Centaur Propellant Acquisition System

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The desirability of replacing the hydrogen peroxide settling system of the Centaur D-1S with a capillary acquisition system is evaluated. A comprehensive screening is performed to select the most promising capillary fluid acquisition device, and thermal conditioning and fabrication techniques. Refillable start baskets and bypass feed start tanks are selected for detailed design. Critical analysis areas are settling and refilling, start sequence development with an initially dry boost pump, and cooling the fluid delivered to the boost pump to provide the necessary net positive suction head (NPSH). System comparisons indicate that the start baskets using wicking flow for thermal conditioning, and thermal subcooling for providing boost pump NPSH, are the most desirable systems for future Centaur acquisition system development.

Introduction

DURING low-gravity coast, vehicle drag and disturbing acceleration may position propellant away from the tank outlet. Engine start under these conditions will cause vapor to enter the pumps, producing cavitation, unsteady engine operation, and possible feed system failure. To eliminate these undesirable occurrences, means must be provided to position liquid in the sump and over the tank outlet. The method currently used on Centaur is to settle the propellants by using small thrusters to apply a linear acceleration to the vehicle. This method, while well-proven, imposes mission constraints in waiting for propellant to be settled and weight penalties which are a function of the number of engine burns. The use of a capillary or surface tension device to trap propellants over the outlet in low gravity is a more advanced, but less proven technique. The weight penalty for the surface tension device is less sensitive to the number of engine burns, and provides added mission flexibility in allowing quick engine startup.

Capillary devices perform the function of retaining propellants over the tank outlet for boost pump and engine startup. This study examined both the requirements of cryogenic capillary acquisition systems in performing this function and the interaction of the acquisition system with related vehicle systems.

Systems interacting with the acquisition system are shown in Fig. 1: the pressurization, vent, and propellant gaging systems; main engines, boost pumps; and propellant ducts.

Capillary acquisition systems fall into two main classes: partial acquisition devices, such as start baskets or start tanks that rely upon fluid settling for refill; and "total" acquisition concepts, such as liners or channels that cover a substantial portion of tank area and maintain continuous contact with the main liquid pool. A partial acquisition concept operates by maintaining liquid over the outlet in sufficient quantity to allow engine firing until the main liquid pool settles. The settled liquid refills the acquisition device. During initial engine firing, vapor enters the acquisition device volume. Capillary device geometry must be designed so that the entering vapor does not create adverse liquid spilling from the basket away from the engine outlet, or cause difficulties in later refilling the device with liquid. Total control devices are either maintained full of liquid during main engine burns, or refilled between burns by capillary pumping, venting, or mechanical pumping.

Since the acquisition system interacts with many other systems in the vehicle, comparison of acquisition systems cannot be done by merely looking at the acquisition device alone. Consideration was given to all changes to the vehicle caused by the particular acquisition system being implemented.

Ground Rules

The baseline vehicle configuration was the Centaur D-1S, as defined in Ref. 1. This Centaur D-1S represented a minimum-change D-1T configuration (Centaur currently used with Titan), modified to be compatible with the Space Shuttle interface, operations, and safety requirements. Since that time, there have been a number of changes in this configuration as a result of later studies. However, the data in this paper represent the results using the original configuration, which was the baseline when this study was conducted. Approximately 95% of the existing Centaur D-1T components remain unchanged for the D-1S.

The baseline D-1S thermodynamic vent subsystem consisted of coiled tube heat exchangers, pump/mixers, shutoff

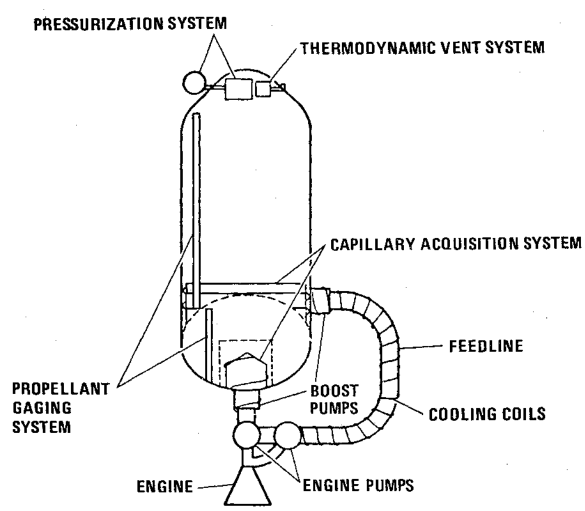

Fig. 1 Capillary acquisition subsystem interfaces.

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Index category: LV/M Fuel and Propellant Systems (including Storage and Transfer).

