A step change to a lower flowrate was then assumed to occur. Along this line the flowrate also varies in a continuous manner. Assuming a tank with hemispherical ends, no special outlet provisions, and a gas/liquid interface near the wall that has a curvature corresponding to the local bond number, oxygen has longer transfer times than hydrogen for 10% residuals. Larger propellant line diameters reduce the transfer time by increasing the mass flow that will create a given suction dip height. A line diameter of two inches as currently used in the Centaur would probably be unacceptable due to the long transfer times or high acceleration requirements. A four inch line diameter would appear to be acceptable at about an 8 hours transfer time with an acceleration of 10**-4 g; furthermore, if a two step flow is used to limit the flow near the end, the transfer time is reduced to 3 hours. Therefore, a reasonable acceleration level can be used for reasonable residuals.

GRAVITY FEED

- GRAVITY FEED USES HYDROSTATIC HEAD FROM ARTIFICIAL GRAVITY TO COUNTERACT PRESSURE DROP IN FEEDLINE
  - FLOWRATE IS DETERMINED BY BALANCE BETWEEN HYDROSTATIC HEAD AND PRESSURE DROPS
- HYDROSTATIC HEAD SOURCES
  - VERTICAL LINES
  - PROPELLANT IN TANK
- PRESSURE DROP SOURCES
  - LINE FRICTION
  - COMPONENT LOSSES
  - INLET/OUTLET AND ELBOW LOSSES
- COMPLETE ANALYSIS NEEDS DETAILED FLUID SYSTEM CONFIGURATION
- SIMPLE ANALYSIS LOOKS AT ONLY FLOWRATE FOR VERTICAL PIPE SECTION
  - HYDROSTATIC PRESSURE HEAD FROM VERTICAL LINE ONLY
  - PRESSURE DROP FROM VERTICAL LINE FRICTION ONLY
  - INDEPENDENT OF LINE LENGTH

Figure 11

A tethered depot can possibly use gravity feed as a passive fluid transfer technique. Gravity feed uses hydrostatic head to provide the driving force to counteract the pressure drop associated with a certain mass flow. The hydrostatic head is determined by the vertical separation between the gas/liquid interfaces of the supply and receiver tank and the density of the liquid. The pressure drop results from line friction, component losses, and changes in the direction of the flow. A complete analysis would require a detailed fluid system configuration. However, an idea of the minimum requirement for tether length can be determined by looking at a simple case where all the pressure drop is in vertical lines.

