CRYOGENIC PROPELLANT ACQUISITION AND TRANSFER

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SUMMARY

The technologies required to successfully design the acquisition and transfer systems for the shuttle are in the areas of storage tank fluid dynamics and thermal conditioning, pressurization and pumping system interfaces, and receiver tank thermodynamics.

Shuttle tradeoff studies which are being performed will have a direct impact on acquisition system design.

Comparing bladders, diaphragms, bellows, linear acceleration, dielectrophoresis and capillary devices for propellant acquisition indicates the selection of capillary devices based on versatility, reusability and weight. Considerations in design of a cryogenic acquisition system are fluid dynamics, thermal conditioning and fabrication.

Pressurization and pumping considerations involve prevention of tank pressure decay, feedline conditioning, and pump transient tradeoffs.

Transfer line and receiver tank considerations involve configurations, and flow rates based on thermal conditioning, chilldown, geysering and venting requirements.

Conclusions are that present studies are adequate to satisfy preliminary design requirements. However, additional studies are necessary to verify advanced concepts which could improve shuttle payload capability.

Future studies are recommended in areas which would have the greatest impact on shuttle performance and versatility.

ACQUISITION DEVICE SELECTION

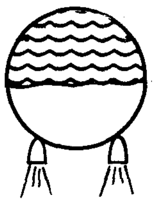
For shuttle restart and propellant transfer it is imperative to have an efficient means of liquid acquisition in subcritical storage tanks. The technique used most commonly on existing vehicles is linear acceleration to bottom the propellants prior to engine restart. This approach while operationally acceptable for a single restart mission has significant weight penalties and vehicle dynamic problems which are magnified for a multiple restart vehicle such as the shuttle orbiter. Linear acceleration also forces a constraint on the mission because of the time required for settling and the vehicle perturbation caused by settling thrust.

Bladders, bellows and diaphragms are useful in positive expulsion applications for small tankage using non-cryogenic fluids. Positive expulsion devices are applicable only for a small number of recycles. For cryogenic fluids, brittleness, permeability and membrane tears have limited recycling demonstrations. Work in cryogenic positive displacement devices currently centers around LeRC with contractual studies being undertaken at Bell and Martin for cryogenic bellows of 304 stainless and at Boeing for cryogenic bladders of gold coated Kapton. Diaphragm work is being done for LeRC by Arde. None of these devices show sufficient promise to satisfy shuttle recycling capability. If significant technology breakthroughs are made in recycling of positive expulsion devices, they should be reconsidered for the cases where they appear competitive. The most likely application is the oxygen tanks where pressurant requirements for collapsing generated vapor are not excessive.

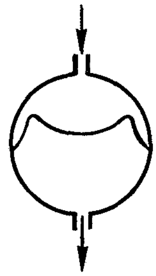
Dielectrophoresis has some merit in its ability to actively expel vapor using dielectrophoretic forces thus possibly circumventing the need for thermal conditioning of the acquisition device. Its disadvantage lies in its weight and complexity. For most propellant acquisition applications in large scale vehicles, the weight of the dielectrophoretic control surfaces approach that of the surface tension device. The dielectrophoretic system has the additional weight and complexity associated with the power supply and electrical hardware. Additionally, safety problems using dielectrophoresis in a LOX environment have not been completely resolved.

The surface tension device is the most promising acquisition concept based primarily on weight, complexity and reusability considerations. Capillary devices have the capability of being completely passive, and supplying pure liquid to a pump inlet with minimum start up transient eliminating the need for a recirculation system with proper feedline conditioning. If proper propellant cleanliness levels are maintained and design loads are not exceeded, the capillary device should be fully reusable within a minimum amount of periodic checkout required to assure system integrity.

