Space Shower Habitability Technology

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A zero gravity, whole body shower concept has been developed under contract NASI-9819 that provides crewmen with bathing facilities similar to those used on Earth. The concept integrates the habitability parameters of performance, comfort and crew considerations into the shower design. Experimental test results are presented for both one-gravity and zero-gravity conditions concerning these parameters and their effectiveness in providing a shower to cleanse man's hair and body and in affording him a psychological lift. Zero-gravity testing was accomplished in a KC-135 aircraft flying a series of parabolic curves attaining a weightless environment for approximately 20 sec. The manned testing demonstrated that a whole body shower is feasible in a zero-gravity environment and that the amount of water required averages only ½ gallon. In addition, it was determined that water removal from the stall area can be accomplished with an air velocity of 40 fps. However, due to the accompanying high electrical power consumption, the water collection technique by air flow must be accomplished by a specialized technique.

Introduction

MANNED space flights in the future will be characterized by their long duration and broad range of passenger talent and training. Provisions for personal hygiene during these long durations must include the cleansing of the whole body and hair to satisfy the physiological, psychological and social needs of the crew members. These provisions must be compatible with the spacecraft systems as well as the crewmen.

The absence of gravity on manned extended space missions causes the mechanism of whole body bathing to be different from that experienced on Earth. Surface tension becomes the dominant natural force which allows the wash water to collect on the shower's internal surfaces as well as on the skin. Shower stalls and associated hardware must be designed to effectively collect the water. An external force is required to remove this water and transport it to a collection site where the water can be stored for subsequent processing. In addition, performance parameters, comfort parameters, and crew considerations must be provided to maintain a habitable environment in which the crewman can safely perform the bathing function.

Shower Concept Development

The investigators developed shower concepts to provide the crewmen with bathing facilities similar to those used on Earth. The baseline mission requirements given in Table 1 were used to formulate these concepts. Examination of one-gravity cleansing techniques and shower protocol indicated that there were three items that are basic for cleansing the body of foreign matter, dead skin, and body secretions[1]: 1) a mechanical action which helps to dislodge and break down the foreign matter and dead skin; 2) a chemical agent which breaks down and emulsifies the oils; 3) a solvent to pick up and carry off the accumulated materials. This is accomplished by using the hands or a wash cloth for a massaging and lathering action, soap for an emulsifier, and water as the solvent. In zero-gravity conditions, management of the solvent becomes the major concern.

Performance Parameters

Water Distribution Techniques

The two basic criteria that establish the amount of water used or wasted and the effectiveness of the shower itself are nozzle type and nozzle location. These criteria determine the manner in which water is distributed onto the subject during the wetting and rinsing operations. The hollow cone spray concentrates most of the liquid at the outer edge of a conical pattern while the solid, or full-cone, spray distributes

Table 1 Contract baseline mission requirements

Mission Model	
Mission Duration	2 yrs
Resupply Capability	None
Gravity Mode	Zero—One *g*
Mission Objective	Extended
Crew Model	
Number of Crew	6–12
Height of Man	6 ft
Weight of Man	160–190 lb
Atmosphere Model	
Cabin Total Pressure	7.0 to 14.7 psia
Carbon Dioxide Partial Pressure	0.5 to 0.7 percent of cabin total
Relative Humidity	55–15%
Temperature	65 to 75°F adjustable
Shower Requirements	
Shower cycle every 2 hrs	
Wash hair and full body	
Removal of humidity from air (to atmosphere model)	
Provide comfortable air temperature and flow	

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Table 2 Nozzle flow rates

Over-all personal preference rating	Nozzle Delavan—D Bete —B	Nozzle Flow Rates GPM Pressure, psig 10	20	30	40	50	60
1	B-W5080F (solid cone)	0.25	0.35	0.43	0.50	0.56	0.61
3	D-LDA 80 (hollow cone)	...	0.53	0.66	0.76	0.84	0.92
—	D-LDA 100 (hollow cone)	...	0.67	0.83	0.94	1.06	1.16
—	D-FS 9 (flat spray)	0.26	0.33	0.38	0.47	0.54	0.66
2	D-WS 6 (hollow cone)	0.30	0.42	0.52	0.60	...	0.74
—	D-WS 10 (hollow cone)	0.50	0.71	0.87	1.00	...	1.20
3	D-WSS 6 (solid cone)	0.30	0.42	0.52	0.60	...	0.74
3	D-WSS 10 (solid cone)	0.50	0.71	0.87	1.00	...	1.20
—	D-FS 107 (flat spray)	0.43	0.53	0.60	0.74	0.85	1.08

the droplets nearly uniformly across the conical pattern. The flat spray nozzle produces a narrow elliptical spray pattern with a reasonably uniform droplet distribution across the pattern.

