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DEVELOPMENT OF A BLADDERLESS TANK FOR SPACE SHUTTLE

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INTRODUCTION

Requirements for water management for the Space Shuttle are largely undefined, and only the basic metabolic requirement--3 lb/man-day--can be assumed. Water to meet this and other requirements may either be stored or be available from the fuel cells if these are selected as the electrical power supply. Even in the latter case, some water storage will be required for transition periods, as a backup in case of temporary fuel cell failure, and for marginal cooling.

The degree of purity and potability of stored water can vary according to its use. It seems likely that all drinking water must be sterile in accordance with NASA/MSC Specification SD-200. The water quality required for other uses, such as body washing and toilet flushing, are undefined.

In any case, the bacterial content of stored water must be controlled. The ease of bacterial control depends in part upon the characteristics of the tank in which the water is stored. If the tank can be rendered sterile before use, the stored water can be kept sterile much more easily. Then the tank itself must contribute to--or at least not detract from--the effectiveness of bactericidal measures employed to maintain water quality during Space Shuttle operation. In addition, the tank should be amenable to accurate measurement of water quality.

The potable-water technology used in the Lunar Module was first reviewed in the light of these requirements. The LM bladder-type tanks were adequate for that vehicle, but it seemed to us that bellows tanks offer greater possibilities in satisfying the long-term requirements of the Space Shuttle program. This paper summarizes the results of our studies and the present state of development of bellows-type tanks for long-term potable water storage.

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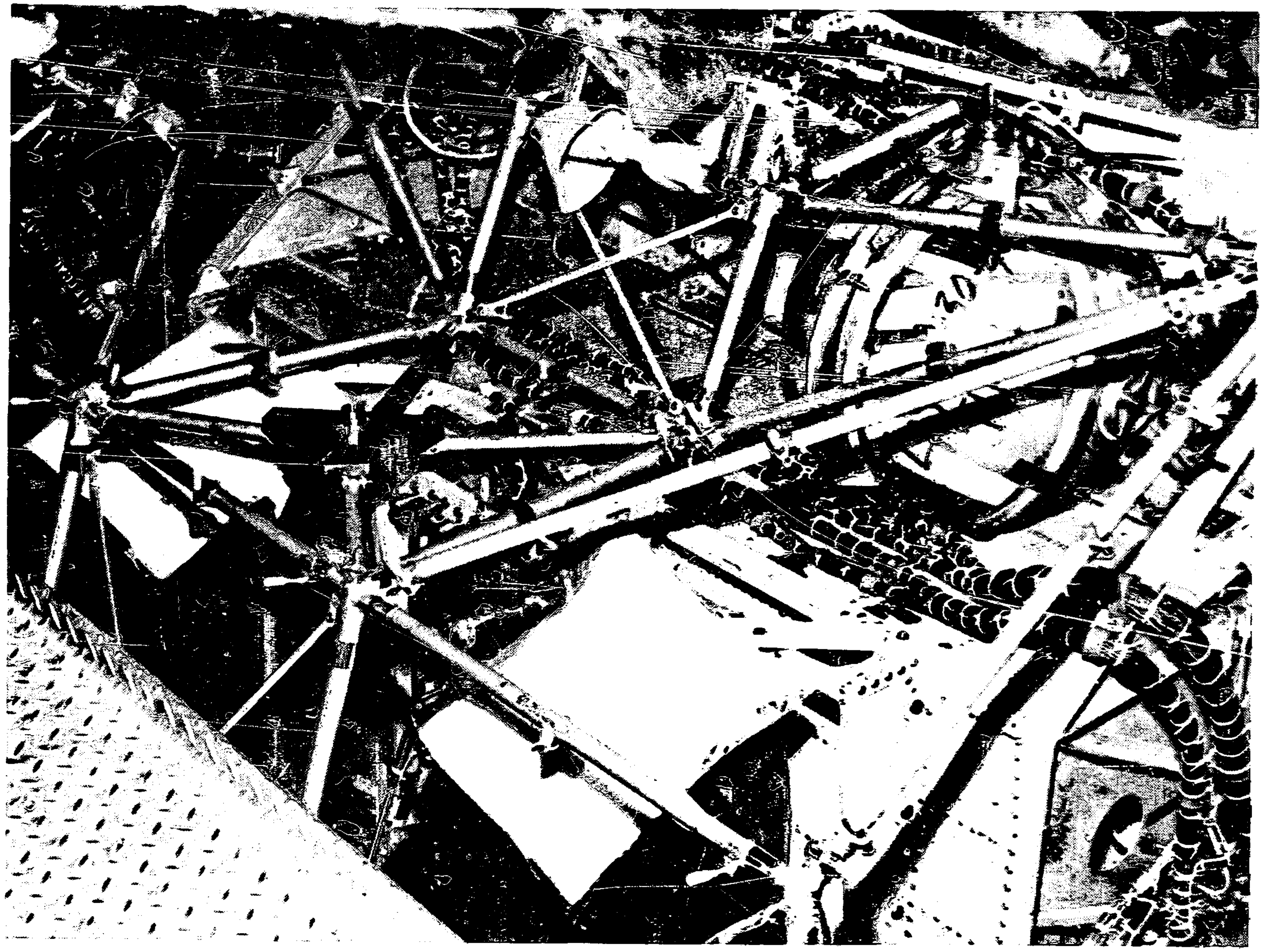
LM ASCENT STAGE BLADDER TANK

The two tanks containing the water used for drinking, food reconstitution and cooling are outside the pressure hull on opposite sides of the docking adaptor.