ACQUISITION DEVICE SELECTION

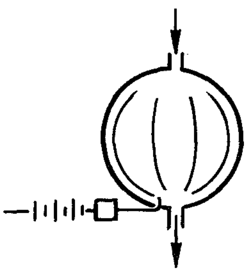


LINEAR ACCELERATION

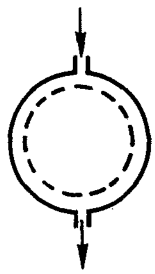


POSITIVE DISPLACEMENT

BLADDERS, DIAPHRAGMS, BELLOWS



DIELECTROPHORESIS



SURFACE TENSION

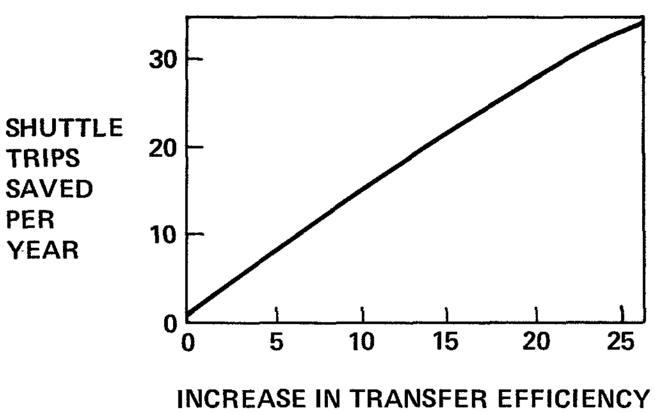
SHUTTLE TRIPS

Capillary devices will be utilized for shuttle subcritical acquisition systems based mainly on weight, complexity and reusability considerations. Acquisition and transfer systems will also be required for the transfer of fluid payload from the EOS to other orbital vehicles such as space tug, lunar shuttle and nuclear ferry or to an orbital fluid depot. The importance of increasing the efficiency of shuttle fluid acquisition and transfer systems is illustrated in the figure for a series of shuttle missions requiring propellant transfer. NASA/MSFC data project the following yearly loading requirements.

Nuclear Ferry to Synchronous Orbit	1,000,000#
Nuclear Ferry to Moon	1,500,000#
Lunar Shuttle	480,000#
Space Tug	480,000#
	3,460,000#

The curve is based on an E.O. Shuttle vehicle supplying this propellant requirement in 35,000 lb increments. Propellant transfer efficiency is affected by storage tank expulsion efficiency and boiloff, transfer line and receiver tank chilldown and vented propellants. It is estimated by MSFC that a transfer efficiency of 75% could be achieved for this mission by using ground testing and analytical tools as the only basis for the design. If orbital test data is obtained for transfer system design then transfer efficiencies could exceed 90%. The propellant savings accruing from technology advances incurred from ground based and orbital testing and analytical studies can have a significant impact on reducing shuttle missions required for orbital propellant transfer.

SHUTTLE TRIPS SAVED vs. TRANSFER EFFICIENCY



ASSUMPTIONS:

35,000 LB. PROPELLANT PER TRIP

3.5 X 10^6 LB. REQUIRED/YR. FOR NUCLEAR FERRY, LUNAR SHUTTLE, & SPACE TUG

TRADEOFFS - CRYOGENIC TANKAGE

For systems where vapor supply is required, such as FCP, APU, ECLSS and ACPS, supercritical systems must be compared with subcritical systems. Subcritical systems of this type require that acquisition devices be used which supply high density fluid in a low gravity environment independent of vehicle or propellant orientation.

The use of integrated tankage is another concept being considered to save weight and minimize components. An integrated tankage system would require the use of a hybrid total acquisition/partial acquisition capillary device to satisfy mission requirements. Compartments could be designed for continuous low gravity outflow in series with compartments designed for engine restart which would be refilled with settled propellant. If separate tanks are selected, individual systems would be designed for each subcritical storage tank requiring low gravity feedout.

Other tradeoffs deal specifically with acquisition system design philosophy. The use of cryogenic capillary devices imposes restrictions on the pressurization system which must be adhered to in order to prevent vapor formation in the capillary device. The use of an autogenous hot gas pressurization system during engine firing can cause vapor to be generated in the start basket. A tradeoff is required between the weight of increased pressurant required if using a cool gas pressurizing system and the weight of a start tank to isolate the capillary device from the effects of hot gas system ullage collapse.

Feedline conditioning system weight and pump transients is another tradeoff which affects capillary device design. The cooling capacity of a thermodynamic vent system can be used to maintain a liquid filled feedline by intercepting the heat leak through the feedline insulation and the heat input from the engine or receiver tank. Maintaining feedline liquid in a state of readiness for withdrawal can reduce pump transient operating periods, thereby effectively minimizing mission constraints due to transfer effects and minimizing pump development problems.

