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THIN FILM COMPOSITE MATERIALS - PHASE II

(A Continuation of Supporting Task No. 37
of Air Force Contract F33615-81-C-2013)

Final Report for Period April 1, 1986 to December 31, 1986

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SUMMARY

The three tasks of this program have been completed as follows:

Task 1. The expandable radiation system requirements were established in discussions with Louis Chow of AFWAL.

Task 2. The expandable radiator concepts previously proposed, with extensions and some innovations, have been evaluated by preliminary mechanical designs. Nine concepts were considered; for eight of these, preliminary designs and bills of materials were prepared. Several different methods of liquid collection and radiator expansion and contraction were considered. The calculated masses associated with these designs permitted them to be contrasted for energy storage efficiency. The contrasts of water versus ethylene glycol as working fluid, system saturation temperature, and system shape were also evaluated. The systems with the best efficiency and workability were the "Rotating sphere stowed in cylinder", and the "Roller retracting cylinder with sponge and squeeze bar".

Task 3. The materials evaluated were Kevlar coated with silicone, EPDM, or neoprene rubber, with the following results:

1. Tensile testing of coated Kevlar fabric is very difficult because of slippage in the Tensometer grips. It will be necessary to fabricate test cylinders of coated Kevlar that can be stressed in an inflation test. It may be possible to calibrate a tensile test versus these results; however, the inflation test is probably more practical for these special materials.

2. A method was developed for measuring water vapor permeability. Neoprene and EPDM are promising as coatings with good water resistance; however, a study of the effect of coating weight on permeability should be done.

3. The strength losses and water resistance losses due to flexing and fabric creasing were negligible. These results validated the use of coated Kevlar for this application.

4. Although adhesive bonded seams and sewn seams were both fabricated, we were not able to adequately evaluate them during this project.

5. Blocking tests and water-rubber compatibility tests indicated that the rubber coated Kevlar we used is potentially a suitable material for the expandable radiator.

6. Kevlar priming formulations were uncovered so that L'Garde can coat Kevlar for future optimization of the elastomer formulation.

Although not specified in the original proposal, some energy considerations were also developed:

1. The force on the end of the radiator when vapor is suddenly admitted to the evacuated volume is calculated.

2. The relative importance of the condensation, conduction, and radiation resistances to heat transfer is calculated, showing that the radiation resistance is 100 times as large as the others.

3. The system temperature at equilibrium in space as a function of position relative to the sun and earth is calculated. Position must be carefully managed to prevent a freeze-up of the system.

In a final section, recommendations for future work and an expandable radiator implementation plan are presented.

ACKNOWLEDGEMENTS

The help of several associates at L'Garde is gratefully acknowledged:

Thai Do and Cor Van Overeem prepared some of the figures.

Jim Flickinger, Jim Trailer, Ken Keeper, David Friese and Jim Linn carried out the lab work.

Ronnie Lowe, Judy Winslow, and Lory Pang typed the report and managed the figures and tables.

Walt Pearson and Gordon Veal did the mechanical design work. Walt also designed and implemented the modifications of the deMattia flex tester. Gordon designed the Tensometer grips used to hold Kevlar.

Koorosh Gidanian and Gayle Bilyeu advised on the materials study.

David Siegelman and Mitchell Thomas read and improved the final report.

Sasan Faizsaket did the radiative heat transfer calculations.

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1.0 EXPANDABLE RADIATOR SYSTEM REQUIREMENTS

The system requirements specified by AFWAL were established in discussions with Louis Chow of that facility. They are:

A. System Size

1. When packaged for shipment on the space shuttle, it must be no larger than 8 feet in diameter and 40 feet long.

2. The area of the input openings to the radiator is to be 1/4 the total radiator cross sectional area.

3. The radiator cannot be left expanded in space for extended periods of time, so a contraction scheme must be part of the design.

B. Environmental and Operating Conditions

1. There are two levels of waste heat output that are of interest: 0.1 to 1.0 Mw for a prototype, and 10. to 100. Mw for the space application.

2. The space application will require a polar orbit of 100 minutes. The radiator should be ready for use 4 minutes of this time, and it should be designed to operate for 2 minutes continuously.