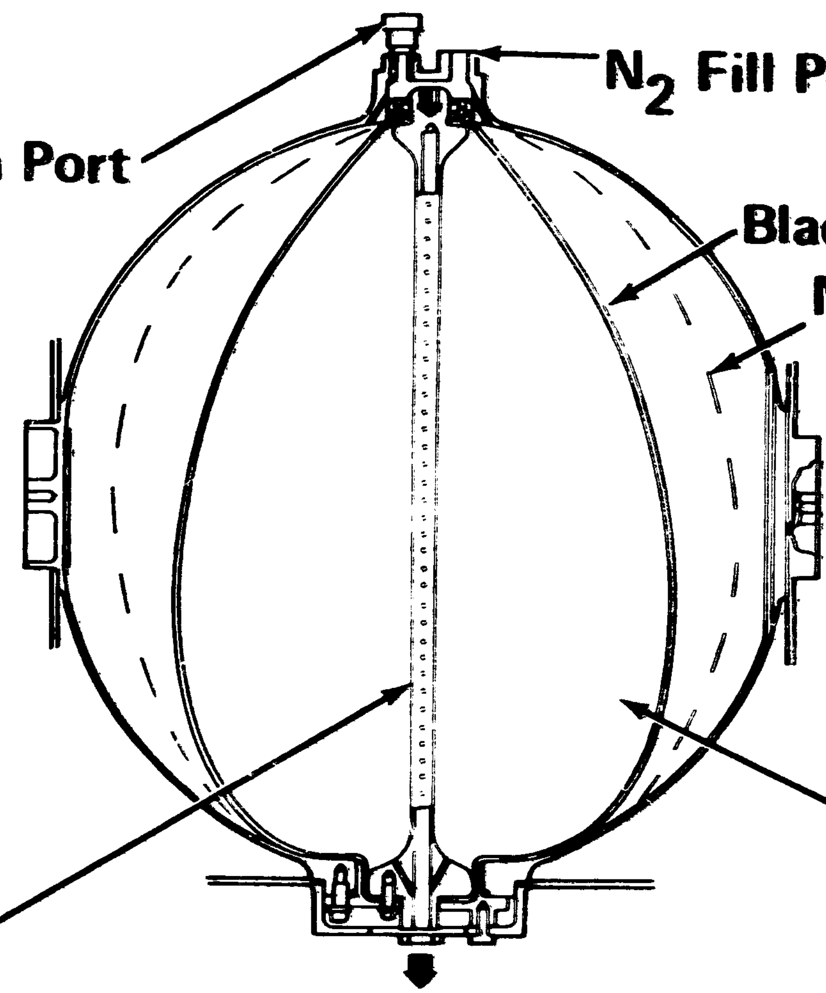
LM ASCENT STAGE BLADDER TANK



BLADDER TANK - LUNAR MODULE/ASCENT STAGE

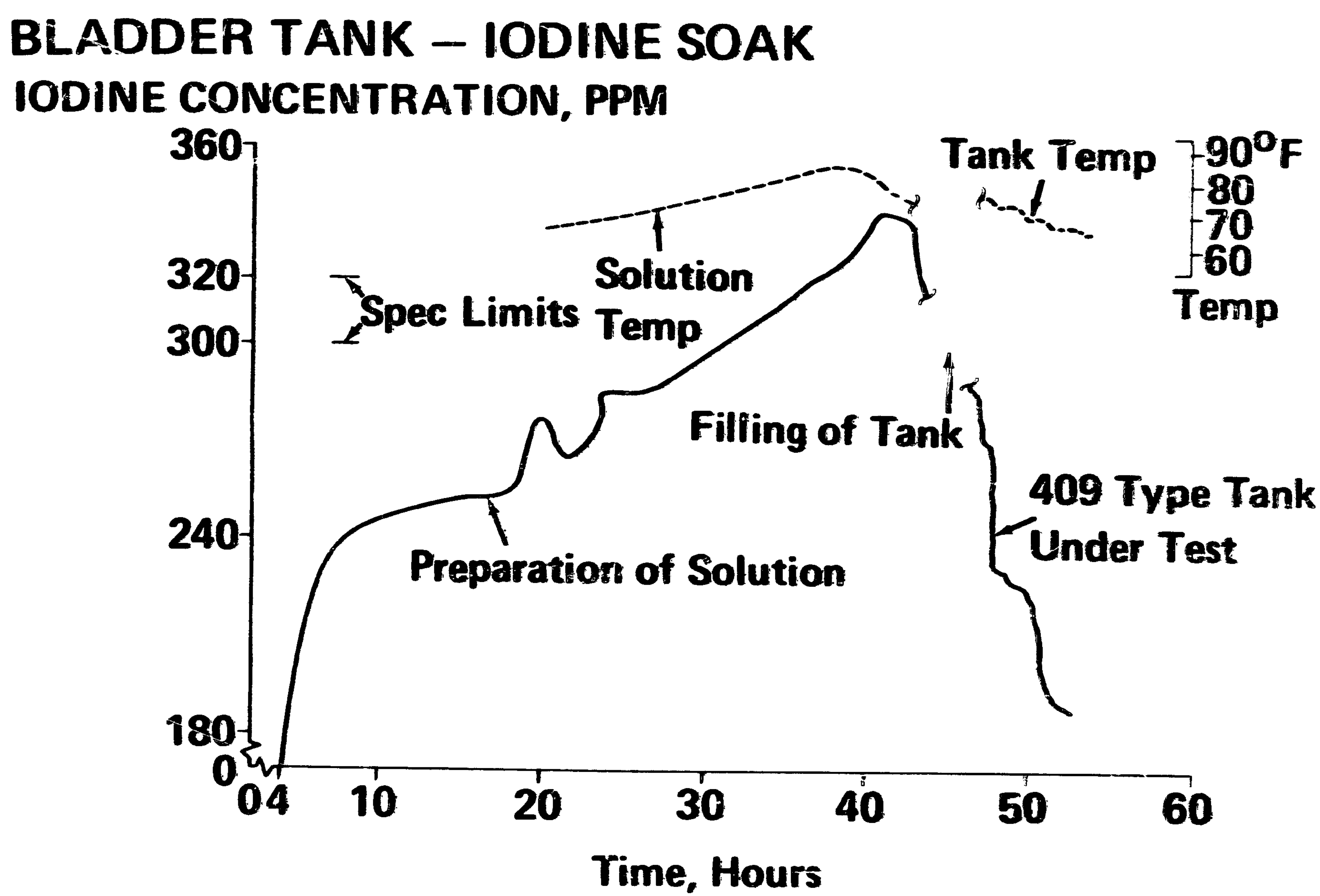
Approximately 42.5 lb of water are contained inside the bladder at launch time. Nitrogen gas in the cavity between shell and bladder provides the pressure necessary to expell water on demand from the astronauts. This pressure varies as a function of volume, and in case of high Δ p's in the water distribution network, not all water can be expelled. The instrumentation port communicates with pressure and temperature transducers, the signal, of which is electronically integrated for volume indication by the WQMD (Water Quantity Monitoring Device). The tank is manufactured by welding together two identical hemispherical shells spun from aluminum. The bladder and stand pipe assembly is inserted through the "bottom" opening. The bladder is made of silicone rubber which can be permeated by iodine and nitrogen. Once assembled, the bladder must be kept wet and pressurized to avoid collapse and resultant bonding.

BLADDER TANK – LUNAR MODULE/ASCENT STAGE



BLADDER TANK - IODINE SOAK

Iodine is put into the tank for sterility control; it has a tendency to leave its aqueous solution, permeate through the bladder and find its way to the aluminum shell where it reacts with the aluminum through cracks in its protective coating. Depletion is rather drastic and attempts have been made to satisfy the aluminum's reaction capability by soak procedures. Prior to launch, iodine is concentrated at the 300 to 320 PPM level in deionized water which is pumped into the bladder. Within 10 hours the concentration is cut by approximately 50% without any signs of stabilization. Because of this lack of success this procedure has been cancelled by the LM Program.



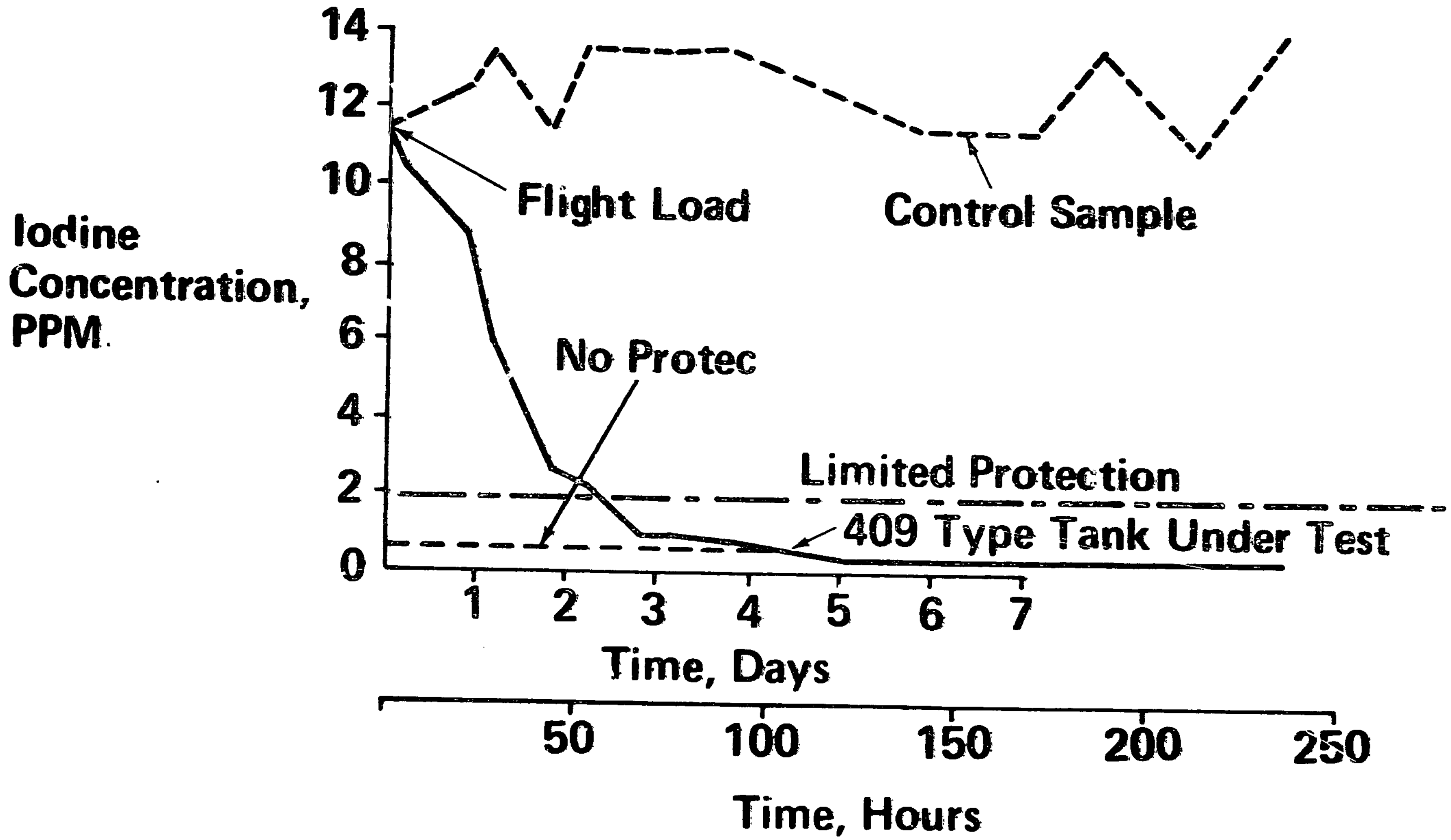
BLADDER TANK – IODINE SOAK
IODINE CONCENTRATION, PPM
360
320
300
240
180
0
04
10
20
30
40
50
60
Time, Hours
Spec Limits
Solution
Temp
Preparation of Solution
Filling of Tank
Tank Temp
90°F
80
70
60
Temp
409 Type Tank
Under Test