Spray angles and nozzle pressures were investigated in order to provide coverage of various body areas such as the arms without overspray and resultant use of excessive water. Table 2 is a summary of various nozzles tested and personal preference ratings. The Bete nozzle (B-W5080F) with a 25° cone angle was determined as optimum. The minimum pressure necessary for a well-developed spray cone was determined to be 10–15 psi. Beyond this value, pressure has a relatively minor effect on the spray angle. Since increased pressure causes increased flow, 20 psi pressure was selected for water conservation.

Nozzle location was evaluated by comparing its capability to wet and rinse the skin with the amount of water used. Figure 1 shows the three general nozzle locations investigated. One nozzle concept uses a nozzle fixed at one point within the shower enclosure. This localized spray requires the body to be continuously repositioned, making the wetting and rinsing of the skin and its folds difficult. Thus, excessive water is required. The manifold, or a series of fixed nozzles, provides a general spray that easily wets the skin. However, it is difficult to rinse the body folds; an excessive amount of water is used.

The hand held, movable nozzle incorporates an on-off thumb controlled water valve attached to a flexible hose. This permits a localized spray for controlled wetting of the skin with water provided on demand. Also, this permits rinsing of the body folds from any direction desired. This concept was selected as it incorporates the optimum features of wetting and rinsing with a controlled water usage.

Water Collection Techniques

Two techniques for removal of the shower waste water from the shower enclosure were investigated. The air flow method involves three variations, air drag, vacuum pickup, and evaporation. Analytical calculations for a free volume zero-gravity environment and one-gravity tests were performed to obtain the minimum air velocities required to move water effectively. The calculations indicated that 1 fps was the minimum velocity required to move water droplets effectively. One-gravity tests indicated that 33.3 fps was the minimum velocity required to move water (a solution of distilled water and cleansing agent) along an acrylic surface.

Mechanical techniques of water collection use the capillary action of towels and/or sponges to collect water which has accumulated on surfaces. The mode of water collection selected for use with the zero-gravity shower must be compatible with the mission model, that is a two-year mission with no resupply. This mission model indicates that the water used in the shower must be reclaimed. Reclamation of shower water collected in a towel or sponge would involve the use of additional water recovery equipment. The need for providing support equipment, plus the complication of cleaning the sponge and the equipment, were considered sufficient cause to eliminate mechanical collection devices from consideration.

Shower Stall Configurations

Several shower stall configurations were considered for this personal hygiene program. They were various combinations of round, square, and triangular shapes. Collapsible and disposable enclosures were also considered but were rejected due to the volume, weight, and design complexity required to meet the mission model requirements. A square cross section was discarded because of the large floor space required, and inefficient utilization of volume. In general, a triangular configuration required the smallest volume, but did not provide the desired freedom of movement for showering. The configurations (as shown in Fig. 2) selected for further study

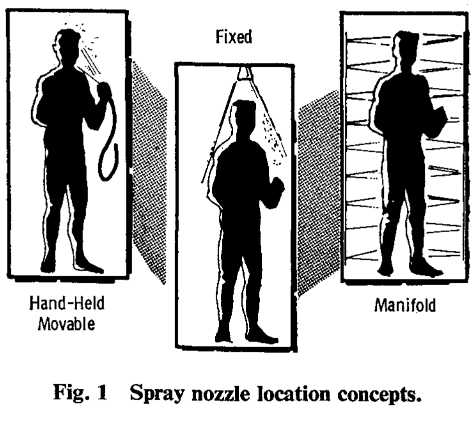

Fig. 1 Spray nozzle location concepts.