3. The radiator will be tested in space at one year intervals. At those times it will become coated on the inside with the working fluid. Either the fluid will need to be removed completely (which could only be done by opening the system to space), or the inside surface of the system will need to be compatible with the fluid over a period of years.

4. The system temperature will be between 200. and 400K; however, it will need to be greater than 273K if water is to be used.

5. While expanded, the system will be subjected to a maximum of 0.1g force. The launch forces will be those for the space shuttle.

6. The outside surface will be subjected to radiation intensity from the sun as a 6000K black body at 1350.W/M^2.

C. Requirements of Operation During Checkout Testing and Deployment

1. The expected lifetime in orbit is 10 years.

2. Testing will be at one year intervals.

3. The expected time between maintenance is 3 years.

4. The reliability should be high, but this has not been specified quantitatively.

2.0 MECHANICAL SYSTEM EVALUATION

A. Purpose

Preliminary mechanical designs have been developed to evaluate the expandable radiator concepts that have been previously proposed.

B. Summary

In each design it is assumed that the radiator will be sent into space in collapsed form as cargo in a space shuttle. It will be inflated in space, and be able to contain and later condense vapor generated by waste heat boiling. Each system incorporates a liquid recovery method, and a method of collapsing the radiator back to its initial size for storage.

Because of its high strength to weight ratio, Kevlar fabric was selected as the material of construction for the body of radiator. The inside of the fabric would be coated with a vapor barrier to prevent loss of the working fluid. The outside would be coated with a high emissivity material that would also shield the Kevlar from degrading ultra-violet radiation. Although it has not been completely determined what mass of coating will be needed, a 50% to 100% increase in fabric weight often is appropriate to account for the coating.

Nine concepts were considered for containing the saturated vapors. For eight of these, preliminary designs and bills of materials were prepared. Several methods of collecting the condensed liquid and of collapsing the expanded radiator were incorporated into the various designs.

Other contrasts evaluated were --

- o Water vs. ethylene glycol as the working fluid
- o 75°C vs. 100°C as the saturation temperature
- o The effect of cylinder length on efficiency for the cylindrical systems.
- o The effect of cylinder diameter on efficiency for the cylindrical systems.

The conceptual designs were done for a cylinder 8 feet in diameter and 40 feet long as a base case, with longer lengths also considered. Each design includes a thermal and meteoroid protective cover over the system in stowed position to prevent freezing and damage during idle periods.

Each type of expandable radiator will be discussed at length below; however, Table 1 shows a summary of their major features and problems.

C. Operating Procedures

The operating sequence for all of these systems would be --

1. Open protective cover.

2. Apply an expansion gas pressure of approximately 7.1 Pa (1 x $(10)^{-3}$psi) to expand the radiator to its full size. This gas would be supplied by a water heater to produce the water vapor needed to expand the system in a controlled manner. Very little of the system capacity would be wasted by this preliminary expansion, but since it could be done slowly the forces acting on the fabric of the system would be small. All the radiators associated with the waste heat generator would be expanded initially before the time of use; this would minimize the impulse into each of them from the common manifold when they were all pressurized at once.

3. A sensor would determine when each radiator was fully expanded to indicated readiness; the spin motor would then be turned on for the rotating devices. This rotation will help to clean surfaces for faster condensation and promote heat transfer at the condensing surface, as well as to direct the liquid to the largest circumference for collection.