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Table 1 Recommended acquisition subsystem candidates

Fluid Conditioning Candidates	Capillary Device Thermal Conditioning Candidates	Boost Pump Thermal Conditioning Candidates	Propellant Ducting Thermal Conditioning Candidates
1. Start Basket – Screen device over outlet & sump provides liquid for thermal conditioning requirements between burns from a liner or channel sized to remain full during the entire mission. Lightest weight & least complex fluid containment concept. If main tank pressurization is required, however, cold gas pressurant requirements severely penalize this concept. 2. Start Tank – Bypass Feed Device – Separate tank of approximately the same volume as the start basket is located near sump of main tank. Outflow requirements, inner screened requirements, liner & channels are similar to those of start basket. Valves are used to control outflow & refilling. Only the start tank must be pressurized for main engine start.	1. Acquisition Device Cooling – Uses active cooling coils wrapped around device. Cooling coils are fed throttled vent fluid from compartments inside acquisition device. Cools contained fluid sufficiently to prevent vaporization. 2. Thermal Subcooling – Uses active cooling coils similar to Concept 1 but cools contained fluid enough to provide boost pump NPSH. This concept could eliminate main tank pressurization subsystem, potentially reducing subsystem weight by 540 lb. Useful for start basket concept. 3. Pressure Conditioning – Uses cold helium to suppress vaporization in contained liquid. Because of large pressurization subystem weight penalties, this concept is applicable only to start tank.	1. Wrap Drive Shaft Area Near Pump With Cooling Coils – Heat is taken out near contained fluid. Heat can be removed readily from drive shaft housing, but heat removal from drive shaft & impeller between burns is an extremely difficult problem. 2. Purge Turbine With Cold Helium – This system requires a cold helium purge. Drive shaft cooling is difficult. No pump modifications are required & thus is least complex. 3. Purge Turbine With Cold Helium & Use Cooling Coils to Intercept Incident Heating – More uniform cooling & design flexibility in removing heat by two methods. Pump cooling from sources other than turbine are handled by cooling coils. Note: If Candidates 1 to 3 are not satisfactory in eliminating vaporization in contained boost pump fluid between burns, the more complex candidates employing gearbox purging or drive shaft purging will be required. Modifications required to implement these cooling schemes are too complex to be adopted.	1. Wrap Duct Length With Cooling Coils – Throttle vent fluid & wrap cooling coils around duct. (Consider use of hydrogen to cool LO_2 duct.) Advantages are elimination of line chilldown and time in start sequence required for engine chilldown & propellant bleed lines. 2. Flush Propellant Lines at Either a Low Continuous Rate or at a High Rate for a Specified Period Just Before MES – This eliminates the complexity of wrapping cooling coils around the line. (A portion of line just downstream of boost pump may be required to keep boost pump cooled efficiently.)

valves, regulators, and filters. The study evaluated modifications required to thermally condition the contained fluid in the capillary devices. This entailed additional cooling loops in parallel with the main bulk heat exchanger.

The integrated propellant acquisition and thermodynamic vent subsystems designed in this study provide pressure control both within the Orbiter payload bay and during the flight mission profiles for the same environmental conditions used in Ref. 1. The propellant acquisition and thermodynamic vent subsystems designed in this study neither impose constraints on the operation of the Shuttle, nor affect Centaur/Shuttle abort compatibility.

Flight profiles for the study were a single-burn planetary, a two-burn synchronous equatorial, and a five-burn low Earth orbit mission. These profiles, as well as heating rates and nominal tank pressure levels, were obtained from Ref. 1. Parameters not specified were generated using analytical or empirical techniques consistent with the design of Centaur D-1T and D-1S.

Candidate Systems

The objective of screening candidate systems was to identify possible methods of accomplishing capillary propellant acquisition for the Centaur D-1S and to evaluate these approaches based upon weight, feasibility, and operational advantages to determine which candidates compare favorably to the baseline hydrogen peroxide system.

In determining candidate acquisition subsystem concepts, capillary device fluid containment, pressurization, thermal conditioning, structure and assembly, and feedline thermal conditioning were considered separately. Initially, all possible means of satisfying mission and vehicle requirements were identified for each concept category. Each fluid acquisition