BLADDER TANK - IODINE DEPLETION

The current practice is to load the bladder with deionized water (NASA/MSC Spec PF-1C) which contains approximately 11.5 PPM iodine. At this level taste and odor are noticeable, but effective bacterial kill in water and exposed surfaces is assured. Within 3 days the iodine concentration diminishes to approximately 2PPM.

At this point, according to the flight profile, the astronauts have arrived on the moon and will begin to use the water. At the 5-day mark the concentration may have fallen below the 0.5 PPM level at which sterility cannot be assured. The iodine depletion function is fairly predictable even though it may vary from tank to tank. The 2.0 - 0.5 PPM range is satisfactory in taste and odor, but some investigators have expressed doubts as to its reliability in retaining sterility.

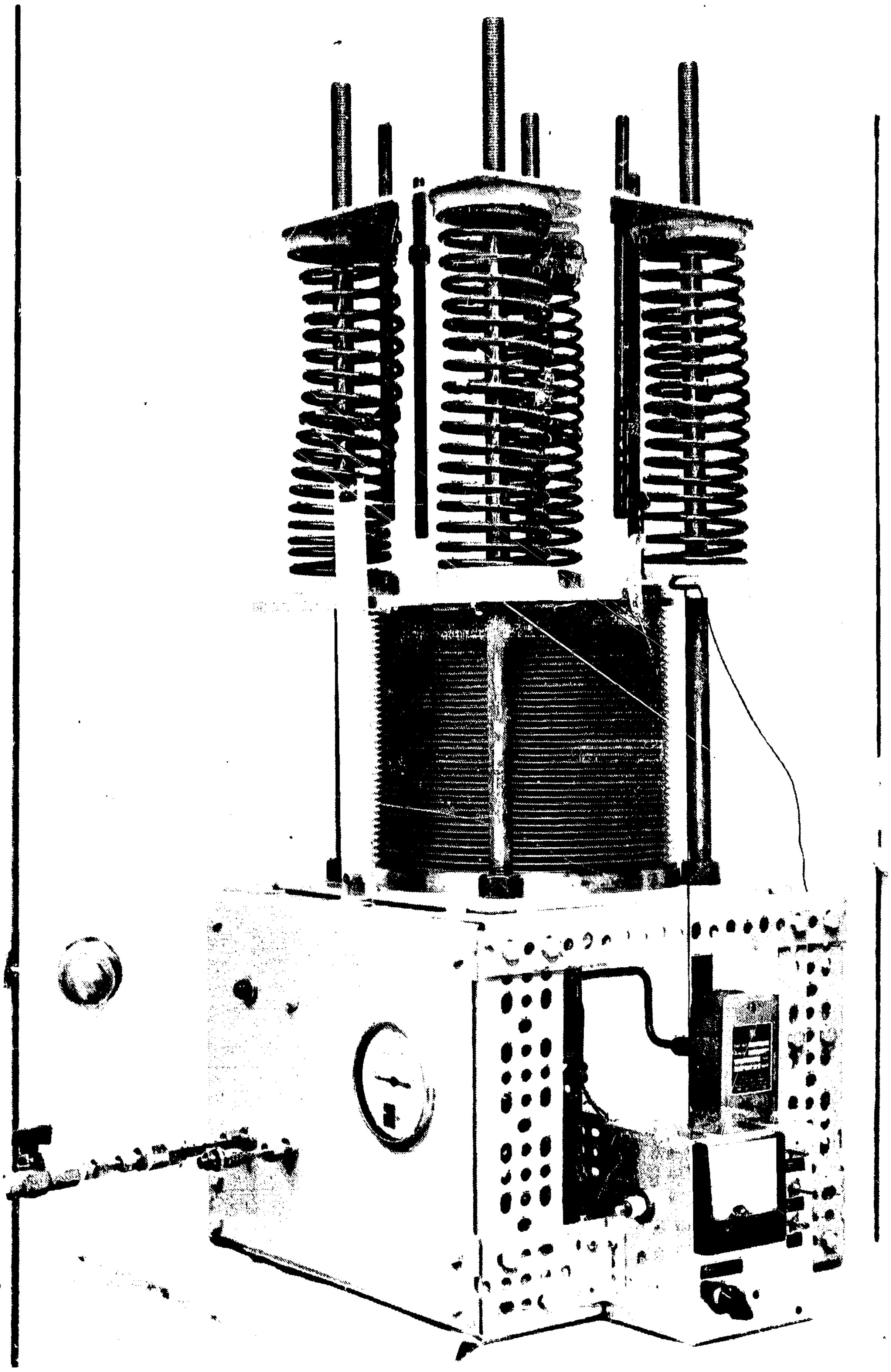
BLADDER TANK – IODINE DEPLETION



BELLOWS TANK TEST SETUP

The bellows tank tested was designed by Sealol Inc. for the storage and expulsion of propellants in the auxiliary propulsion system of the Saturn SIVB stage. It was lent to Grumman Advanced Development to investigate its suitablity for potable water service in the Shuttle. The tank was mounted on a chassis and equipped with the necessary fitting and controls. Provisioning of quick disconnects, front, and a linear potentiometer, right side, were advantageous. Since the tank came without an external pressure dome, constant rate coil springs were used to provide a positive expulsion force.