4. Steam will pressurize each radiator (power sequence).

5. Safety system will prevent exceeding the design pressure.

6. Pump turns on for liquid return.

7. Spin motor would be turned off when substantially all liquid has been recovered. Brake would stop spinning.

TABLE 1. TYPES OF EXPANDABLE RADIATOR

DESIGN	DESCRIPTION	METHOD OF LIQUID COLLECTION	METHOD OF SYSTEM CONTRACTION	MAJOR PROBLEMS
1	Rotating sphere, stores flattened	Centrifugal force pulls water to pump	Tether pulls fabric in	Rotating seals Small capacity
2	Roller retracting cylinder - fixed wiper	Wiper collects liquid as friction rollers pull fabric in	Friction rollers pull fabric	Rollers may pull unevenly, fabric may bunch up
3	Cylinder with moveable wiper	Wiper moves across surface	Tether pulls cylinder in from end	Little control over folding & wiper effectiveness
4	Tapered rotating cylinder	Centrifugal force pulls water to pump at system base	Friction rollers pull fabric	Rollers may pull unevenly. Rotating seals
5	Tapered rotating cylinder with liquid return channel	Centrifugal force pulls water to pump at system base	Tether pulls cylinder in from end	Little control over folding. Rotating seals
6	Cylinder with drum roll-up	Squeezes liquid ahead of rollers	Drum rolls up fabric from outer end	Small capacity. Hard to control drum.
7	Sock-type cylinder	---	Outside roll-up like a sock	Since fabric is not elastic, this won't work
8	Rotating sphere stowed in cylinder	Centrifugal force	Retracting disk is pulled into storage cylinder cables	Rotating seals
9	Roller retracting. Sponge with squeeze bar.	Sponge wipes incoming fabric	Friction rollers pull fabric	Rollers may pull unevenly. Fabric may bunch up.

8. Retraction system operates in response to minimum system temperature so that condensing water does not freeze on the sides of the radiator before it is packaged.

9. Thermal cover is closed.

D. Comparisons

1. Containing the Gas Volume.

A spherical shell will contain the maximum volume per unit surface area, and thus potentially has the best ratio of contained energy to system mass. A cylinder is not as efficient as a volume holding device, but its straight sides suggest an easier liquid collection system. Because of the requirement of a large volume that could be quickly filled, all the designs used either a sphere or a cylinder, or a combination.

The usual radiator has a relatively large surface to volume ratio to promote very rapid transfer of heat. For the radiators considered here although the relative surface area is minimal, the waiting period of 96 minutes between radiator uses gives enough time for the liquid condensation and collection as shown by Chow and Mahefkey [8].

2. Collecting the Liquid.

There are five methods considered for collecting the liquid:

o A moving wiper that travels up and down the length of an expanded cylinder to wipe liquid from the inner surface. The motion of the wiper would be controlled by a motorized system of ropes and pulleys. It was soon recognized that it would be difficult to control this mechanism so that the fabric surface would be effectively wiped. Therefore this concept was not retained in the final series of designs, although initially used in Design #3, see Table 1.

o A stationary wiper blade that the fabric is pulled against when the latter is brought in for storage was included as a less cumbersome design. This was used in Design #2.

o When the wiper blade is converted to a donut-shaped sponge that wipes the incoming fabric, one can be more sure to reach the fabric interstices. In this design a clamping bar system was incorporated to periodically squeeze the sponge into the pump inlet channel. This was used in Design #9.

- o The roll-up drum used in Design #6 takes up the radiator fabric from the far end of the cylinder. Wringer rolls preceding the drum push the liquid toward the inlet end of the system. When the fabric has been rolled up as much as possible, there is still a sizeable cone shaped area from which the liquid must be extracted for return to the boiler feed supply. At this point inflatable bladders could expand to squeeze the remaining liquid toward a pump intake.

- o A rotating system was used in Designs #1, 4, 5 and 8. The centrifugal force will cause the liquid to flow toward the largest radius where a pump inlet is located.

Of these designs, the wiper sponge seems most workable.

3. Methods of Radiator Expansion and Contraction.

The force required to expand the radiator is provided by internal vapor pressure. It is proposed that the radiators would be expanded to their full size by a very low inflation vapor pressure, before they are further pressurized by the vapor containing the waste heat. The systems later used for contraction would serve to break and control the expansion. When the vapor begins to condense, the pressure and temperature in the radiator will decrease. A pressure control system is recommended to cause contraction of the radiators, and thus maintain the pressure and temperature for faster condensation.
incorporated into the designs:

- o The drum take-up roll used in Design #6 stores the fabric in a controlled way, but only experimentation with the fabric selected will show to what extent this can be done without wrinkles on the roll. A major problem with this method is that the take-up drum stores a cylinder of diameter (D) on a roll of length (D/2) plus the size of end supports. This means that the useful radiator diameter is smaller than for other designs that store the fabric in bellows folds.

- o Designs #2, 4, 8 and 9 use friction rolls to pull the fabric in from the cylinder and push it into storage.

Experimentation with an actual system will he necessary to evaluate the effectiveness of this setup.