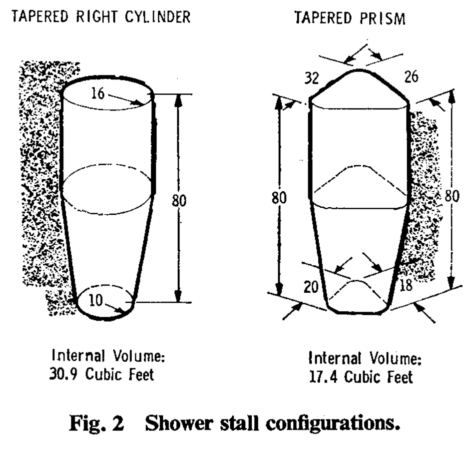

Fig. 2 Shower stall configurations.

are based upon the anthropometric measurements[2] for the 0.95th percentile man. In addition, the following considerations influenced these shower stall selections: 1) provide sufficient room or space within stall for a crewman to shower with relative freedom of movements; 2) provide for any features which are necessary to supplement or be compatible with the method(s) of water collection to be used during shower operation; 3) require a minimum floor space and volume, consistent with other considerations; 4) provide for maximum ease of cleaning the stall after showering is complete; and 5) satisfy the limiting dimensions of the KC-135 aircraft (used for zero-gravity tests).

Furthermore, serious thought was given to shower stall compatibility with the water collection methods. Since the air drag technique was considered a feasible one for the removal of water from the shower enclosures, the shower stalls ought to be designed with the minimum practicable cross-sectional area in order to obtain maximum air velocity. In Fig. 3 are the calculated air flows-vs-air velocities for the selected shower configurations. The data indicate that unreasonably high air flows would be required in order to obtain velocities high enough (33 fps) to move water along the upper surfaces of either configuration. However, with the circulation of approximately 700 cfm, sufficient velocity can be reached at the bottom of the tapered triangular configuration to move water by air drag. The data also show that free volume air velocities are greater than 1 fps in both shower stalls for air flows greater than 200 cfm.

Restraint Devices

Restraint is required in a zero-gravity environment to permit the crewman to control his movements adequately so that he can enter the stall, position his body, wash all areas of his body, and assist in leaving the stall. These restraints must be easily accessible and neither interfere with the water collection techniques nor with the showering and cleaning operations.

Simple U-shaped handholds were selected to permit the crewman to enter and leave the shower stall. Two such handholds were attached to opposite sides of the upper portion of the stall. This also aided in repositioning and centering the body within the enclosure.

Once inside the stall, unrestrained movements of the hands and arms were required to wash all areas of the body. This was accomplished with the use of two inverted U-shaped foot straps fastened to the floor of the stall. These foot restraints consisted of flexible straps that allowed the test subject to easily slip his feet in and out of the restraints. They provided a convenient means to restrict the up-down motion. In addition, the test subject could restrain and balance himself with one foot while washing the other foot. This permits continuous showering operations without any interruptions for adjustments or for fastening harnesses.

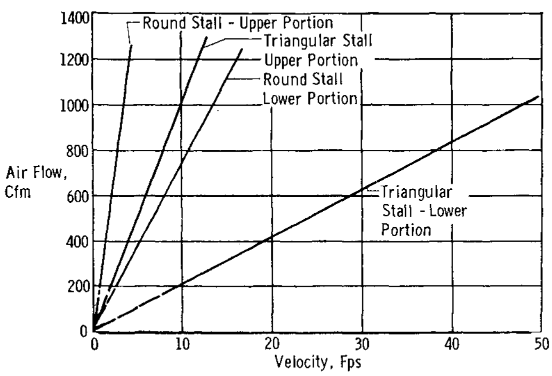

Fig. 3 Velocity vs air flow through selected shower stalls.

Comfort Parameters

Water Temperature

Water temperature is a consideration when determining crew comfort while bathing the body. As was done in the case of nozzle preference, subjective tests were performed to obtain a range of water temperatures suitable for crew comfort in one gravity. (A summary of the results from approximately fifty shower tests are shown in Fig. 4.) It is interesting to note that water temperatures below the average skin temperature of 93°F were considered uncomfortable cool. Above 118°F, temperatures were considered uncomfortable hot; at 125°, the subjects could not spray the water constantly on the skin. The lower comfort temperature was 99°F, the upper threshold of comfort was 110°F. The longer the subject remained in the shower, the more he could tolerate, according to his comments, this upper limit. The most desirable temperature, according to all subjects, was 105°F.