Table 2 Recommended capillary device fabrication candidates

Component or Process	Fabrication Alternatives
Screen Material	1. Aluminum screen where available 2. CRES screen for low micron ratings where aluminum is not available
Screen Mesh	1 Dutch twill screen for wicking applications 2 Square-weave screen where refilling is of overriding importance
Screen Pleating	1. Nonpleated screens are baseline approach 2. Pleated screens where fabrication is not a problem & surface area requirements are high
Screen Backup	1. Perforated aluminum plate is baseline approach 2. Coarse screen should be used if extra stiffness is important 3. Open isogrid offers increased strength
Screen Attachment	1. Resistance welding is baseline method 2. Bolting should be used where screen must be removable
Cooling Tube Attachment	1. Dip brazing for small devices 2. Resistance welding of extruded webbed tubes for large devices

system candidate was conceptually designed to meet Centaur D-1S mission requirements and was then evaluated based upon approximate weight and operational advantages compared to the baseline hydrogen peroxide system. Candidates were screened only to the point at which they could be logically rejected. For example, if a device could not be conceptually designed to meet Centaur D-1S requirements, it was eliminated without determining system weight. Further, if the weight exceeded existing system weight by more than 20%, the concept was rejected. If the concept still remained a candidate, then operational advantages or disadvantages compared to the existing system and to other candidate acquisitions were assessed.

Thermal conditioning and pressurization candidates were compared based on relative advantages and disadvantages, complexity, and weight. Promising fabrication alternatives were determined for screen-to-backup material joining, backup material selection, barrier material selection, load support and cooling tube attachment. Recommended candidates are shown in Tables 1 and 2.

Eighteen capillary fluid acquisition candidates, seven capillary device thermal conditioning candidates, and four pressurization system candidates were considered. Since pressurization will be accomplished when the propellant is unsettled, the use of warm pressurant will cause rapid ullage pressure decay when the cold liquid "settles" through the pressurant. Cold pressurant used to alleviate the problem imposes a severe weight penalty on the capillary acquisition subsystem. Thermal subcooling was identified as a promising candidate for providing boost pump NPSH. This concept uses throttled vent fluid to subcool the main engine inflow in a compact heat exchanger before it enters the boost pump.

Sixteen potential methods were considered for cooling the boost pump. Effective cooling methods were found to be too complex to be adopted. Boost pump cooling was thus considered unfeasible. The nine propellant duct thermal conditioning methods considered were eliminated since a wet line requires a wet boost pump.

To use program resources most efficiently, the recommended subsystems in Table 1 were analyzed to determine which combinations were most desirable. These combinations were then focused upon for the remainder of the study. The process of discriminating between these subsystems was formulated into a decision tree. The main design drivers, considering the Centaur D-1S and other advanced versions of Centaur, are cost, complexity, and weight.

Priority was given to answering the critical questions in the decision tree: 1) Can settling be used to successfully refill the capillary device? 2) Can boost pump NPSH be achieved with thermal subcooling? and 3) Can a successful start sequence be developed without cooling the boost pump? These questions were answered affirmatively, and a system using a start basket with thermal subcooling and uncooled boost pump was selected as the most promising device to be designed. To have two distinctly different subsystems for design and comparison, a bypass feed start tank using an uncooled boost pump was also selected.

Fluid Analysis

Start tank and start basket fluid analyses were performed to determine capillary acquisition volumetric requirements and performance. Initially, the critical questions were addressed: Can a successful start sequence be achieved without cooling the boost pump? Can settling be used successfully to refill the capillary device? A successful start sequence was developed and a conservative analysis affirming successful refilling with settled fluid was performed. Fluid analysis then was continued by determining the effect of start transients and vibrations on capillary device liquid retention. Start basket and start tank sizing were then performed, based upon start sequence, thermal conditioning, residual, and channel volume requirements. Wicking to provide flow for maintaining wet start basket screens was analyzed. Problems of filling on the ground and possible abort of Centaur while in the Shuttle cargo bay were addressed. The interaction of the propellant gaging subsystem with the start basket was also considered.

Start Sequence

A start sequence was selected that avoided costly engine requalification, and resembled the existing Centaur start sequence as closely as possible. The recommended start sequence using start baskets and initially dry propellant ducts is:

1) Open fuel and oxidizer shutoff valves to fill and chill the sump and boost pump.

2) Close the shutoff valves.

3) Start the boost pump and chilldown the lines through the recirculation system.

4) When the boost pump is up to speed, open the shutoff valves and use a normal chilldown sequence for the engine.

The main difference between this start sequence and the existing start sequence lies in the fact that the existing start sequence settles the propellant before start and, therefore, has the boost pump full. The capillary devices have dry boost pumps upon start sequence initiation. The engine shutoff valves are opened to provide the driving pressure for flow. Start sequence flow rate, thrust levels, and chilldown quantities were developed for Shuttle cargo bay and orbital heating conditions.

Settling and Refilling

Examination was made of existing methods of predicting settling time to determine their applicability to Centaur D-1S. For the existing hydrogen peroxide settling system, the settling process occurs at 24 lb of thrust. For the capillary acquisition system, settling occurs during the start sequence with thrust buildup to a maximum level of 30,000 lb during the final stages of settling. Existing correlations proved inadequate—either because they are applicable only to low Weber number flow regions, depend upon semiempirical coefficients that cannot be readily evaluated, or require the use of a complicated computer model that, while applicable to the high Bond number and Weber number regimes where geysering and recirculation are dominant, has limited predesign value due to its running time and complexity.