- o Designs #1, 3, 5 and 8 use one or more tethers to pull the expanded cylinder or sphere into storage. The take-up rate on each of several tethers can be adjusted to bring in the fabric evenly. The tethers can be either inside or outside of the cylinders, however in the current designs they have been located inside.

4. Comparison of Water and Ethylene Glycol as a Working Fluid.

To compare the feasibility of these two working fluids consider the following basis:

- o One standard cylindrical radiator is 8' ID x 40' long; the volume is 2011 ft^3.
- o Time of energy source = 120 seconds
- o Saturated vapor temperature = 75°C
- o Power of waste heat = 1 MW.

Then the energy that must be stored in vapor from a 120 second long heating period is:

$$(10)^6 \text{ watts} \times 120 \text{ sec.} = 120(10)^3 \text{ K-Joules}$$

Table 2 below shows the data and calculations that compare the number of standard 2011 ft^3 (56.95 M^3) radiators needed for water and ethylene glycol per megawatt of waste heat at 75°C.

The comparison of 3.68 radiators/MW for water and 199 radiators/MW for ethylene glycol shows that using water requires much less space in the vicinity of the waste heat source.

Although the radiators designed for ethylene glycol can be 30% to 80% of the weight of those for water, the total weight for 1 MW is still much greater for ethylene glycol --

$$\frac{\text{Wt for Ethylene Glycol}}{\text{Wt for Water}} = \frac{\text{199 Radiators}}{\text{3.68 Radiators}} \times \left(0.30 \frac{\text{wt}}{\text{ratio}}\right) = 16.$$

TABLE 2. COMPARING WATER AND ETHYLENE GLYCOL
Basis: 1 Megawatt

WORKING FLUID	WATER	ETHYLENE GLYCOL
Latent Heat, K-Joules/Kg	2312.	958.
Mass of Vapor Generated, Kg	$120\ (10)^3/2312 = 51.9$	$120\ (10)^3/958. = 125.$
Specific Volume of Fluid at Saturation, $\frac{M^3}{Kg}$	4.04	90.5
Volume of Fluid, M^3/MW for 120 seconds	51.9 x 4.04 = 209.7	125. x 90.5 = 11312.
Number of Standard Radiators Needed per MW	209.7/56.95 = 3.68	11312/56.95 = 199.

One could not justify an ethylene glycol system 16 times as heavy as a water system, therefore ethylene glycol is not a practical working fluid.

5. Comparison of Designs at 75°C and 100°C.

For the 1 MW heat source above we can compare the volume and mass of a system with saturated water vapor at 75°C and at 100°C. This is shown in Table 3 below.

The temperature difference results in the saturation pressure change as shown in Row 2 above. This increased pressure was used to correct the mass of a 75°C design to 100°C as shown in Row 3. The mass of vapor needed to store 1 MW of power absorbed for 120 sec. changes slightly due to the heat of vaporization as shown in Rows 4 and 5, where $120\ (10)^3$ KJ is the energy equivalent. The corresponding volume of stored vapor is much less at 100°C due to the increased pressure, as shown in Rows 6 and 7. Using 56.95 M^3 as the size of one standard radiator, Row 8 displays the number needed at each temperature, and finally Row 9 shows the mass of the needed radiators for 1 MW at 75 and 100°C.

Apparently there is a large mass saving in using the higher saturation temperature. Using the strongest Kevlar fabric available one could go to a

TABLE 3. COMPARING WATER AT 75 and 100°C
Basis: 1 Megawatt

1.	Temperature, °C	75.	100.
2.	Water Vapor Pressure, KPa	39.3	101.3
3.	Mass of One Standard Radiator, Kg, Design #9	88.5	114.
4.	Heat of Vaporization KJ/Kg	2312.	2249.
5.	Mass of Stored Vapor, Kg/1 MW	$120\ (10)^3/2312 = 51.9$	$120(10)^3/2249 = 53.3$
6.	Vapor Specific Volume, M^3/Kg	4.04	1.67
7.	Stored Volume, M^3	51.9 x 4.04 = 209.7	53.3 x 1.67 = 89.1
8.	Number of Standard Radiators	209.7/56.95 = 3.68	89.1/56.95 = 1.56
9.	Mass of 1 MW System, Kg	3.68 x 88.5 = 326.	1.57 x 114. = 179.

pressure of 209.KPa, which corresponds to a water saturation temperature of 121°C. Because of the change in specific vapor volume to 0.856m^3/Kg, the mass of a 1MW system would be cut approximately in half to 90Kg/1MW for 2.44m (8 ft.) diameter cylinders.