Water and Cleanser Quantity

In a zero-gravity environment the property of surface tension permits the water to adhere to the surface of the skin. It was reasoned that this property would allow more efficient utilization of water and cleanser during the soaping and scrubbing phases, but that slightly more water may be used during the rinsing phase. It was concluded that the amount of water required for showering in one gravity would be about the same as required in zero gravity. Showering operations were conducted in one gravity to determine required water quantities, which would be verified for zero gravity during later testing in a KC-135 aircraft.

Approximately 50 showers employing six separate test subjects were conducted. Distilled water, simulating actual spacecraft conditions, and a liquid cleanser were used. The test subjects were instructed to wash their entire bodies and hair using the hand-held movable spray nozzle discussed earlier. In addition, each subject was instructed to use what they considered to be a normal amount of water and cleanser for the wetting and rinsing operations. The results of the tests were very surprising, even to the test subjects. The quantity of water used ranged from 3.0–6.2 lb per shower with the average amounting to 4.8 lb or 0.58 gal of water per shower. The average amount of cleansing agent used was 13g, the maximum being 18g per shower. The average time for a complete shower was nine minutes.

The test data indicate that the most important factors affecting water usage is the test subject's individual preference, and the cleanser's sudsing ability. Although the flow rate for any nozzle increases with higher pressure, the test data did not

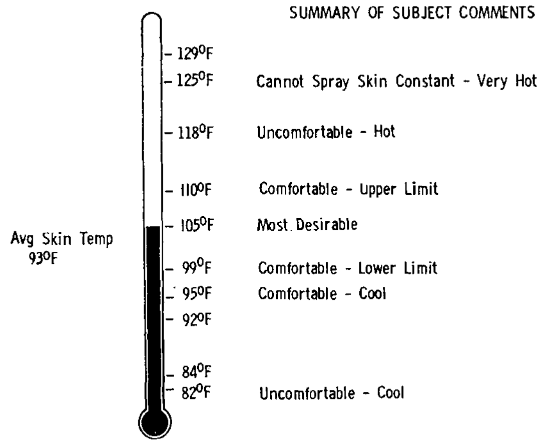

Fig. 4 Water temperature summary.

Table 3 Air temperature limits

Skin condition	Air velocity, fps	comfortable dry bulb temperature limits, °F		
		30% RH	30–70% RH	70% RH
Dry	0.5–1	80–90	75–85	70–80
	2–4	90–100	85–95	75–85
Wet	0.5–1	115–130	100–110	95–105
	2–4	125–135	105–115	100–110

substantiate a higher total water usage with higher water pressures. Also, the amount of water used was not necessarily higher for showering operations of longer duration.

Air Temperature and Humidity

Air temperature and humidity levels were investigated to determine the range of comfort for the test subjects while showering. The results from this investigation are given in Table 3.

The principal items which affected human comfort, while a test subject was showering, were the dry bulb temperature, relative humidity, the air flow velocity, and the wetness or dryness of the crewman. They were varied. Subjective comments were obtained from the test subjects while showering. Trends seen from the data agreed, in general with numerous other tests concerning human comfort, that have been conducted by other organizations. These trends indicated the following: 1) for the same air velocities, dry bulb temperatures necessary for comfort levels were lower for high humidity levels than for low humidity levels; 2) for increasing air velocities, dry bulb temperatures necessary for comfort levels were higher with the width of the comfort band becoming smaller; and 3) dry bulb temperatures for human comfort are higher when the subject is wet than when he is dry. The data substantiates the need for the incorporation of a variable air temperature control within the shower stall to satisfy comfort needs.

Crew Considerations

Cleanser Selection

The cleansing agent used in the zero-gravity shower must not only sufficiently aid in cleansing the body and controlling bacteria on the skin, but must also be compatible with water retrieval techniques and units used to reclaim the shower waste water.

Presently there are emulsifiers available that have varying chemical compositions. These different agents act as biodegradable soaps that do not halt bacterial growth and can be broken down by bacteria, biostatic soaps which control the growth of bacteria, and as biosidal soaps which actually deactivate the bacteria. (A shower is generally described as refreshing and revitalizing. To enhance this feeling, the cleansing agent should not only help control bacterial growth but also give a feeling of cleanliness after each shower.) Ordinary bar soaps were not considered because of their high sudsing and their toxic effects on the eyes. Ideal cleansing agent should not be toxic on the body, should not dry out the skin, should not sting or irritate the eyes, and should not cause internal toxicity.