SUPERCRITICAL VS. SUBCRITICAL STORAGE

INTEGRATED VS. SEPARATE TANKS

HOT GAS VS. COLD GAS PRESSURIZATION OF SUBCRITICAL STORAGE

FEEDLINE CONDITIONING VS. PUMP TRANSIENT

SUBCRITICAL VS SUPERCRITICAL

The combination of subcritical storage and low gravity liquid feedout dictates the use of a propellant acquisition device. The principal advantage of supercritical storage compared to subcritical storage is the ability to supply high density fluid with no propellant acquisition device. Technology advancements in cryogenic acquisition device and transfer will increase subcritical system confidence and allow tradeoffs to be made on a direct weight basis.

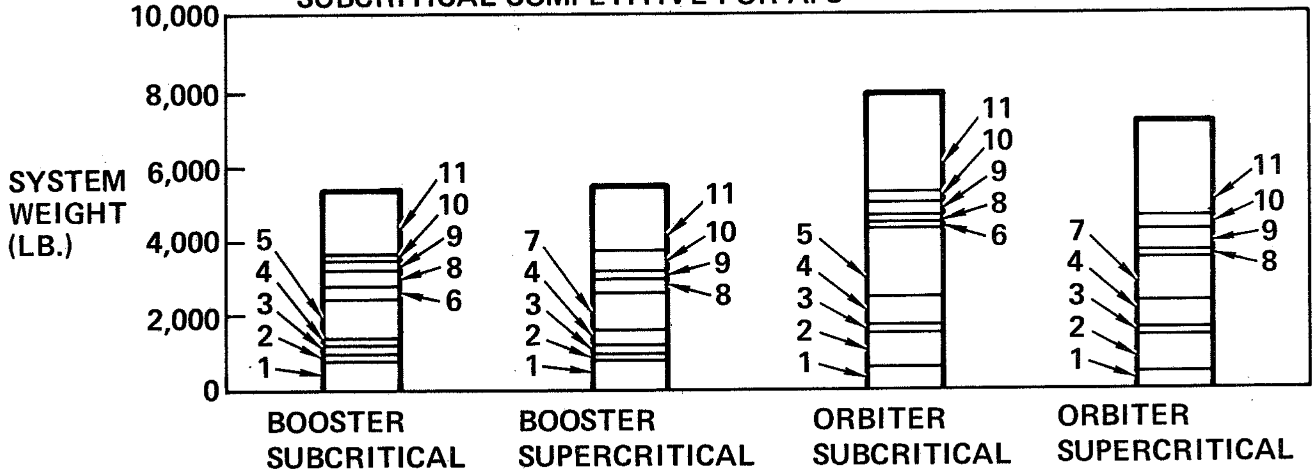
For cases where liquid flow is required, such as the OMS, subcritical storage and supply is the only feasible approach. For cases where vapor is the required supply state, supercritical storage becomes competitive with subcritical. Supercritical storage has a higher tank weight than the subcritical due to the higher storage pressure. For the APS application, accumulators to provide sufficient vapor to minimize pump transient, are required for the subcritical storage mode. Weight comparisons show that the supercritical and subcritical storage modes are competitive for both orbiter and booster.

If the subcritical storage mode is used exclusively for power, environmental control, orbit maneuvering and auxiliary propulsion, reductions in GSE, and weight will result. Reliability and safety constraints also enter into the tradeoff.

The discussion is intended to point out that subcritical storage systems are required for the shuttle. Technological improvements in acquisition and transfer devices will result in improved subcritical storage methods and could eliminate dual storage techniques.

SUBCRITICAL vs. SUPERCRITICAL STORAGE

SUBCRITICAL REQUIRED FOR OMS,
SUBCRITICAL COMPETITIVE FOR APS



LEGEND:

1. THRUSTORS
2. LINES
3. VALVES
4. REGULATORS
5. ACCUMULATORS
6. ROTATING MACHINERY
7. STORAGE TANKS
8. GAS GEN. & HT. EXCH.
9. ACCUMULATOR RESIDUAL
10. ΔI_{sp} (CONDITIONING)
11. PROPELLANT