Another method of computing settling time is an approximation sometimes used for predesign calculations. This method merely multiplies the free-fall time (the time between initiation of thrust and fluid impingement on the aft blukhead) by a constant to account for liquid geysering and energy dissipation after liquid impingement on the aft bulkhead. The justification for using an approximation of this type is that the constant can be chosen to yield a conservative settling time value and that no better simple method is available at this time. Settling calculations were performed using this method and the start sequence thrust profile.

Thrust barrel refilling calculations were performed to determine available time for LO_2 capillary device refilling. As shown schematically in Fig. 1, the thrust barrel consists of a cylindrical shell placed symmetrically over the LO_2 tank outlet and capillary device to distribute the load from the thrust structure. Holes on the top and sides of the thrust barrel allow propellant to reach the tank outlet and vapor to leave the thrust barrel during refilling. Thrust barrel refilling times with existing holes were unacceptably long (three to six sec) because of the short time available for capillary device refilling. Thrust barrel refilling time was, therefore, reduced to about one sec at main engine thrust conditions by increasing the side hole area from 0.69 ft^2 to 4.12 ft^2, and the top hole area from 1.18 ft^2 to 3.48 ft^2.

Settling and thrust barrel refilling calculations were used to compute available start basket refilling time. The fourth burn on the five-burn mission was found to have minimum refilling time for both LO_2 and LH_2 start baskets. For the LO_2 tank, refilling time was 15.66 sec (18.90 sec of burn time minus 1.54 sec for thrust barrel refilling and 1.70 sec for settling). For the LH_2 tank, refilling time was 15.07 sec (18.90 sec of burn time minus 3.83 seconds for settling).

Refilling calculations performed for the start basket assumed only hydrostatic pressure as the driving pressure with no dynamic refilling. Refilling was considered not to start until settling (and thrust barrel refilling) was complete. Screen wetting was assumed to exist during the entire refilling period. The screen retention pressure thus inhibited refilling during the entire period. Capillary device refilling was computed based on pressure differences between the inside and outside of the capillary device.

For the LO_2 start basket, refilling calculations were carried out incrementally. As shown in Fig. 2, the LO_2 basket was broken down into the three regions: a sump, a cylinder, and a cone. Equations were formulated and solved for each region as a function of screen open area, as presented in Table 3.

System design calculations indicated that screen open area will be 32%; thus, capillary device refilling will take place within the allowable 15.66 sec. The LO_2 basket screen is 50×250 mesh.

For the LH_2 start basket, a similar analysis was used with a single-step procedure to compute refiling time as a function of screen open area. Results appear in Table 4. A standpipe height of 5.58 in. was used to minimize trapped vapor volume. Screen open area is anticipated to be 29%; thus, refilling will take place within the allowable 15.07 sec. The LH_2 basket is divided into two compartments; the top is 40×200 mesh screen; the lower is 50×250 mesh. The compartments are separated by 14 mesh screen.

Start tank refilling was successfully accomplished by venting the start tanks to 5 psia below the main tank pressures. This pressure difference was maintained by venting during refilling.

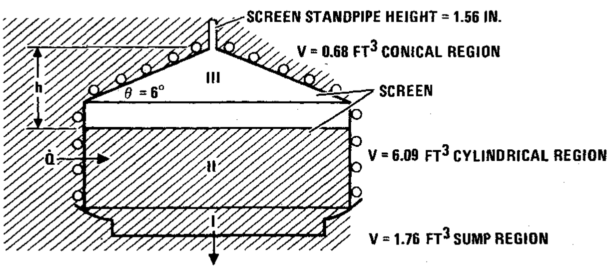

Fig. 2 LO_2 start basket refilling.

Table 3 LO_2 start basket refilling time

Screen Open Area (%)	Refilling Time (sec)			
	Sump	Cylinder	Cone	Total
12.5	0.61	3.86	9.0	13.47
25	0.30	1.93	4.5	6.73
50	0.15	0.96	2.25	3.36
100	0.08	0.48	1.13	1.69

Table 4 LH_2 start basket refilling time

Screen Open Area (%)	Refilling Time (sec)
12.5	10.9
25	5.45
50	2.72
100	1.36

Thermal Analysis

Thermal analysis was performed in the areas of thermal subcooling, start basket and start tank thermal conditioning, tank pressure control, and boost pump thermal conditioning. Major emphasis was placed upon the critical areas of thermal subcooling to provide boost pump NPSH and start basket thermal conditioning to prevent screen dryout.