Literature and samples of various cleansers were acquired. Initial investigation eliminated several cleansers from further consideration because of failure to meet the above criteria. Those cleansers that survived initial investigation were used by various subjects in showers to evaluate (see Table 4) the following considerations: ease of body coverage; resultant feeling of cleanliness; toxic effects on the body; suitability for washing hair; ease of rinsing; and sudsing effect (small suds desirable). In addition to these investigations, tests with coupon swabs were performed to evaluate their effectiveness in bacteria removal and prevention of bacteria growth. After the comparison between various characteristics of the currently available cleansing agents, pHisoHex and Miranol® were determined to be the two skin cleansers desirable for use in the zero-gravity whole body shower.

Carbon Dioxide (CO_2) Buildup

The increase of CO_2 in the small shower stall (17.4 ft^3) was determined while the test subject was simulating showering movements. Measurements were taken in the sealed enclosure until the CO_2 level reached the maximum specified value of 0.75% of the total pressure. This test was performed at an atmospheric pressure of 11.94 psia. The CO_2 levels shown in Fig. 5 have been corrected for 7.0 psia, which is the minimum atmospheric pressure specified in the Mission Model (Table 1). At this pressure the limiting CO_2 level of 0.75% of the total pressure will be reached in 4.5 min. Results indicate that cabin air makeup is required to maintain the specified CO_2 level in the shower enclosure during the nine-minute shower operation.

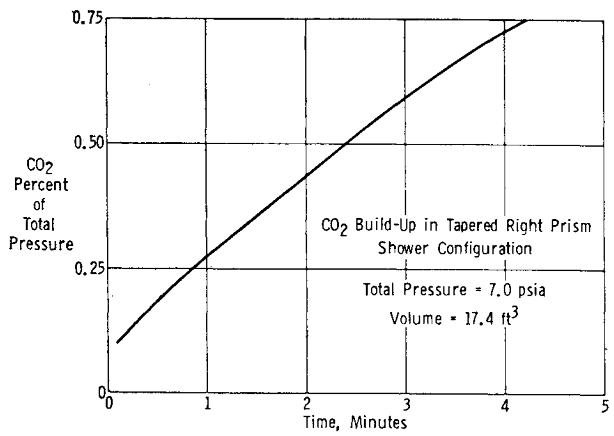

Fig. 5 Carbon dioxide buildup for atmospheric pressure of 7.0 psia.

Table 4 Comparison of candidate skin cleaners

	Chemical composition	Bacteria growth characteristics	Toxicity to skin & eyes	Sudsing activity	Alcohol content
Basic H	Organic biodegradable elements	Biodegradable	Nontoxic	Low	No
Zephiran chloride	Alkyldimethybenzylammonium chlorides	Limited bactericidal	Toxic to eyes	Low	Yes
Triton DF-12	Polyethoxylated straight chain alcohol	Biodegradable	Toxic to eyes	Low	Yes
Miranol	Surfactant	Very mild bactericidal	Nontoxic	High	No
pHisoHex	Entsufan & 3% hexachlorophene	Biostatic	Nontoxic	Low	No

Bacterial Removal

Samples of bacteria were taken to determine what types were added to the shower waste water, what types were found on various parts of the body, and to examine the ability of showering to remove bacteria from the body. Samples of bacteria were taken of influent and effluent shower water and from the left axilla, the groin, and between the toes, both before and after showering. A definite ten-fold reduction of bacteria in the groin and toe region of the test subject occurred when the subject washed, using pHisoHex as a cleansing agent. A definite seven- to ten-fold reduction of bacteria occurred in the groin and toe when the subject used -Miranol as the cleansing agent.

A comparison was made between the types and quantities of bacteria removed from the body areas by showering, with the types and quantities of bacteria added to the shower effluent. This comparison led to the conclusion that a good portion of bacteria was removed from the body during the toweling off (drying) process where the scaly skin was removed, taking some of the bacteria with it. Typical bacteria types found in these tests were E. Coli, staphylococcus, bacillus, and streptococcus.

A definite correlation exists between the way a person showers and the quantity of bacteria removed. The difference in the amount of total bacteria removed in the showering process is demonstrated between the different subjects and the different methods of bathing by the same subject in replicate showers. The more scrubbing and friction created by the soap or water in washing to break down the surface tension, the greater the total number of bacteria recovered (or removed) from the subject. Soap and warm water are definitely required for a person to feel completely clean and comfortable after showering. Greater bacteria removal justifies making soap a requirement in showering.