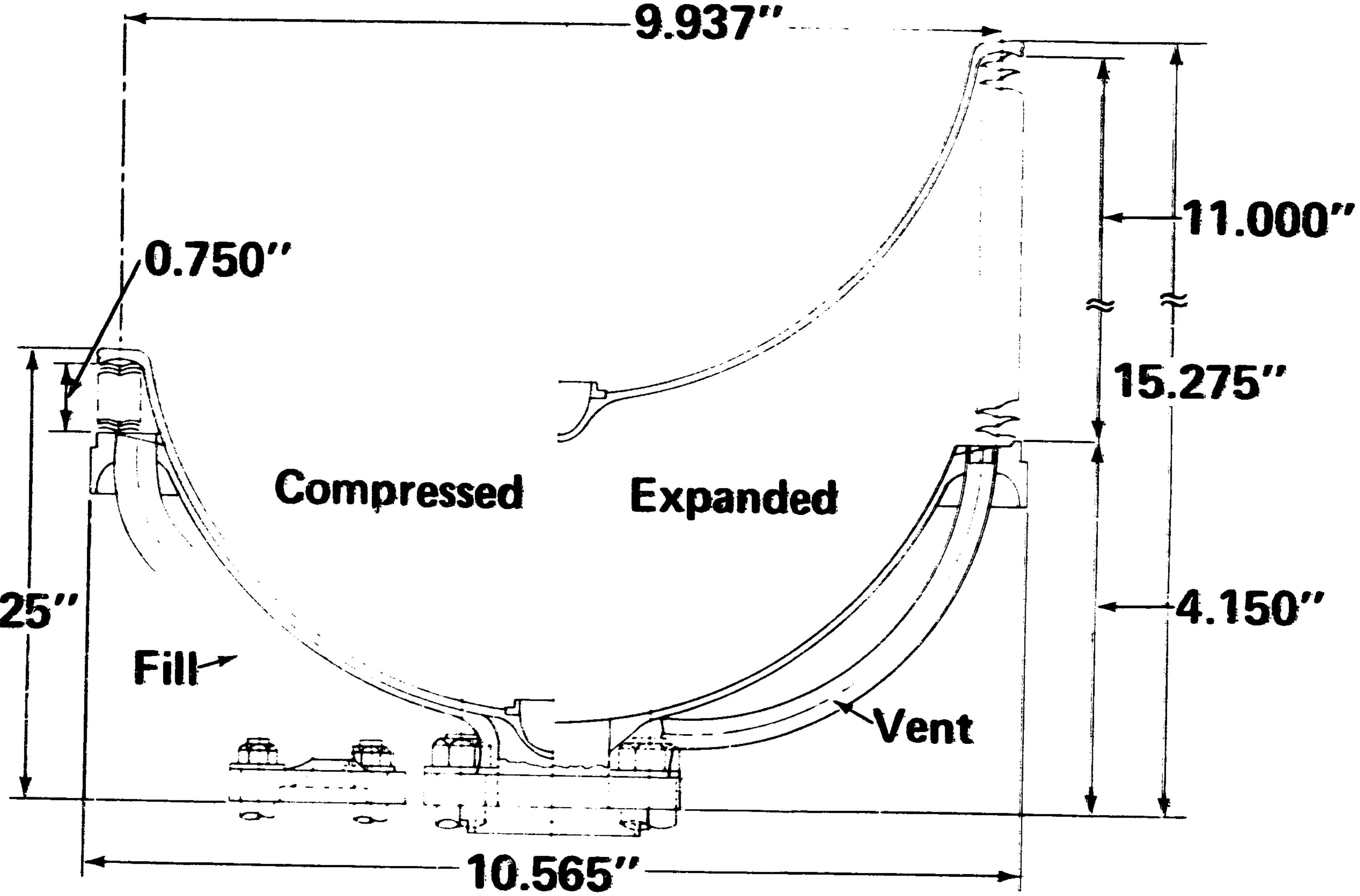
BELLOWS TANK TEST SET-UP



BELLOWS TANK-SATURN SIV B

The bellows, key component of the bellows tank assembly, was fabricated by welding together 37 convoluted bellows in the "nesting ripple" pattern. This pattern was used because of its long stroke capability and good pressure resistance. From a compressed height of 0.75" the bellows will expand to 11" when fully stroked to store 29.3 lbs of water. The bellows were made of 0.006" thick 347 stainless steel. Plastic deformation reduces the remaining strength with each cycle which is not significant since 1,000 life cycles are routinely exceeded, and bellows can be redesigned for elastic deformation. For best corrosion resistance Hastelloy-C is recommended; commercially pure titanium will double the strength-to-weight ratio of steel.

BELLOWS TANK – SATURN S IV B



COMPARISON OF DESIGN FEATURES: BLADDER TANK VS BELLOWS TANK

FEATURE	BLADDER TANK	BELLOWS TANK
Dry Weight (Pressurizable Ass'y)	5.3 lb (Optimized)	16.8 lb (Not Optimized)
Basic Configuration	Sphere 14.8" OD	Cylinder 10.6" OD 15" L
Adjusted Gross Volume (Cylinder)	3,370 in^3	1,350 in^3
Expulsion Capacity (Water)	42.5 lb	28.9 lb
Expulsion Efficiency	98.3%	99.3%
Weight Efficiency	89.0%	63.3%
Spatial Efficiency	34.9%	58.9%
Materials	Aluminum & Rubber	Stainless Steel
Pressure Differential	15 psid	7 psid (No Pressure Dome)

COMPARISON OF OPERATIONAL FEATURES: BLADDER TANK VS BELLOWS TANK

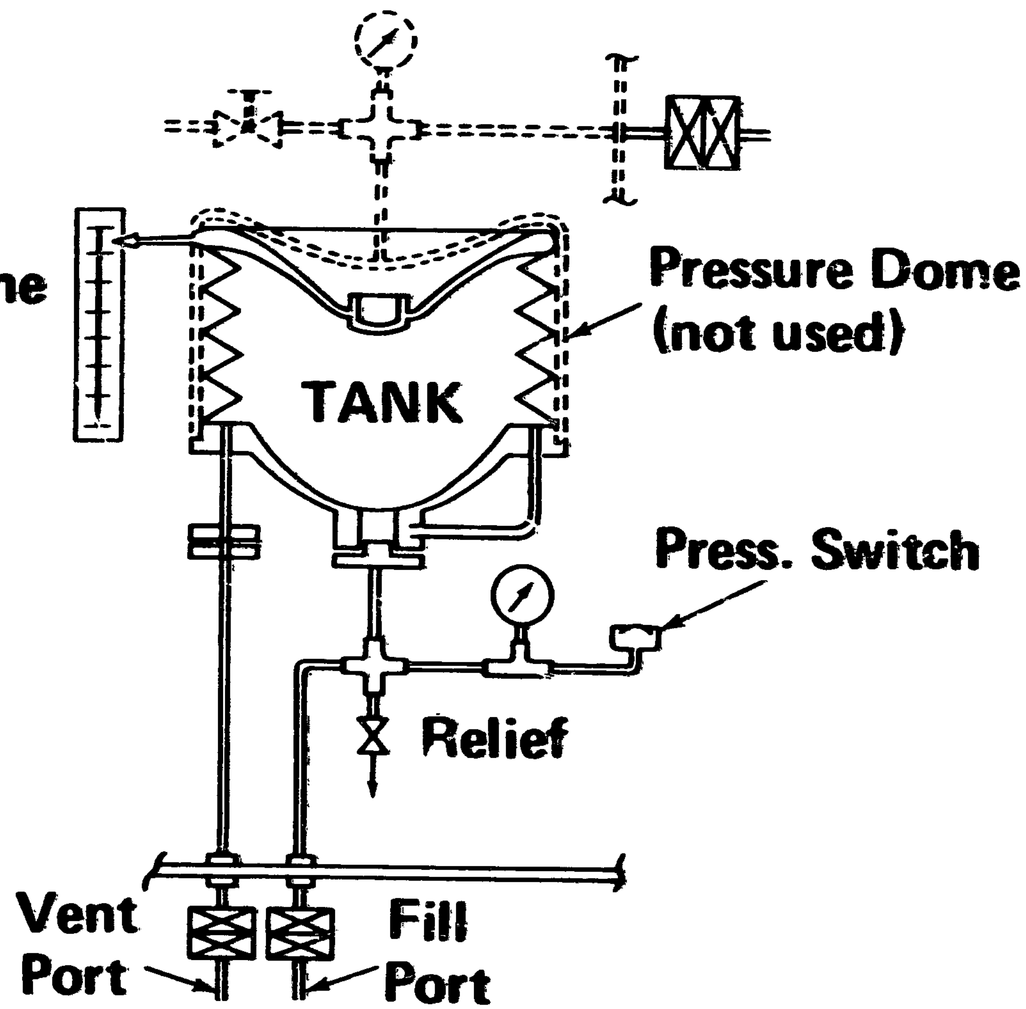
FEATURE	BLADDER TANK	BELLOWS TANK
Phase Separation	o Irregular & Permeable Membrane o Bactericide Depletion o Water Gasification o Corrosion Hazard	o Regular & Impenetrable Membrane o Minor Corrosion Hazard
Microbial Protection	o Cannot Be Autoclaved In Situ o Bactericide Required o Odor & Taste Problems	o Can Easily Be Autoclaved In Situ o No Bactericide Required o Odor, Taste Not Noticible
Cleaning	o Assembly Difficult To Clean o Organic Solvents Cannot Be Used	o Assembly Can Be Cleaned In Situ o Strong Organic Solvents Permissible
Storage	o Bladder Requires Special Storage Fixture o After Ass'y, Bladder Must Be Kept Moist & Pressurized To Prevent Bonding	o Unlimited Shelf Life
Volume Monitoring	o P & T Transducers o Requires Calculation o Setting of Reference Conditions	o Linear Potentiometer o Simple & Accurate o Not Affected By P & T

BELLOW TANK-FLUID-MECHANICAL SCHEMATIC

In the test set-up a pressure switch with both audio and visual alarms and a relief valve were required to protect the bellows. In the absence of a pressure dome, line pressure during filling and steaming becomes the differential pressure effective across the unsupported bellows. A pressure dome would be fed by a constant pressure gas supply to expel the liquid volume at constant pressure as opposed to the present practice of variable pressure expulsion. Additionally, the pressure dome, perhaps with a teflon liner, will provide circumferential guidance for the bellows.