Thermal Subcooling

To provide satisfactory boost pump operation, adequate subcooling must be supplied to prevent cavitation. The subcooling must be sufficient to intercept heat input to the fluid entering the boost pump as well as to provide boost pump NPSH. These requirements are 4 Btu/sec and 0.12 psi for the LH_2 boost pump, and 4 Btu/sec and 0.72 psi for the LO_2 boost pump. In the existing Centaur, pressurant is used to subcool the liquid flowing to the pumps and suppress boiling. For the start basket application, throttled vent fluid is used to remove heat from this fluid to achieve subcooling. Heat exchangers were analyzed for supplying boost pump NPSH by cooling the liquid flowing to the boost pumps. This thermal subcooling concept eliminates main tank pressurization and requires pressurization only for auxiliary systems such as attitude control. The heat exchanger concept uses throttled vent fluid to cool any propellant flowing to the boost pumps.

Sufficient heat must be transferred in the subcooler to remove heating to the hot-side fluid from the warm boost

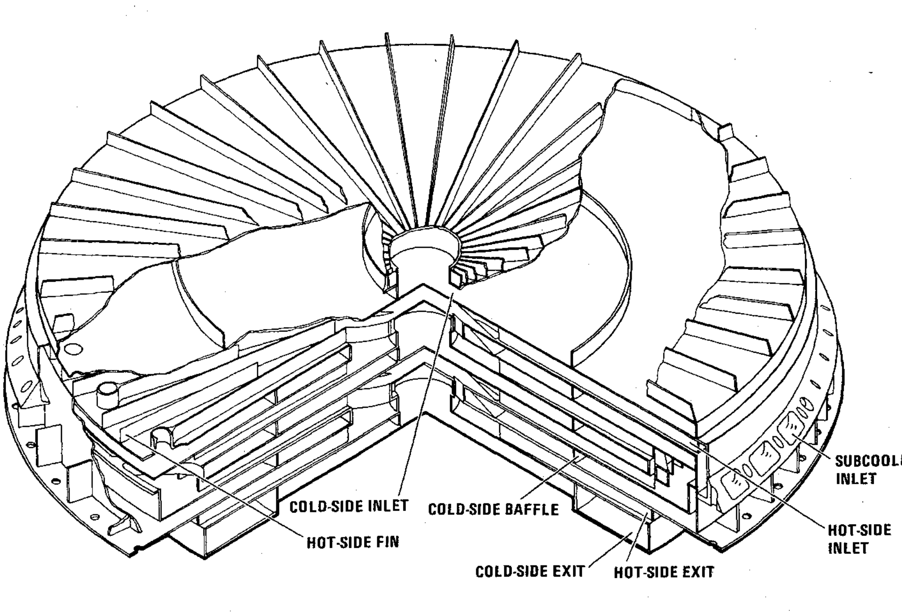

Fig. 3 LO_2 tank thermal subcooling.

pump and bearings, provide boost pump NPSH, and counteract any pressure drop caused by the thermal subcooler itself.

Screened channels of 235×2300 mesh provide liquid flow to the hot side of the exchanger. The cold side fluid is also extracted from the screened channels and is throttled to a lower pressure and temperature before entering the subcooler. Multi-pass, parallel-flow heat exchangers were used. Several configurations were examined for both the LO_2 and LH_2 subcoolers. The objective in designing the heat exchanger was to provide high heat exchanger effectiveness coupled with a low pressure drop. The subcooler designed for the LO_2 tank is shown in Fig. 3.

Start Basket Thermal Conditioning

The objectives of the start basket thermal conditioning were to prevent dryout of the start basket outer screens and to prevent vapor formation in the screened channels feeding the subcoolers. Screen dryout must be prevented because capillary devices for wetting fluids operate by keeping vapor out of the contained liquid space. If screens dry out, vapor can enter freely, allowing the wetting fluid to migrate from the screened enclosure. Vapor formation in the start basket will occur due to pressure changes, incident heating, or liquid removal. Screened channels within the start basket prevent vapor from entering the subcooler and capillary device thermal conditioning system. To obtain satisfactory subcooler and capillary device thermal conditioning, the channels must be kept full at all times. To prevent heat input to the channels from causing vaporization in the channels, the capillary device cooling system is designed to maintain the basket surfaces slightly below saturation temperature.