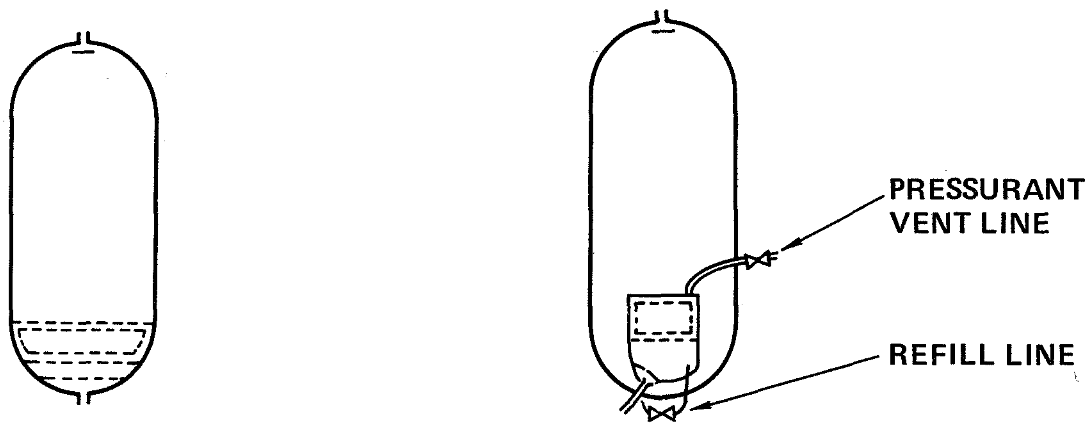
INTEGRATED STORAGE SYSTEM (SUBCRITICAL COULD REDUCE COMPONENTS)

Capillary devices may be divided into two classes; restart devices which rely on propellant reorientation for refill and transfer devices which operate in a continuous low gravity environment. The system shown schematically illustrates a transfer device, such as needed for ACPS requirements, in series with a restart device as required by an OMS restart.

The capillary device in the first tank is subjected to possible pressure collapse prior to engine cutoff if a hot gas pressurization system is used. This pressure decay would result in bulk boiling and possible vapor formation in the capillary device. Vapor entrained in the liquid flowing to the engine pumps disrupts smooth pump operation and increases the chances for cavitation in the pump. The LH_2 tank capillary device configuration must therefore use cold gas during firing to prevent this bulk boiling.

An alternate scheme which allows hot gas pressurization to be used, employs a start tank with a refill valve to thermally isolate liquid from the OMS tank during any ullage collapse subsequent to engine cutoff. This system has the weight penalty of the start tank, refill system and controls and introduces a nonpassive component in the acquisition system configuration. This weight and complexity increase must be traded off against the pressurization system weight saved.

Restart Combined With ACPS



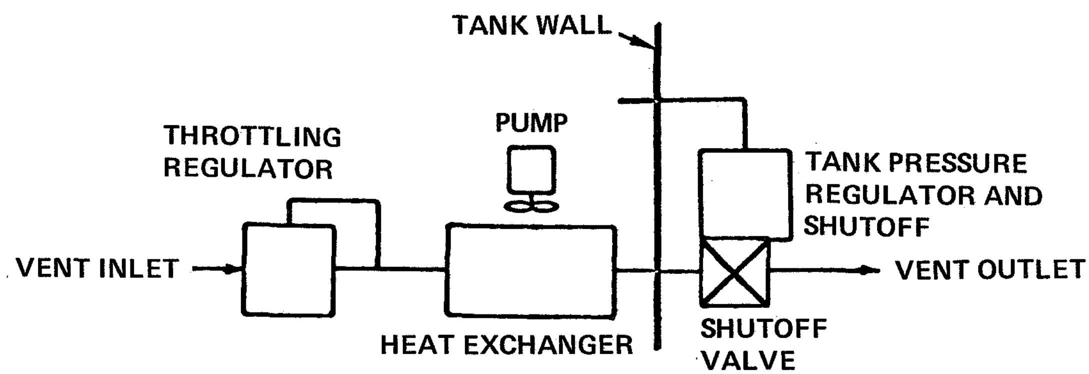
LH_2 TANK
CAPILLARY DEVICE

LH_2 TANK
START TANK &
CAPILLARY DEVICE

THERMODYNAMIC VENT SYSTEM

A cryogenic capillary device requires a technique to prevent vapor from forming within its contained liquid. A thermodynamic vent system was shown to be the optimum method for venting LH_2 storage tanks in studies by Convair for MSFC and Lockheed for LeRC. This type of vent system, shown schematically operates by throttling tank fluid to a low temperature and pressure allowing heat to be transferred to the vented fluid. The temperature difference between the vent fluid downstream of the throttling valve and the fluid in the tank allows heat to be transferred from the tank to the vent fluid. Transferring sufficient heat to the vented fluid will allow a superheated vapor to be vented, thus minimizing the weight of fluid vented. A pump-mixing device may be utilized to reduce heat exchanger weight by increasing hot side heat transfer coefficients. Effective mixing is essential for destroying temperature stratification in the tank and effective controlling tank of tank pressure. This type of thermodynamic vent system has demonstrated its ability to control tank pressure to within one psi, thus minimizing the deleterious effects of large tank pressure reductions as would occur in a tank blowdown.