From a contamination control view point the many components and interconnecting fittings are undesirable. Note especially the "dead ended" pressure switch line. Mechanical volume gaging can be obtained by either observing gage pressure, or by reading the indicator attached to the upper endplate.

BELLOWS TANK – FLUID–MECHANICAL SCHEMATIC



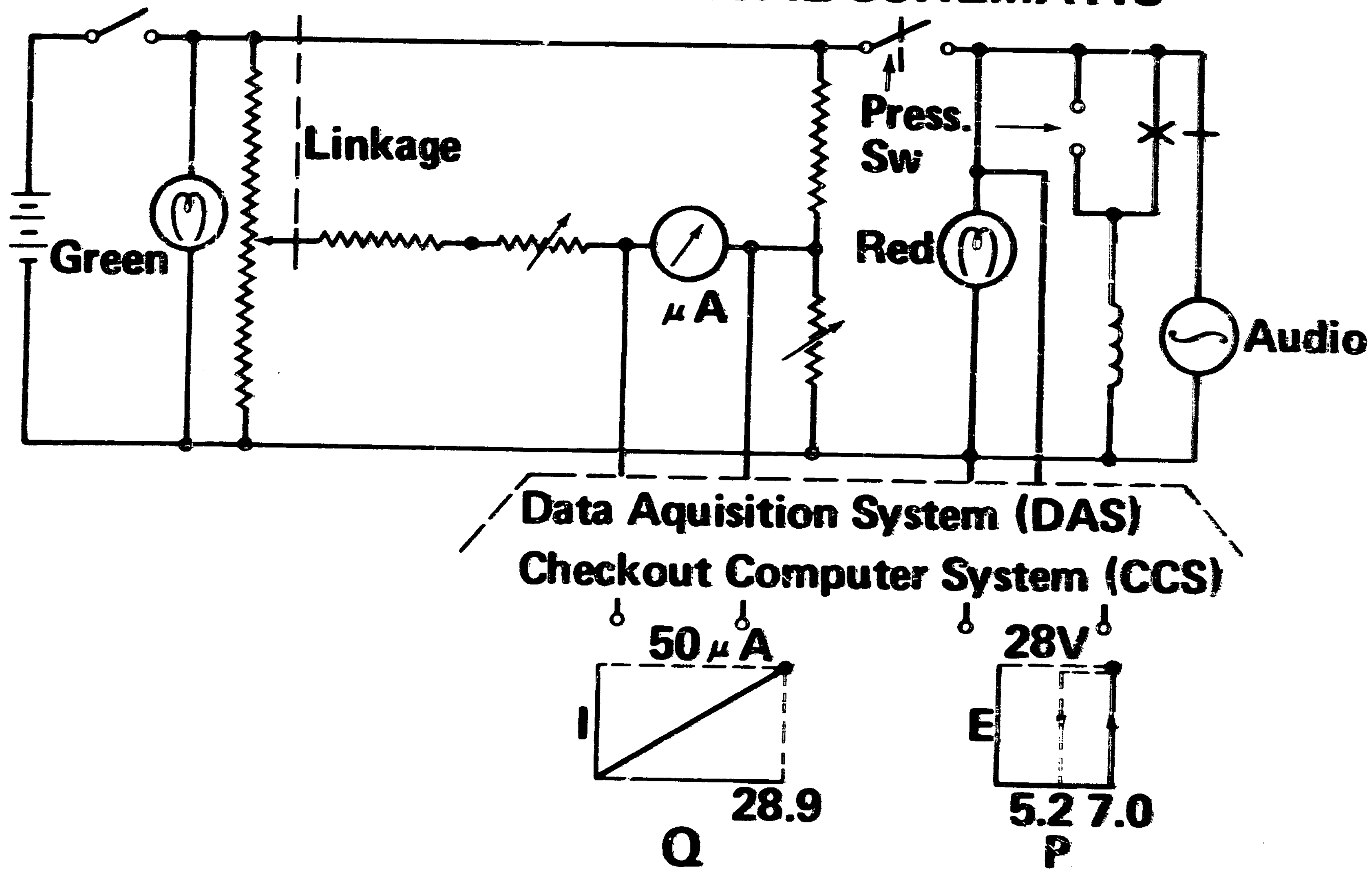
BELLOWS TANK - ELECTRICAL SCHEMATIC

A Model # 4046-1 potentiometric displacement transducer, manufactured by the Controls Division of Research Inc., was linked to the upper end plate by means of a shaft and pulley arrangement to adapt its stroke to that of the bellows. Two other potentiometers permit null and gain adjustment of the microameter such that full-scale deflection corresponds to the bellows stroke or to the volume actually expelled, whichever is preferable.

The pressure switch when actuated by a rising tank water pressure will actuate the visual and andio alarms. A latching relay will lock in the audio alarm until the attendant will depress the reset button.

The vehicle data acquisition system will receive two types of signals: (1) 50 uA corresponding to a full tank loaded with 28.9 lbs of water, (2) 28V DC corresponding to overpressurization if the water pressure exceeds 7 psig. Due to the hysteresis of the pressure switch the alarm will stay on until pressure is reduced below 5.2 psig.