The primary approach to start basket thermal conditioning was to use throttled vent fluid in cooling coils attached to the outer screened surface. This concept was studied in detail with design drawings developed showing cooling subsystem hardware, and cooling coil attachment and routing. This system had a high vent fluid penalty and cooling coil weight penalty because of the high condensation heat loads. Condensation, by itself, will not cause screen drying. However, if cooling tubes are designed to intercept heat input that could cause screen drying (forced convection, free convection, or conduction from superheated vapor), then all the cooling capacity of the throttled vent fluid will be used up in a short length of tubing if condensation occurs. No cooling capacity will then be available for the remainder of the cooling loop, and incident heat transfer could cause screen drying. Thus, an active thermal conditioning subsystem must be designed for condensation heat transfer.

Table 5 Start basket volumetric requirements

Requirement	LH_2 (ft^3)	LO_2 (ft^3)
Start Sequence		
Sump & Pump Chill & Vent	1.64	0.02
Sump & Pump Fill	2.18	1.53
Boost Pump Startup	5.60	1.57
Engine Chilldown	11.11	0.83
Settling (Main Engine)	9.54	1.41
Thrust Barrel Filling (Main Engine)		1.28
	30.07	6.64
Thermal Conditioning		
Subcooling Flow	1.53	0.30
Conditioning Flow	13.6	1.29
Channel Volume	2.17	0.18
Residual Volume	0.97	0.12
Trapped Vapor (Bottom Compartment)	0.38	
Total	48.62	8.53

Several options were considered for reducing cooling system weight penalty. One option used a pumping system consisting of a surge tank and compressor to return the throttled cooling fluid to the main propellant tank. This approach can also be used to return subcooler coolant to the main propellant tanks. Passive cooling was briefly analyzed, using wicking fluid provided by wicking channels, parallel plates, or parellel screens. Cooling system alternatives were evaluated as separate options in comparing the baseline system with start baskets and start tanks.

System Design

Preliminary designs were made of both a start tank and start basket for both the LO_2 tank and the LH_2 tank.

The start baskets for both fluids are basically similar in that they have an outer screen cooled by liquid from screened

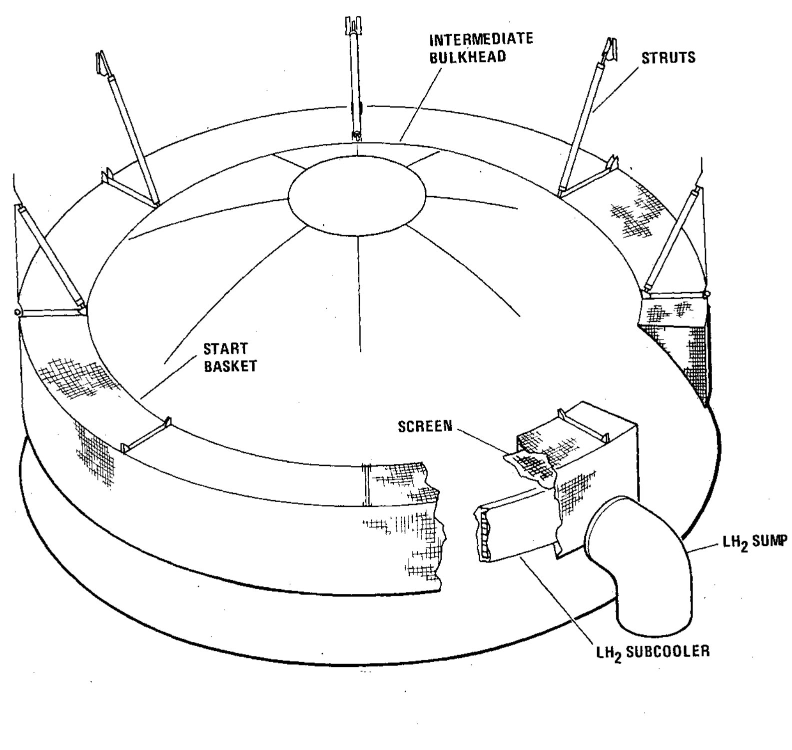

Fig. 4 LH_2 start basket and subcooler.