SCHEMATIC OF BULK HEAT EXCHANGER VENT SYSTEM



ACQUISITION SYSTEM THERMAL CONDITIONING

The thermodynamic vent system cooling capacity can be used to prevent vapor formation due to localized heat leaks, and to maintain the capillary device fluid in a slightly subcooled state. This cooling capacity can also be used to maintain pure liquid in the feedline. The liquid supply required to assure sufficient vent fluid cooling capacity, may be bled off the capillary device. After cooling the capillary device, the vent fluid passes through a compact heat exchanger/mixer unit. The mixer unit is located and sized to control temperature stratification in the tank and thus aids in the control of tank pressure. The cooling system is sized to maintain slightly subcooled liquid in the conditioned area at all times while not exceeding the cooling capacity of the vent fluid. The cooling capacity of the GH_2 may then be used to maintain the LO_2 tank in a vent free condition with pure liquid contained in the capillary device and feedline.

The mixer function is to control tank pressure by setting up a flow pattern which will cause energy removal from the tank to be evidenced by a drop in ullage pressure. The mixer configuration should minimize velocity patterns in the vicinity of the capillary device in order not to impose excessive cooling requirements on the vent system cooling coils. The second function of the mixer, if used in a compact heat exchanger vent system, is to reduce heat exchanger length by increasing hot side heat transfer coefficients.

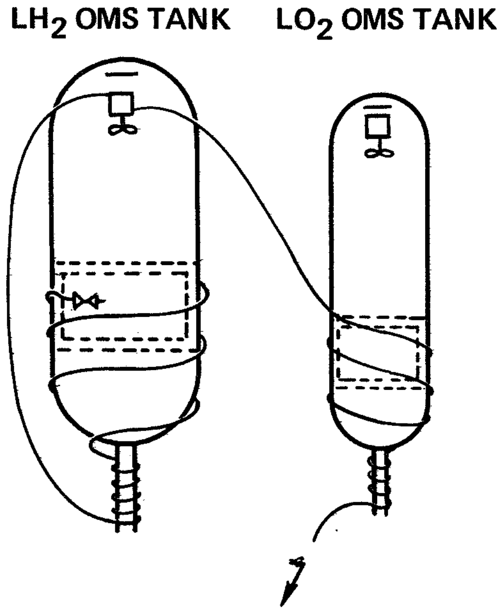
Cooling systems of this type were investigated by Convair under contract NAS8-21465 for MSFC and will be examined for shuttle payload propellant transfer by Convair under Contract NAS8-26236 with MSFC. Experimental studies are being conducted by Lockheed for AFRPL to verify the outflow and fluid conditioning performance of a prototype LH_2 capillary device for an AMPS type mission. A cryogenic capillary device evaluation related to the shuttle is being conducted by Martin for MSC with the objective of developing parametric design data and a scale model prototype capillary device for LN_2 testing.

Mixing has been thoroughly investigated in the chemical engineering literature for processes relating to blending of mixtures. Recent work for spacecraft applications has been conducted to evaluate the effect of mixing on reducing temperature stratification in a heated tank in order to control pressure rise. Destratification studies are in progress at GD/Fort Worth for MSFC to develop analytical models and correlate them with non-cryogenic small scale and large scale tank tests for both subcritical and supercritical fluid. Mixing flow patterns are being examined by Lockheed under contract to LeRC in order to determine fluid velocities under a variety of mixing configurations. For mixing applications, AiResearch has under development a brushless DC motor for LeRC.