Verification of Parameters

System Hardware Description

After the analytical work and some preliminary testing was concluded, a prototype shower system was constructed in order to evaluate the various shower concepts in both one-gravity and zero-gravity environments. This system is shown schematically in Fig. 6. The system offered an ability for collecting water by the air drag method, the vacuum collection technique, and the evaporation technique. The air flow system consisted of the blower, ducting, dampers, heaters and controls. It allowed for variation of the air flow rate from 200 cfm to 1100 cfm. The dampers also allowed the system to dump all air and receive fresh air (open loop), to dump a percentage of the air (bleed loop), and to completely recirculate the air (closed loop). A large vortex liquid-gas separator was located in the main air duct system and was used with the air drag and evaporation methods of water removal from the shower stall. A smaller separator was fabricated and used with the separate vacuum water collection system. The vortex concept was developed in one gravity, using scale models in various orientations relative to gravity.

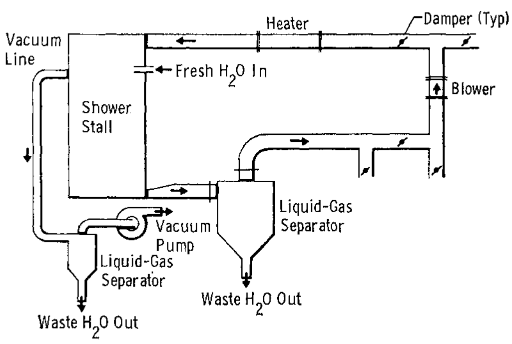

Fig. 6 Test hardware schematic.

The water module consisted of a nine-gallon, fresh water bladder tank, a nine-gallon, waste water bladder tank, and a 2200 psig gaseous nitrogen pressurant bottle. The water was pumped from the vortex liquid-gas separator sump to the waste water tank. Fresh water was pressurized to the shower stall nozzle. A separate electrical control module contained the necessary circuit breakers and electrical controls for the water pump, water heater, air blower, air heaters, and vacuum pump.

One-Gravity Verification of Parameters

Additional one-gravity tests were conducted to verify and finalize such shower parameters as the quantity of water used per shower; the most desirable water temperature; the water pressure required in the spray nozzle to rinse the cleansing agent off the body effectively; and the amount of cleansing agent required. All the tests were conducted in a closed-loop air drag configuration with a 10 cfm bleed. The stall was allowed to dry out between each shower. Each test subject took his shower in the nude so that quantities of water and cleanser could be determined as accurately as possible. A summary of the test results is as follows: 1) average quantity of water used—2210 ml or 0.58 g. (does not include water for cleanup of shower); 2) average pHisoHex cleansing agent used—13 g; 3) average time for shower and removal of residue water—9 min; 4) ideal showering air temperature—110°F; and 5) confirmed ideal water temperature of 105°F (±5°).

Zero-Gravity Verification of Parameters

Zero-gravity testing was accomplished aboard the KC-135 aircraft. Both the round and triangular shower stalls were tested with the air drag and vaccuum water collection techniques. The following is a summary of the related parameters;

1. Stall configuration

The test subject preferred the larger cross-sectional area provided in the round shower, thus allowing for necessary movements without interference from the shower walls. The space provided by the triangular shower, while not desirable, was adequate.

2. Nozzle usage and location

The hand held movable nozzle gave excellent body coverage for wetting and soaping operations and a spray that resulted in a high efficiency of water usage. During rinsing operations the test subject found it necessary to aid the nozzle pressure effect by wiping or brushing water from the body.

3. Hair washing

A complete head wash was conducted by the test subject in the triangular shower, with four parabolic maneuvers required to complete the operation (two for wetting and soaping and two for rinsing). Scrubbing of the head was actually easier in zero gravity than in one gravity; there was no tendency for the soapy water to run down into the eyes. Rinsing of the hair was readily accomplished by directing the water spray on the scalp and rubbing with the hand.

4. Water behavior

As a result of the zero-gravity testing, new information on water behavior was obtained. Verified was that surface tension of the water is the predominant force permitting water to adhere to the skin. However, comments from the test subject and observation of film recorded during showering activities indicate that it is no more difficult to shower in zero gravity than in a one-gravity environment. Hair washings are easily accomplished. Water and soap are easily brushed from the hair, skin, and body folds with the hands. Water does not hamper the subject's breathing system; a snorkle is not required.