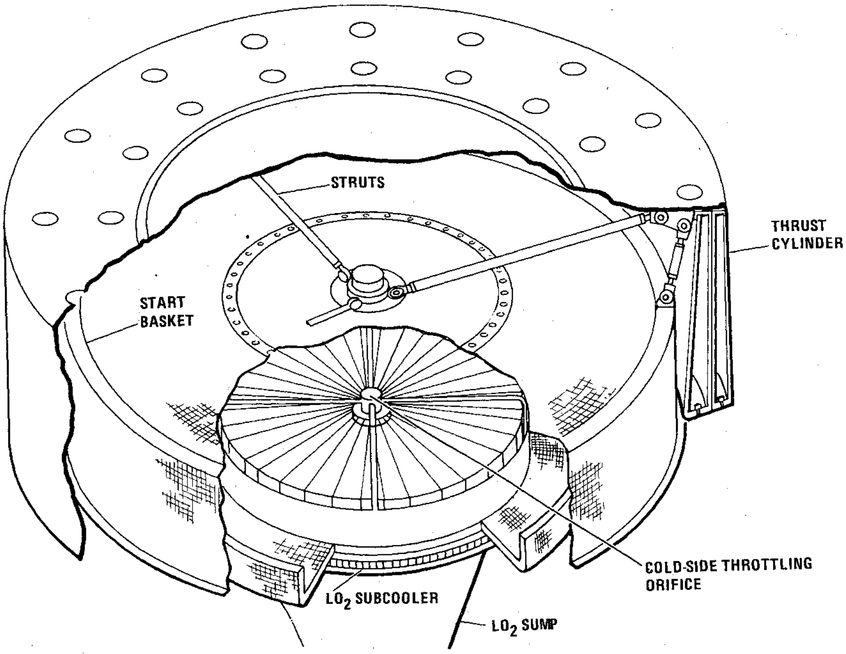

Fig. 5 LO_2 start basket and subcooler.

Table 6 Five-burn mission payload weight penalty (lbm)

Weight Penalty Element		Option 3	2	5	1	7	8	6a	4a	6	4
Capillary Device	LH_2	138.3	138.3	138.3	–	138.3	221.5	138.3	138.3	138.3	138.3
	LO_2	38.8	38.8	38.8	–	38.8	104.7	38.8	38.8	38.8	38.8
Cooling Coils	LH_2	–	–	131.6	–	131.6	–	131.6	131.6	131.6	131.6
	LO_2	–	–	18.8	–	18.8	–	18.8	18.8	18.8	18.8
Assorted Hardware		11	11	11	–	11	5	11	11	11	11
Subcooler Weight	LH_2	18.8	18.8	18.8	–	18.8	–	18.8	18.8	18.8	18.8
	LO_2	23.8	23.8	23.8	–	23.8	–	23.8	23.8	23.8	23.8
Dumped Fluid, Subcooler	LH_2	–	38	–	–	38	–	–	38	–	38
Payload Penalty	LO_2	–	119	–	–	119	–	–	119	–	119
Dumped Fluid Capillary	LH_2	–	–	–	–	–	–	263.4	263.4	415	415
Device Cooling	LO_2							154.9	154.9	394	394
Dumped Fluid Start Tank	LH_2	–	–	–	–	–	12.4	–	–	–	–
	LO_2	–	–	–	–	–	21.3	–	–	–	–
Vac System, Subcooler	LH_2	5.9	–	–	–	–	–	5.9	–	5.9	–
(Pumping Coolant Back to Tank) Includes Boiloff + Battery + Hardware	LO_2	11	–	–	–	–	–	11	–	11	–
Vac System, Capillary	LH_2	–	–	–	–	22.9	–	–	–	–	–
Device Cooling	LO_2	–	–	–	–	12.6	–	–	–	–	–
Vac System, Subcooler &	LH_2	–	–	23.8	–	–	–	–	–	–	–
Capillary Device	LO_2	–	–	15.6	–	–	–	–	–	–	–
Vol Penalty Due to Not Loading Fluid Because of Vol Displaced by Added Hardware		30.2	30.2	51.7	–	51.2	22.7	51.4	50.3	51.3	50.3
Residual Payload Penalty	LH_2	21.3	21.3	21.3	80	21.3	70	21.3	21.3	21.3	21.3
	LO_2	114.5	114.5	114.5	84.5	114.5	114.5	114.5	114.5	114.5	114.5
Δ Chilldown Penalty due to Start Sequence		1014.1	1014.1	1014.1	979.8	1014.1	1014.1	1014.1	1014.1	1014.1	1014.1
Thrust Barrel Revisions		11.2	11.2	11.2	–	11.2	11.2	11.2	11.2	11.2	11.2
Settling System Including Peroxide Payload Penalty		–	–	–	165.2	–	–	–	–	–	–
Pressurization System		64	64	64	431	64	378	64	64	64	64
Total Weight		1502.9	1643.0	1697.3	1740.5	1849.9	1993.4	2092.9	2231.8	2483.5	2622.5
Δ Weight Compared to Baseline		-237.6	-97.5	-43.2	0	+109.4	+252.9	+352.4	+491.3	+743.0	+882.0

Options:

1. Baseline D-1S
2. Start basket, passive cooling, subcooler flow dumped overboard.
3. Start basket, passive cooling, subcooler flow pumped back into the tank.
4. Start basket, active thermal conditioning & subcooler flow dumped overboard.

4a. Uses vent rate adjusted to suit "g" level.

5. Start basket, active thermal conditioning & subcooler flow pumped back into tank.
6. Start basket, active thermal conditioning dumped overboard, subcooler flow pumped back into tank.