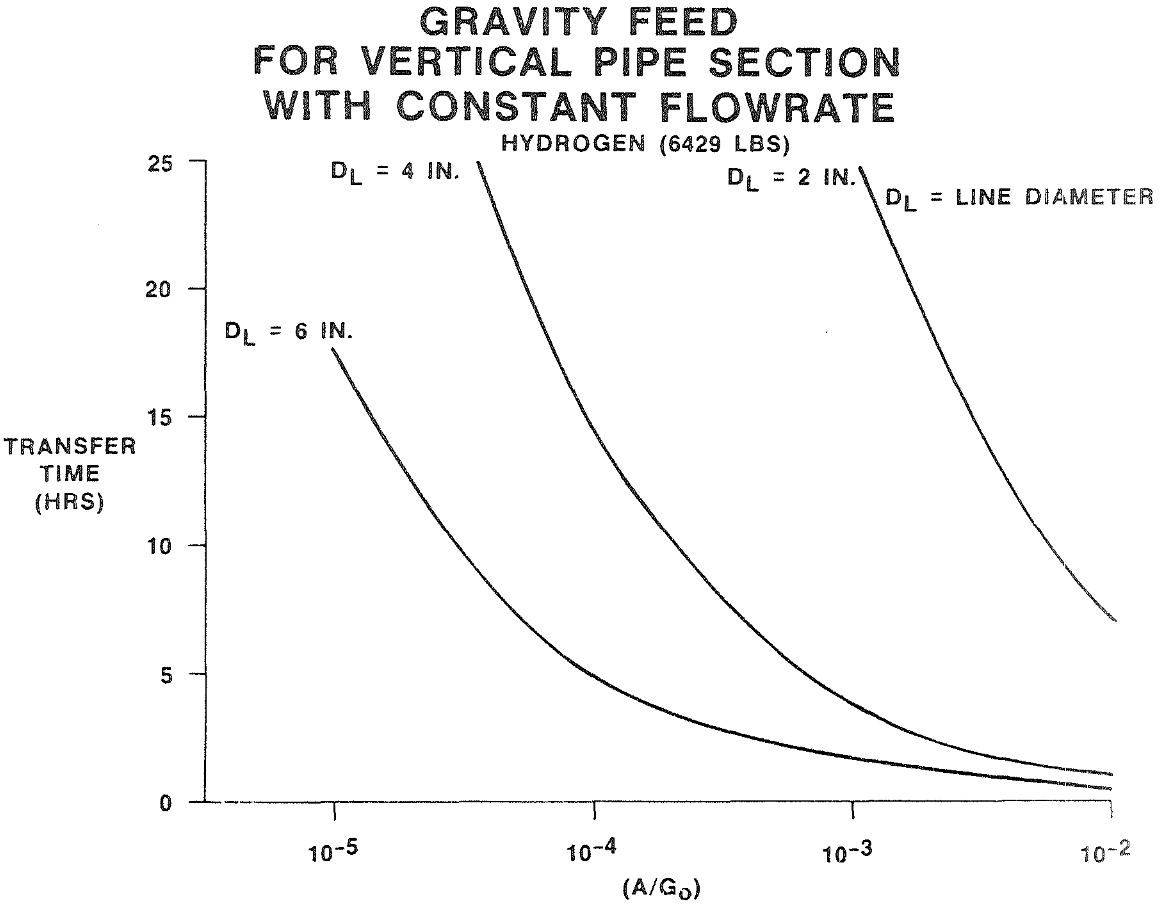


Figure 12

Each plotted point is transfer time assuming a constant flowrate during the transfer; therefore, flowrate varies continuously along each line of constant diameter. Hydrogen is the limiting propellant for determining gravity feed transfer time because of its low density. If 8 hours is assumed to be the maximum acceptable transfer time, the tether length with a line diameter of four inches would be about one half a nautical mile. This simple analysis would say that gravity feed can be used with a reasonable tether length; however, because of the low density of hydrogen and relatively low acceleration levels a tether can produce, a tether will require much more tether length to produce an increased hydrostatic head to compensate for a larger realistic pressure drops. This may cause transfer time to become excessive, although this still may be acceptable if gravity feed is used as a backup mode of operation.

OTHER DEPOT REQUIREMENTS

- DEPOT SHOULD PROVIDE HAZARD CLEARANCE FROM EXPLOSIONS AND CONTAMINATION
- BOTTOM END MASS SHOULD NOT DEORBIT WITH TETHER BREAKAGE
- OPERATIONS BETWEEN THE END MASSES SHOULD NOT BE EXCESSIVELY DIFFICULT
- DEPOT SHOULD NOT ADVERSELY AFFECT TETHER DYNAMICS
- SPACE STATION MAY REQUIRE ZERO GRAVITY FOR MICROGRAVITY LABORATORY

Figure 13

Besides fluid transfer the tethered depot has a number of other requirements. The depot should provide hazard clearance from other space station hardware to prevent catastrophic or long term damage from explosion or contamination. If the tether breaks the bottom end mass should not deorbit to prevent the loss of the bottom end mass and damage or injury on the ground. The operations between the end masses, such as transfer of the OTV, men, etc., should not be excessively difficult so that the depot can be fully utilized. The depot should not adversely affect tether motion to insure safety and space station control. A space station/depot configuration may be required that allows a low acceleration level for a microgravity laboratory at the manned part of the space station. Of these requirements , operations involving transfer of men and materials between the end masses appears to be the hardest to meet.