ACQUISITION SYSTEM CONSIDERATIONS

THERMAL CONDITIONING

- VENTING
- CAPILLARY DEVICE COOLING
- DESTRATIFICATION
- PRESSURIZATION



ACQUISITION SYSTEMS CONSIDERATIONS
FLUID DYNAMICS

Most cryogenic capillary device fluid dynamic problems have already been encountered in noncryogenic capillary device applications. For large tankage applications, the most significant fluid dynamic problem which exists is the prediction of reorientation times and fluid configurations in high inertia fields. Reorientation of the fluid from its initial low gravity position to a location where capillary device refilling may be accomplished has a direct effect on capillary device sizing since during this reorientation period the liquid supply to the engine must come directly from the capillary device. This problem has been recently investigated by Convair, Martin and McDonnell-Douglas under contracts to MSFC and MSC, however, additional work is needed particularly in predicting decay of turbulence subsequent to liquid impingement on the aft bulkhead. Techniques for reducing settling time by use of baffles or dual thrust modes should be investigated in more detail.

Refilling of a capillary device with collected fluid is a significant problem for a multi-restart, high Weber number settling case. Turbulent fluid can impinge on the partially empty capillary device causing it to become completely wetted before all the vapor can be replaced by liquid. Use of non-wicking screens, flow baffles, dual thrust modes and refill valves are means which have been explored to eliminate this problem. Refilling should be investigated in conjunction with reorientation. Some drop tower studies are planned at LeRC. Previous analytical investigations have been made at Convair, Lockheed and McDonnell-Douglas.

Draining of a tank with a capillary device under high Bond number conditions has been investigated by Convair under contract NAS8-21465 with MSFC. For low Bond number conditions with highly curved interfaces, LeRC has conducted drop tower investigations in baffled and unbaffled tanks. Lockheed is attempting to develop an analytical model of draining for LeRC which correlates the experimental data. LeRC plans to conduct additional drop tower studies to evaluate draining of low gravity capillary devices in order to predict outflow efficiency in terms of residuals.

Wicking along screens and between perforated plates may be used to prevent drying out of a capillary device which is subjected to heating. Analytical and experimental studies of screens have been conducted at Convair to simulate low gravity wicking.

Retention capability of a screen is normally found by the well known bubble point test method. Stability limits for screens have been obtained for square weaves by Martin for MSFC using drop tower tests. Additional testing is needed to evaluate hydrodynamic stability of dutch twill screens. The effect of heat transfer on retention has been qualitatively evaluated by Convair at normal gravity in experiments for MSFC. Additional work is required to obtain a quantitative evaluation of heat transfer effects on retention and screen wetting at low gravity.

ACQUISITION SYSTEM CONSIDERATIONS

FLUID DYNAMICS

- REORIENTATION
- REFILLING
- DRAINING
- WICKING
- RETENTION

ACQUISITION SYSTEM

FABRICATION

Cryogenic capillary device structural designs must reflect the requirement for minimum heat leak and minimum weight configurations. Low heat flux can be obtained by using low thermal conductivity supports and placing the internal support points away from tank insulation penetrations. The primary structural considerations are designing the capillary device to resist impingement loads, screen pressure drops and deflections which could cause structural failure of the configuration or alteration of the screen micron rating. Important factors to be incorporated into the design are repairability and ease of assembly. Any repairs required should be possible without having to remove the capillary device from the tank. Assembly procedures should, if possible, consider installing the capillary device into the tank in assemblies or subassemblies in order to minimize activity on and handling of the capillary device. The design must also consider the filtration properties of the screen and propellant cleanliness to eliminate screen clogging problems. Procedures need to be established for capillary device in-tank checkout during servicing by measuring capillary device bubble point and screen pressure drops.

Although capillary devices of up to sixty two inches in diameter have been manufactured for noncryogenics, no large scale cryogenic devices have been fabricated which remotely approach the size needed for shuttle. Shuttle reusability requirements dictate development of advanced handling, cleanliness and repairability procedures. A critical need exists for a fabrication study to establish practical methods of assembly, handling, checkout, cleaning and refurbishment of large scale capillary devices for cryogenic applications.

ACQUISITION SYSTEMS CONSIDERATIONS

FABRICATION & STRUCTURAL DESIGN

- LOW CONDUCTIVE SUPPORTS – MINIMUM HEAT SHORTS
- FABRICATION
- ASSEMBLY
- CHECKOUT
- REFURBISHMENT

PRESSURIZATION AND PUMPING INTERFACES

The primary interface consideration between the acquisition system and pressurization system is that the ullage pressure should not be allowed to decay and cause bulk boiling within the capillary device.