5. Restraints

Slip-in foot restrainers, provided in the shower, functioned satisfactorily and were a help to the test subject in conducting showering operations. Hand-hold restrainers located on the vertical shower walls, would have been more effective if they had been mounted from the ceiling of the shower thus giving better support during parabolic maneuvers.

6. Cleansing agent

Liquid pHisoHex was the cleansing agent determined from one-gravity tests to be the best for body cleansing and shower operation. Cleanser was applied from a flexible plastic "squeeze" bottle directly to the hand for soaping the body. Application of the cleanser presented no particular problems, except that a method of restraining the container while not in use was needed. Addition of the cleanser appeared to have no effect on the water behavior within the shower other than to give better wetting of the skin and shower walls.

Conclusions

Major obstacles which had to be overcome to wash man successfully and comfortably in zero gravity were: to understand and control water behavior in zero gravity, and to provide a habitable environment within the shower enclosure. A summary of shower parameters is presented in Table 5, the major conclusions resulting from prototype shower testing are:

1) A whole-body shower in a zero-gravity environment is feasible. Although some additional development is necessary to finalize optimum detail hardware configuration, there are no major technology problems preventing the provision for a whole-body shower in a space environment. Zero-gravity testing has demonstrated techniques of accomplishing all facets of a showering operation and water distribution on body surfaces, cleanser application and body scrubbing, body rinse, and of removal and recovery of waste water into a storage container.

2) Water removal from the body and shower solely by means of high velocity air (air drag) is not practicable, owing to the high air flow required and the accompanying high electrical power consumption. However, use of the hands for wiping water from the body and a specially designed "squeegee" for wiping water from the shower walls are satisfactory methods of orienting waste water for pickup and removal by a high velocity air stream.

3) The optimum shower stall configuration is a right cylinder in the upper portion, tapered to a smaller diameter at the bottom. Inside walls should be as free from obstructions, joints, and intersecting walls as possible, to facilitate moving water along the walls to the outlet duct.

4) The amount of water required for a complete shower is small, averaging about $\frac{1}{2}$ gallon excluding shower stall cleanup. Because of the use of a hand controlled nozzle, the tendency of water to cling to the body, and the nozzle design and operating parameters the water quantity is small. The optimum water temperature is in a 10° range centering around 105°F.

5) A liquid-gas separator was developed for use with the operating parameters of the shower. The vortex separation concept was used and found to work efficiently with high reliability in zero gravity.

A final concept for a zero-gravity shower system module is shown in Fig. 7. This concept incorporates controls for the crewman's comfort and employs minimum amounts of water and power.

Table 5 Summary of shower parameters

	Water
quantity:	0.5 gallon
temperature:	99–110°F
nozzle:	25° solid cone
location:	hand-held movable
	Cleansing Agent
quantity:	15 gr max.
type:	biostatic-low sudsing
form:	liquid
	Air
free volume velocity:	1 fps
outlet velocity:	33 fps
temperature:	90–110°F
humidity:	approx. 70% RH
CO_2 control:	10 cfm Bleed
	Miscellaneous
showering time:	9 min
towelling time:	2 min
stall:	tapered round, 31 ft^3 max.
restraints:	feet & multiple hand holds
power:	350 w peak
lgs:	vortex type

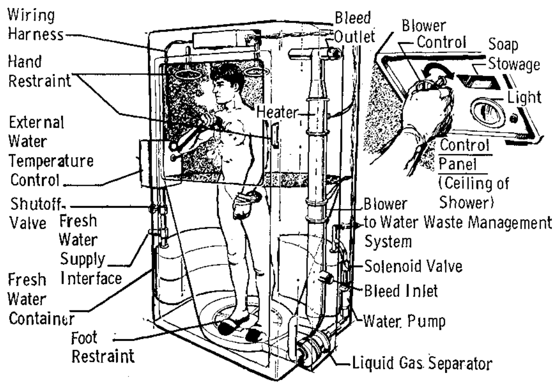

Fig. 7 Zero-gravity shower module air drag concept.

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[2] Webb, P., *Bioastronautics Data Book*, NASA, Scientific and Technical Information Division, Washington, D.C., 1964.