DEPOT/SPACE STATION CONFIGURATIONS

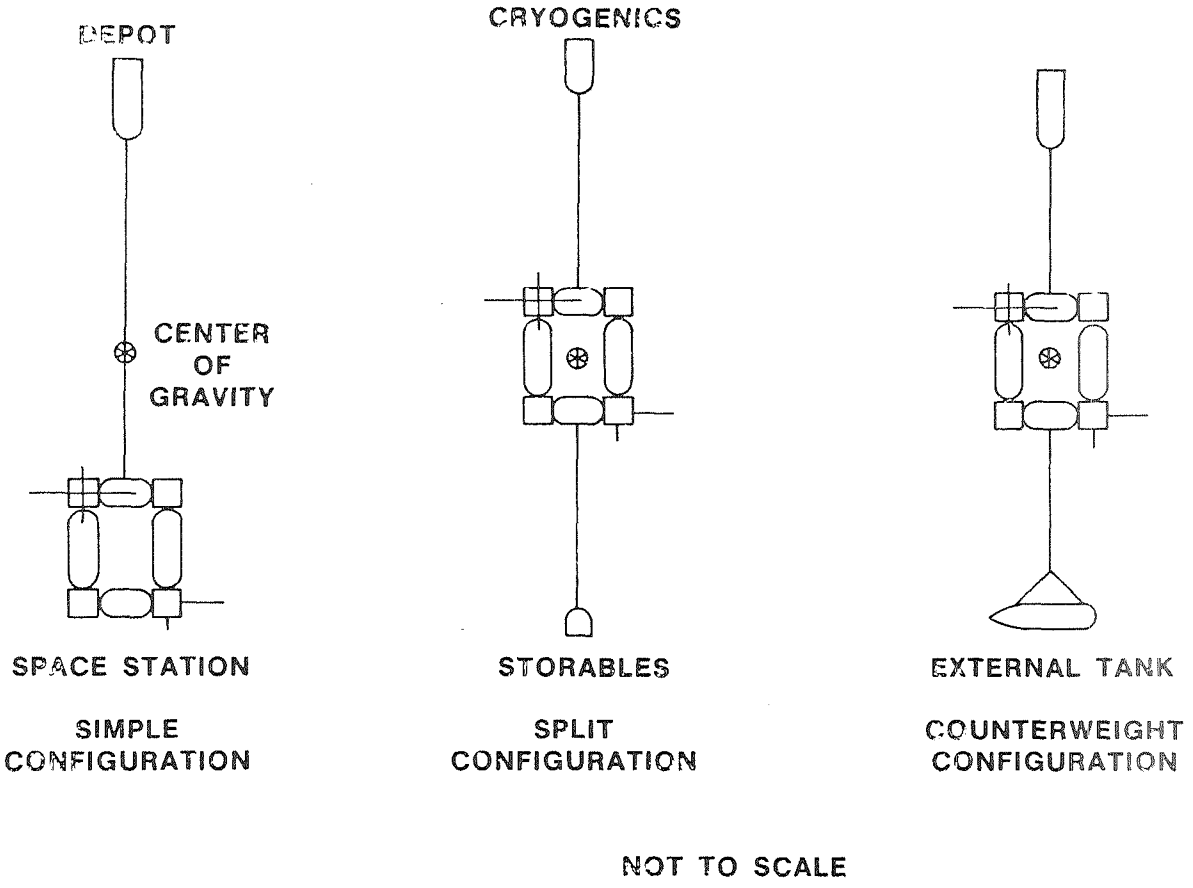


Figure 14

A simple configuration would be a depot, where an OTV would be fueled, attached with a single tether to a space station; however the resulting center of gravity of this system is not at the space station. Options to provide zero gravity at the space station include spliting the depot into cryogenic and storable facilities and tethering in opposite directions from the space station or using a counterweight, such as an external tank or other tethered system. If at least one piece of the depot is the upper mass with the space station kept at the center of gravity of the system, the bottom mass must have sufficient mass so its tether length limitation to prevent deorbit does not result in too little upper mass tether length for depot requirements.

OTV CONDISERATIONS

- FLUIDS INTERFACE WILL BE REQUIRED
  - BOTH FEEDLINE AND VENT DISCONNECTS
  - FORWARD POSITION IF NO PAYLOAD ATTACHED DURING TRANSFER
  - AFT POSITION IF PAYLOAD ATTACHED DURING TRANSFER
    - CONSIDERATION SHOULD BE GIVEN TO DUAL USE OF VENT AND FEED LINES
- BAFFLES MAY BE REQUIRED TO DAMP SLOSHING
- MINIMUM TANK DIAMETER WILL BE LIMITED TO ENSURE SETTLING
- TANK OUTLET OR VENT MAY BE REQUIRED TO BE OFFSET FROM CENTERLINE
- LARGER FEEDLINES MAY BE REQUIRED FOR GRAVITY FEED
- A LOW GRAVITY FLUID QUANTITY GAGE MAY BE REQUIRED FOR LOADING ACCURACY

Figure 15

SUMMARY

- A TETHER CAN PRODUCE SUFFICIENT ARTIFICIAL GRAVITY TO SIMPLIFY PROPELLANT TRANSFER TO AN OTV FROM AN ON-ORBIT DEPOT
- MARTIN MARIETTA UNDER CONTRACT TO NASA, JOHNSON SPACE CENTER IS STUDYING THE FEASIBILITY, DESIGN REQUIREMENTS, AND OPERATIONAL LIMITATIONS OF USING A TETHER FOR PROPELLANT TRANSFER
  - PRIMARY CONCERN IS SLOSHING
- OPERATIONS TO TRANSFER MEN AND MATERIAL BETWEEN END MASSES WILL REQUIRE EXAMINATION
  - POSSIBLE TRANSFER ALONG TETHER
- TETHERED REFUELING DEPOT APPEARS TO HAVE MINIMAL EFFECT ON OTV

Figure 16