BELLOWS TANK – ELECTRICAL SCHEMATIC



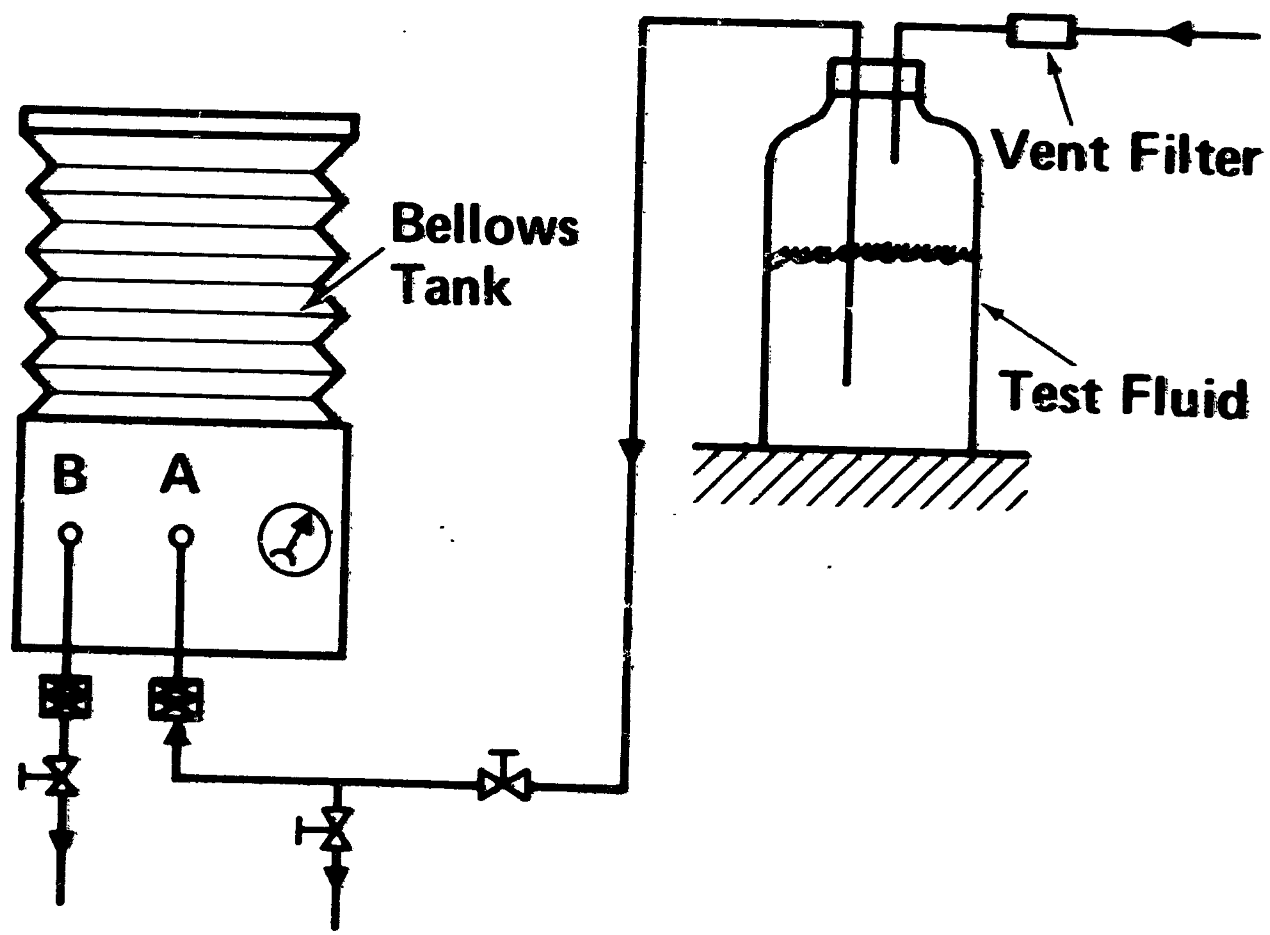
BELLOWS TANK – MICROBIOLOGICAL TEST OBJECTIVES

SCHEDULE	TEST NUMBER	PROCEDURE	OBJECTIVE
Phase A	1; 2	• Sterilize tank in "as received" condition • Load with sterile water under aseptic conditions	• Evaluate effectiveness of sterilization protocols I & II
Phase B	3; 4; 5; 6	• Innoculate with pure cultures • Apply sterilization protocol • Load with sterile water under aseptic conditions	• Establish survival of pure microbial cultures in tank • Eliminate contamination • Verify sterility
Phase C	7	• Challenge tank with mixed innoculum • Apply sterilization protocol • Load with sterile water under under aseptic conditions	• Establish survival of mixed microbial cultures in tank • Eliminate microbial contaminants • Verify sterility • Determine duration of sterility
Phase D	8	• Contaminate tank with mixed innoculum • Apply sterilization protocol • Load with sterile water under aseptic conditions • Withdraw samples at frequent intervals • Subject tank to random vibration loads and temperature cycles	• Eliminate microbial contamination • Verify sterility • Retain sterility for long duration while environmental conditions change • Prove that frequent withdrawals (in conformance to special protocol) do not interfere with sterility
Phase E	9; 10; 11	• Fill with contaminated wash and laundry water • Apply sterilization protocol II • Repeat in case of failure	• Induce contamination normally found in waste waters • Demonstrate survival of normal microbial contamination in tank • Eliminate microbial contamination • Verify sterility • Demonstrate the adequacy of sterilization protocol II & III in dealing with systems failures
	12,[1] 12,[2]	• Apply new sterilization protocol, Protocol III	• Attempt integration with water reclamation system and check retention of sterility

SELECTION OF MICROBIAL CONTAMINANTS FOR CHALLENGING BELLOWS TANK

ORGANISM	CLASSIFICATION	CHARACTERISTICS
Ps. aeroginosa	gram negative rod	• Potential human pathogen, found in the intestinal tract • Common water contaminant; has consistently been a problem in closed water systems (McDonnell/Douglas & Ben Franklin) • Proliferates rapidly, resistant to many disinfectants
B. subtilis	gram positive rod	• Spore former, theoretically a more resistant organism • Representative of organisms found in dust & dirt
S. aureus	gram positive coccus	• Serious human pathogen • Would be collected in wash water of carriers
E. coli	gram negative rod	• Indicators of fecal contamination • Expected to appear after breakdown in water reclamation systems
S. marcens	gram negative rod	• Survives & proliferates at lower temperatures • Often found in water supplies • Convenient marker organism because of its characteristic color on growth media.

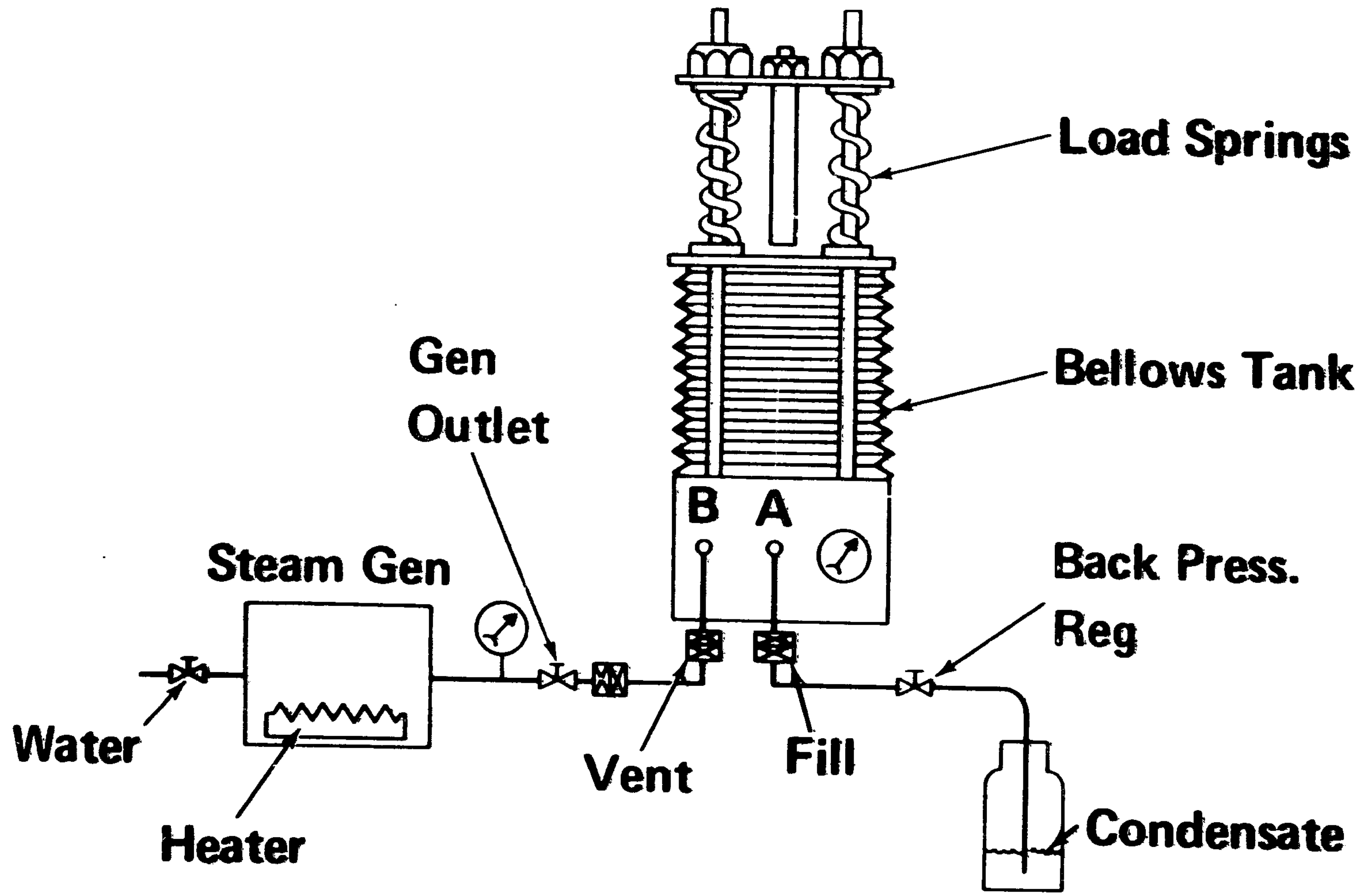
BELLOWS TANK – FILL CONFIGURATION FOR CONTAMINATION TESTING



BELLOWS TANK - STERILIZATION CONFIGURATION

A 3kW electrical steam generator was used to build up pressure inside the bellows against the setting of the back pressure regulator. The steam pressure caused the bellows to expand and opened the convolutes for penetration. Due to heat losses to ambient and heat layering on the inside condensation occurred. The steam feed line was connected to the higher vent port to avoid bubbling through the condensate which had collected at the lower fill port. It was not possible to determine the temperature gradient, but it is assumed that the mean temperature corresponded to the saturation pressure read off the tank gauge. The maximum allowable pressure differential across the bellows limited this procedure to approximately 21.2 psia and 232°F.