Pressure decay due to venting can be minimized by using a thermodynamic vent system as previously described. Pressure decay subsequent to engine cut-off may occur if a hot gas ullage pressurization system is used. If hot gas is injected directly into the ullage, the liquid will not be in thermal equilibrium with the hotter ullage gases at burnout. Tank pressure will decay as liquid sloshes into and cools the ullage. Simultaneous evaporation occurs and thermal equilibrium is approached as the tank contents are mixed. The mixing process, depending upon the amount of fluid in the tank and the type, quantity and amount of pressurant used, may result in vapor being generated by bulk boiling. Analyses of shuttle pressurization system operations should reveal whether this could produce bulk boiling in the capillary device. It should be noted here that utilizing the cooling capacity of a thermodynamic vent system can prevent bulk boiling in the capillary device for small pressure decays. If bulk boiling appears to be a problem, a pressurization system could be used with the pressurant injected up through the liquid outside the capillary device or by injecting cold gas directly into the ullage. With cold gas, the temperature difference between liquid and vapor at burnout should be small enough to minimize ullage pressure decay and prevent vapor formation in the capillary device due to bulk boiling.

If ullage pressure decay with a hot gas system creates too much bulk boiling for satisfactory capillary device operation, it is also possible to use a start tank rather than accept the pressurant weight penalty of a cold gas system. A start tank configuration as conceived by McDonnell Douglas was shown previously. The start tank propellant is isolated from the thermodynamics of the main tank. Heat transfer from the main tank into the start tank will not effect system operation if the start tank pressurization is used to collapse any bubbles formed or if a thermodynamic vent system is used to cool the start tank. This system introduces additional valves which are not necessary on the capillary device designs previously discussed. The weight of the start tank system will have to be traded off against the weight of the additional pressurant required for cold gas injection.

The primary influence of the pumping system is in the fluid quality required to be supplied from the capillary device. If the pump can operate with some vapor during low speed "idle mode" startup, a chilldown recirculation system can be eliminated. Conversely, the use of thermal conditioning as previously shown can produce a feedline which maintains pure liquid close to the engine interface, reducing start-up transient. There is another trade-off between pump inlet conditions and capillary device and feedline outlet requirements.

PRESSURIZATION & PUMPING INTERFACES

ULLAGE COLLAPSE

HOT GAS

COLD GAS

ZERO NPSH PUMPS

TRANSFER LINE AND RECEIVER TANK

Conditioning of a transfer line to retain liquid during no-flow periods can reduce start up transient and overall transfer time. The conditioning system must remove the incident heat leak to the feedline thru the insulation and the heat conducted and radiated from the hot engine or receiver tank. A capillary barrier and feedline vent is required to prevent any vapor which may be generated downstream of the feedline from displacing conditioned liquid in the capillary device.

Chilldown will be accomplished in minimum time and with minimum weight penalty by optimizing transfer line size, insulation, transfer rate and the design of baffle devices for aiding chilldown. In the receiver tank, inlet geysering and means of establishing optimum inlet chilldown patterns must be investigated to eliminate excessive tank pressure rise. It may be possible for some transfer systems to maintain the receiver tank in a non-vented condition during transfer through efficient chilldown techniques. For these cases, a vent device, sized for the steady state condition and similar to the storage tank thermodynamic vent system, would be the only one required. Baffling or directing the inlet flow appears to have the most potential in providing relatively uniform tank chilldown. LeRC has been studying tank inlet geysering problems using their drop tower facility and has additional effort planned to evaluate cryogenic storage tank pressure during inflow including the effect of rapid spray cooling and controlled cooling of tank walls. Work is also planned to determine vent losses during inflow to baffle and retention type capillary devices. MSFC is studying the inlet geysering problem analytically using the Convair developed SURF computer code. This code is a numerical solution to the Navier Stokes equations with surface forces included. Lockheed has studied transfer line and receiver chilldown analytically for MSFC resulting in the development of computer programs for thermodynamic evaluation of these phenomena. Orbital experiments in the space station experiment module are proposed to evaluate line and receiver tank chilldown, geysering and venting.