6a. Uses vent rate adjusted to suit "g" level.

7. Start basket, active thermal conditioning pumped back into the tank, subcooler flow dumped overboard.
8. Start tank bypass feed.

capillary channels inside the start basket. Also, each has an internal subcooler fed from the same capillary channels.

The start tanks are not cooled, but are insulated to prevent excessive heat input and pressure rise. Pleated screen channels at the tank outlet prevent vapor outflow and reduce residuals.

In the start basket configurations, all fluid for the engines passes through the basket and subcooler through engine operation; in the start tank, bypass valves are necessary so that only the initial starting fluid is provided by the start tank.

Capillary Device Volumetric Requirements

Start basket volumetric requirements were determined using the most stringent combination of start sequence usage, trapped vapor, outflow, thermal conditioning, and thermal subcooling requirements. Results are shown in Table 5. Isometric sketches of the LO_2 and LH_2 start baskets and thermal subcoolers are shown in Figs. 4 and 5.

Start tank volumetric requirements were determined based upon the sum of start sequence requirements, main tank settling, screen channel volume, liquid volume required to prevent vapor ingestion, and ullage volume requirements based upon anticipated pressure rise rates. Nonvented start tanks were used to simplify thermal conditioning requirements. Start tank volumes were found to be 8.45 ft^2 for LO_2, and 36.84 ft^3 for LH_2.

System Comparison

Comparisons were made between the capillary acquisition systems designed and the baseline hydrogen peroxide settling and warm helium pressurization systems. In addition to the actively cooled start baskets, passively cooled start baskets using capillary pumping to replace the cooling coils were considered. The options compared were the following.

1) Baseline—pressurization subsystem plus settling system; 2) Start baskets using passive capillary device cooling (wicking) and subcoolers for providing boost pump NPSH with subcooler coolant flow dumped overboard; 3) Start baskets using passive cooling and subcoolers for NPSH with subcooler coolant flow pumped back into the tank; 4) Start baskets using cooling coils for capillary device cooling and subcoolers for NPSH with all coolant flow dumped overboard; 5) Start baskets using coils for capillary device cooling and subcoolers for NPSH with all coolant flow pumped back into the tank; 6) Start baskets using cooling coils for capillary device cooling and subcoolers for NPSH with cooling coil flow dumped overboard and subcooler flow pumped back into the tank; 7) Start baskets using cooling coils for capillary device cooling and subcoolers for NPSH with cooling coil flow pumped back into the tank and subcooler flow dumped overboard; and 8) Bypass feed start tanks with cold helium pressurization. Comparisons were made on the basis of relative reliability, hardware weight, payload penalty, recurring costs, power requirements, and flight profile flexibility for the eight options for each of the three reference missions. Table 6 illustrates a typical comparison. Options are shown in order of increasing weight.

Conclusions

Comparisons indicated that capillary acquisition devices offer greater potential flight profile flexibility than the baseline settling subsystem. The passively cooled start baskets (Options 2 and 3) were lighter than the baseline system (Option 1) in terms of hardware weight and equivalent payload weight for the five-burn mission. The weight advantage will increase for missions with more than five burns.

Capillary device reliability is slightly less than that of the baseline settling system. Start baskets not using the pumped coolant subsystem are estimated to have lower recurring cost than the baseline settling system. The potential flight profile flexibility, weight and cost advantages of Option 2 (passively cooled start basket with subcooler coolant dumped overboard) make this configuration worthy of additional consideration.

Option 3 offers greatest potential payload weight advantage. This option consists of passively cooled start baskets using vacuum pumping subsystems to return subcooler coolant to the tank. A major advantage of this configuration is its insensitivity to the number of burns required. This is because the subcooler operates over the entire mission burn time regardless of the number of burns. These advantages are somewhat offset by reduced reliability, increased cost, and increased power requirements compared to Option 2.

Both passively cooled start basket configurations (Options 2 and 3) have advantages over the baseline Centaur D-1S hydrogen peroxide settling system, which may be of potential benefit for advanced multiburn mission requirements. A development plan[2] was prepared for evolving from current passively cooled start basket technology to the point where a noninterference flight test could be performed on a future Centaur vehicle.

References

[1]Bock, E.H., "Centaur/Shuttle Integration Study," General Dynamics, San Diego, Calif., Convair Report GDCA-BNZ 73-006-8, NAS 3-16786, NASA-CR-134488, Dec. 1973.

[2]Blatt, M.H. and Walter, M.D., "Centaur Propellant Acquisition System," General Dynamics, San Diego, Calif., Convair Report CASD-NAS-75-023, NAS 3-17802, NASA-CR-134811, June 1975.