BELLOWS TANK – STERILIZATION CONFIGURATION



BELLOWS TANK – STEAM STERILIZATION PROTOCOLS

IDENTIFICATION	STEAM APPLICATION CONDITIONS			RESULTS
	PRESSURE	TEMPERATURE	DURATION	
I	20.2 psia	228^{o}F	75 min	Not successful: contaminated at 0 hours
II	21.2 psia	232^{o}F	125 min	Successful: Sterile for 7; 21; 22; 103 days with challenges by pure and mixed cultures but only limited success with wash and laund y waste water
III	21.2 psia	232^{o}F (added insulation)	210 min	Successful: Sterile for 42 days after challenge with highly contaminated wash & laundry waters.

BELLOWS TANK SUMMARY OF MICROBIOLOGICAL TEST RESULTS

TEST	TEST FLUID	CHALLENGE	PROTOCOL	RESULT
A-1	Autoclaved dist water	Random, unidentified	I	Contaminated @ 0 hours
A-2	Autoclaved dist water	Residual from A-1	II	Sterile for ≧ 21 days
B-3, -4, -5, -6	Autoclaved dist water	Pure Cultures	II	Only Ps. aeruginosa survived as pure culture & posed real challenge Sterile for ≧ 7 days
C-7	Autoclaved dist water	Mixed Cultures	II	Sterile for ≧ 22 days
D-8	Autoclaved dist water	Residual from C-7	II	Sterile for ≧ 103 days in in spite of frequent withdrawals & changing environmental conditions
E-9	Wash water solution	Predominantly coliform, other organisms not identified	II	Sterile for > 7 days Contaminated @ 14 days.
E-10	Residence laundry water & synthetic wash water	Predominantly coliform, other organisms not identified	II	Sterile for > 3 days Contaminated @ 8 days
E-11	Autoclaved, distilled water	Residual from E-10	II	Contaminated @ 0 hours
E-12,1	Autoclaved, dist water	Residual from E-11	III	Sterile for ≧ 42 days
E-12,2	Reclaimed water	Random, unidentified	-	Contaminated @ 4 days

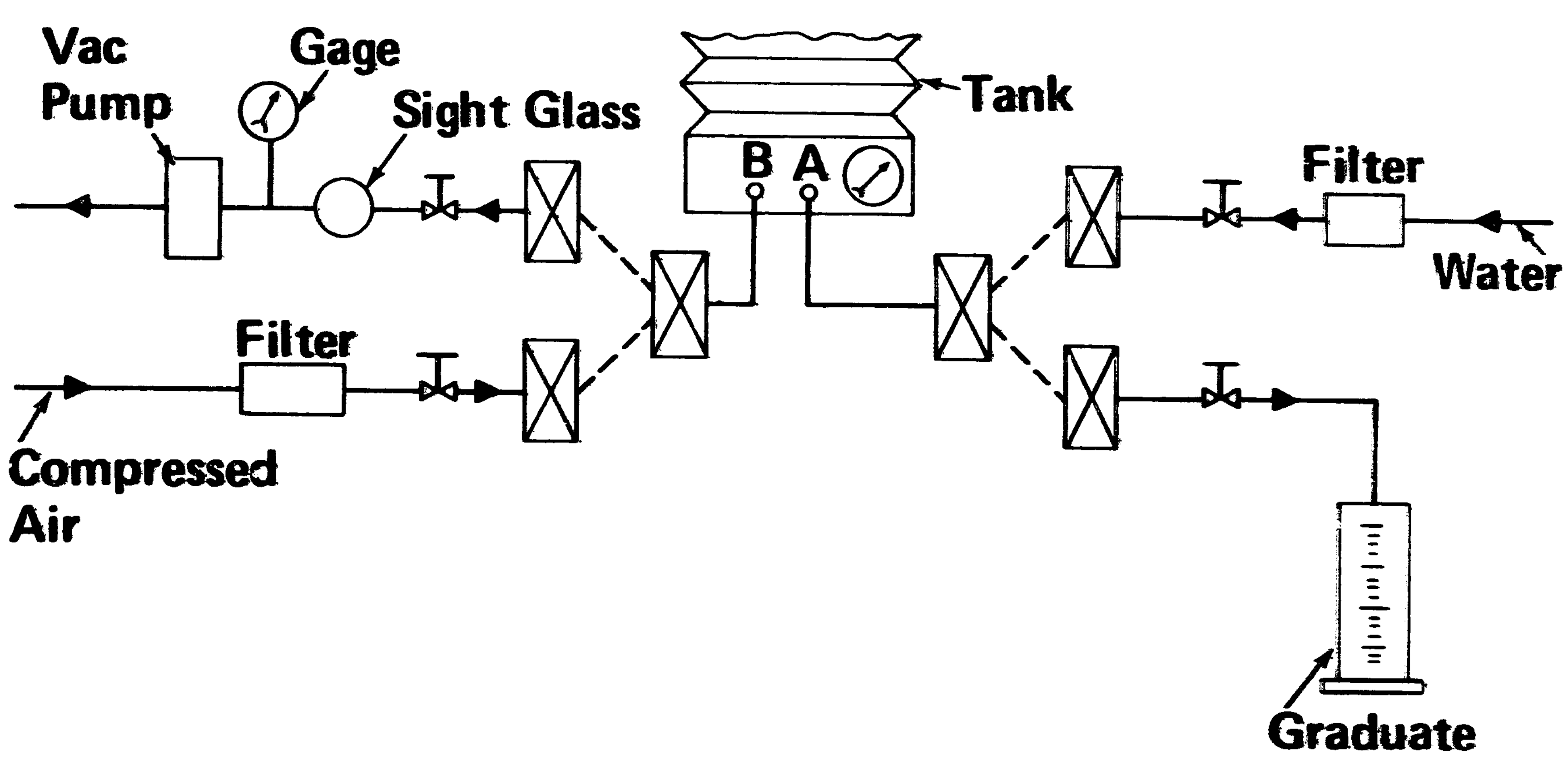
Note: ≧ means no contamination appeared, test simply terminated.

BELLOW TANK-FILL CONFIGURATION FOR VOLUMETRIC TESTING

A vacuum pump was used to collapse the bellows and remove all entrapped air from the vent port while a water supply was connected to the lower fill port. Complete air removal was indicated by the appearance of water in the suction line of the pump. With the vent port closed, water was pumped under pressure into the tank until tne bellows came to rest against its mechanical stop.

The water supply was disconnected, the sampling valve was connected and water withdrawn into a 1,000 ml graduate. Mechanical weights were added to the top plate to assist the coil springs in expelling the water. After the bellows was collapsed, the compressed air through the vent port was used to drive out small quantities of residual water from the passage ways and interconnecting lines. Expulsion efficiency was defined as the ratio of the water expelled by the bellows to the total volume measured with the graduate.