If receiver tank venting during transfer is required, studies performed by Convair for MSFC have shown that a mechanical separator is most efficient under a wide range of inlet qualities and vent rates. This mechanical separator was selected on the basis of weight, reliability, and cost after comparison with compact heat exchanger vent systems, wall heat exchanger vent systems, surface tension devices, vortex separators, and a combined wall heat exchanger/mechanical separator system. Mechanical separators have been built for the Centaur and successfully tested. Before a device of this type could be employed with confidence, an orbital test would be required to accurately simulate receiver tank fluid dynamics and liquid/vapor distribution at the separator inlet.

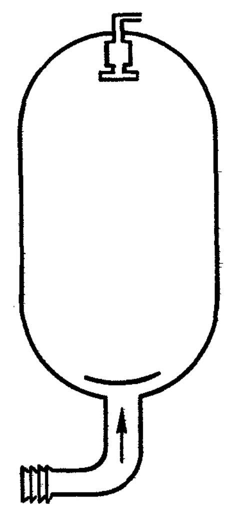
Filling a receiver tank which contains a capillary device could result in trapping vapor within the compartments reserved for liquid. Drop tower tests at LeRC will investigate this problem.

TRANSFER LINE & RECEIVER TANK CONSIDERATIONS

FEEDLINE CONDITIONING

CHILLDOWN	–	TRANSFER LINE
	–	GEYSERING
	–	BAFFLES
VENTING	–	MECHANICAL SEPARATOR

CAPILLARY DEVICE FILLING



CONCLUSIONS

The results of recent and current technology studies indicate that capillary devices are superior to bladders, bellows, diaphragms, dielectrophoretic and linear acceleration devices for restart and transfer of cryogenics. Future emphasis should be placed on advanced development and verification of the capillary devices since they have the greatest potential for shuttle applications. Periodic review of the other methods of acquisition should be made in order to assess the impact of any improvements on shuttle development and performance.

Current studies are developing technology which is directly applicable to shuttle acquisition and transfer problems. Studies sponsored by NASA/LeRC, NASA/MSFC, NASA/MSC and AFRPL are developing analytical methods and ground based experimental correlations in the areas of acquisition device fluid dynamics and thermal conditioning. A smaller amount of work is being done on receiver tank and transfer line problems at LeRC and MSFC. These studies and existing information from recently completed programs provides an adequate technology base for supporting the initial shuttle designs.

Additional technology studies are necessary to increase acquisition and transfer system efficiency. A deliberately conceived, coordinated, integrated plan will expose technology deficiencies and provide the basis for their systematic solution. The plan should encompass analytical investigations, ground based testing and orbital experimental to verify advanced acquisition and transfer technology and to qualify "state of the art" designs.

CAPILLARY DEVICE APPEARS MOST PROMISING FOR CRYOGENIC ACQUISITION

CURRENT STUDIES ARE POINTED TOWARD SOLVING SHUTTLE ACQUISITION & TRANSFER TECHNOLOGY PROBLEMS

FUTURE TECHNOLOGY STUDIES HAVE NOT BEEN SOLIDIFIED IN A COHERENT INTEGRATED PLAN

RECOMMENDATIONS

Future studies should be coordinated to advance the technology which will improve shuttle acquisition and transfer system performance. The main areas for study are in the areas of thermal conditioning, fluid dynamics, and fabrication.

Thermal conditioning studies should be conducted to investigate low gravity destratification, receiver tank and transfer line chilldown techniques, and capillary device and feedline conditioning concepts. Low gravity vent devices should be flight qualified. Boiling heat transfer, heated screen retention properties, bubble dynamics and thermophoresis studies would increase confidence in internal tank thermodynamics, capillary device performance and heat transfer predictions. Orbital testing is necessary for attaining sufficient time at low gravity to obtain accurate thermal data.

Fluid dynamics studies are needed in the areas of reorientation, refilling, geysering, capillary device draining and wicking. These should primarily be low gravity drop tower and orbital tests with analytical studies required in reorientation, refilling and inlet fluid geysering.

Fabrication studies should be initiated to establish practical methods of assembly, checkout, cleaning and refurbishment of large scale capillary devices for cryogenic applications. A typical device should be built and flow cycled in a simulated shuttle environment to demonstrate reusability and ease of checkout.

FUTURE TECHNOLOGY STUDIES MUST BE PLANNED TO SATISFY SHUTTLE REQUIREMENTS

- THERMAL CONDITIONING
- FLUID DYNAMICS
- FABRICATION
- GROUND & ORBITAL BASED EXPERIMENTAL STUDIES