BELLOWS TANK – FILL CONFIGURATION FOR VOLUMETRIC TESTING



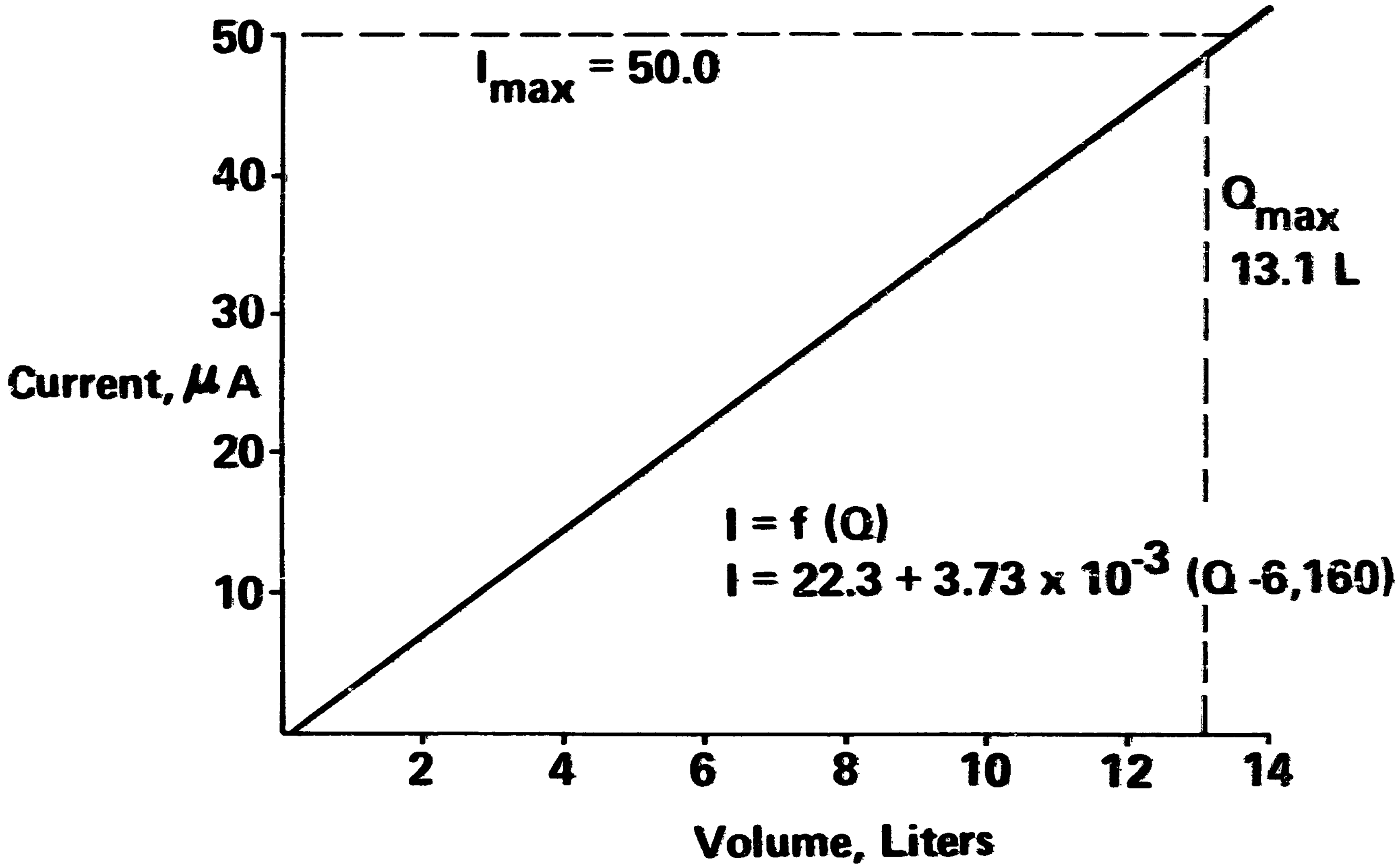
METER VOLUME SIGNAL

The volume meter signal was recorded for specific volumes as measured with 1,000 ml graduates during two complete test runs. A regression analysis was performed on the 40 measurements taken which resulted in the straight line relationship of $I = 22.3 + 3.73 \times 10^{-3}$ (Q - 6,160). The standard deviation was calculated for the residuals:

$$3\,Sxly = \pm 2.05\ \mu A;\ FSD = 50\ \mu A = I_{max}$$

Which means that 97% of all observations can be expected to fall within the band of ± 4.1% of full scale deflection. This is the net deviation which results from the combined effects of linearity of the potentiometer (0.35% claimed by manufacturer), guidance of bellows and linkage and error on part of the observer.

METER VOLUME SIGNAL



CONCLUSIONS

- Mixed cultures and waste waters from hygiene and laundry sources represent a valid microbiological challenge.
- Steam application (Protocol III: 21.2 psia, 232°F & 210 minutes) is effective in sterilizing during launch preparations and after system's failure.
- Repeated <u>in situ</u> sterilizations can be accomplished with ease and pose no additional problems.
- Frequent withdrawals do not affect tank sterility if proper protocol is adhered to.
- Diversity of materials and component designs used in construction of test set up was not observed to interfere with sterility in any traceable way.
- Sterility can be retained for 100-day periods which are sufficient for Shuttle, Skylab II and Space Station applications.
- Tank is suitable for both use by crew onboard launch vehicle and delivery to orbit as part of resupply mission.
- Even though no physical/chemical testing was documented, no adverse odor, taste or coloration effects were observed.
- Volume metering by means of a linear potentiometer is both simple and accurate.
- Design and operations analysis indicates superiority of bellows tank to bladder tank in all aspects except weight effectiveness.
- In view of past flight qualifications and new aerospace applications presently being developed, the tank is considered as an acceptable development risk for the Shuttle.

RECOMMENDATIONS

- Repeat selected tests and perform full range analysis of physical and chemical parameters to ascertain if
  - tank material remains completely inert
  - high temperature associated with steaming creates additional chemical contamination
- Conduct new tests to check compatibility with bactericides (iodine, chlorine, silver)
- Modify tank design by adding light-weight pressure dome with insulation to determine
  - gas requirements for constant pressure expulsion
  - reduction in heat losses and condensation
  - minimum sterilization protocol required (higher temperature & pressure, shorter application period)
- Integrate tank electro-mechanically with operational water management system to
  - identify interface problems with data acquisition & checkout computer systems
  - monitor water inventory status and perform real time mass balances.
  - demonstrate compatibility with on-line potability monitors
  - investigate effectiveness of in situ sterilizations of complete systems
- Use tank as reservoir for bactericide generator concept which will provide protection to ancillary components in water management system

BELLOWS TANK* APPLICATIONS

PROGRAM	CONSTRUCTION MATERIAL	TANK SIZE	APPLICATION	DESIGN REQUIREMENTS
Agena B	St St'l 347	10.4" OD 48 " Stroke 16 GAL.	Auxiliary Propulsion System	Operating Life 500 cycles Ultimate Life 1,000 cycles
Saturn SIVB	St St'l 347	10.6" OD 15" Stroke 3.4 GAL.	Auxiliary Propulsion System (Oxidizer & Fuel)	Operating Life 500 cycles Ultimate Life 1,000 cycles (Plastic Deformation)
Grumman Adv. Development	St St'l 347	10.6" OD 15" Stroke 3.4 GAL.	Potable Water Storage, Waste Water Storage, Decontamination Techniques	Operating Life 500 cycles Suitability for Steam Sterilization
Skylab II	St St'l 321	23' OD 47 Stoke 75 GAL.	Potable Water Delivery & Storage	Operating Life 100 cycles Ultimate Life 200 cycles Expected Life 1,000 cycles Low Iodine Absorption
Supersonic Transport	Inconel 718	27.5" OD 20" Stroke 48 GAL.	Hydraulic Accumulator	Operating Life 20,000 cycles (Elastic Deformation)
Symphonie Satellite	Titanium	8.3" OD 8.7" Stroke 1.8 GAL	Auxiliary Propulsion System (Fuel Storage & Expulsion)	Light Weight

* Tanks designed and made by Sealol Inc. of Providence, Rhode Island 02905