6. Comparisons of 10 meter and 2.44 meter diameter designs.

Before the system requirements had been completely established some cylinder designs with a 10 meter diameter had been considered. A comparison of Design #2, the roller-retracting cylinder, in that size with the 8' (2.44 meter) designs done later is shown in Table 4 below for a 75°C saturation temperature.

TABLE 4. COMPARING 10m AND 2.44m DIAMFTER RADIATORS
75°C

Roller-retracting Design #2, Diameter, M	Nominal 2.44	10.
	Actual 2.0	9.5
Length of geometrically similar design, M.	12.2	50.
Radiator Volume, M^3	37.5	3544.
Stored Vapor Volume per 1 MW system, M^3	209.5	209.5
Number of Radiators needed	209.5/37.5 = 5.6	209.5/3544 = 0.059
Mass of Radiator System as Designed, Kg	81.	1095.
Mass of Radiators Kg/1 MW	453.	64.7
NOTE: These tables are internally consistent; however, comparisons between tables may not be.		

The small diameter system uses 453 Kg/MW; while the large diameter system needs only 64.7 Kg/MW. L'Garde Design #8 gives an example of a larger diameter system initially contained in a 2.44 meter diameter package.

7. Effect of Cylinder Length.

Long cylinders are more efficient for volume holding than short ones because the mass associated with their base support, and fabric and liquid collection system is nearly independent of the cylinder length. Table 5 shows the comparison of a standard length radiator (12.2 meters long) with cylinders 2 and 3 times as long. Although the longer cylinders are more efficient, several problems with longer cylinders may occur:

TABLE 5. COMPARING RADIATORS OF 12.2, 24.4 AND 36.6M LENGTH

(2.44 Meter Nominal Diameter, 2 Meter Inner Diameter)

Cylinder Length, M	12.2	24.4	36.6
Length/Diameter Ratio	6.1	12.2	18.3
Contained Vapor Volume, M^3	37.5	75.9	115.0
Stored Vapor per 1 MW, M^3	209.5	209.5	209.5
Number of Radiators Needed	209.5/37.5 = 5.59	209.5/75.9 =2.76	209.5/115.= 1.82
Calculated Mass per Radiator, Kg (Length Independent)	58.1	58.1	58.1
Fabric Mass	13.7	27.4	41.1
Total Mass per Radiator	71.8	82.5	99.2
System Mass, Kg/1 Mw	5.59 x 71.8 = 401.	2.76 x 85.5 = 236.	1.82 x 99.2 = 180.

NOTE: These tables are internally consistent; however, comparisons between tables may not be.

- o If the radiator or/and heat source is rotating, it may be hard to control the position of the radiator. Will it have adequate stiffness to resist unwanted induced motion?

- o When the fabric is gathered in from a long cylinder, there will be more opportunity for adventitious wrinkles to be created and to grow into bumps and tangles.

- o Long cylinders may not stick out straight from the base. If they turn and twist, they may interfere with each other.

8. The various designs are compared in this section. They are --

DESIGN #	DESCRIPTION
2	Roller retracting cylinder, fixed wiper
4	Tapered rotating cylinder
5	Tapered rotating cylinder with liquid return channel
6	Cylinder with drum roll-up
8	Rotating sphere, stowed in cylinder
9	Roller retracting cylinder, sponge with squeeze bar

The following designs were considered, but are not compared here. They were judged infeasible for the reasons noted.

DESIGN #	DESCRIPTION/PROBLEM
1	Rotating sphere, stores flattened/small capacity
3	Cylinder with movable wiper/poor control of wiper
7	Sock-type cylinder/use of elastic fabric not feasible

The masses of the standard size (2.44m x 12.2m) cylinders of the five feasible designs are compared in Figure 1 below. This also shows the amount of mass devoted to the vapor (V), the hardware (H) and the fabric (F).

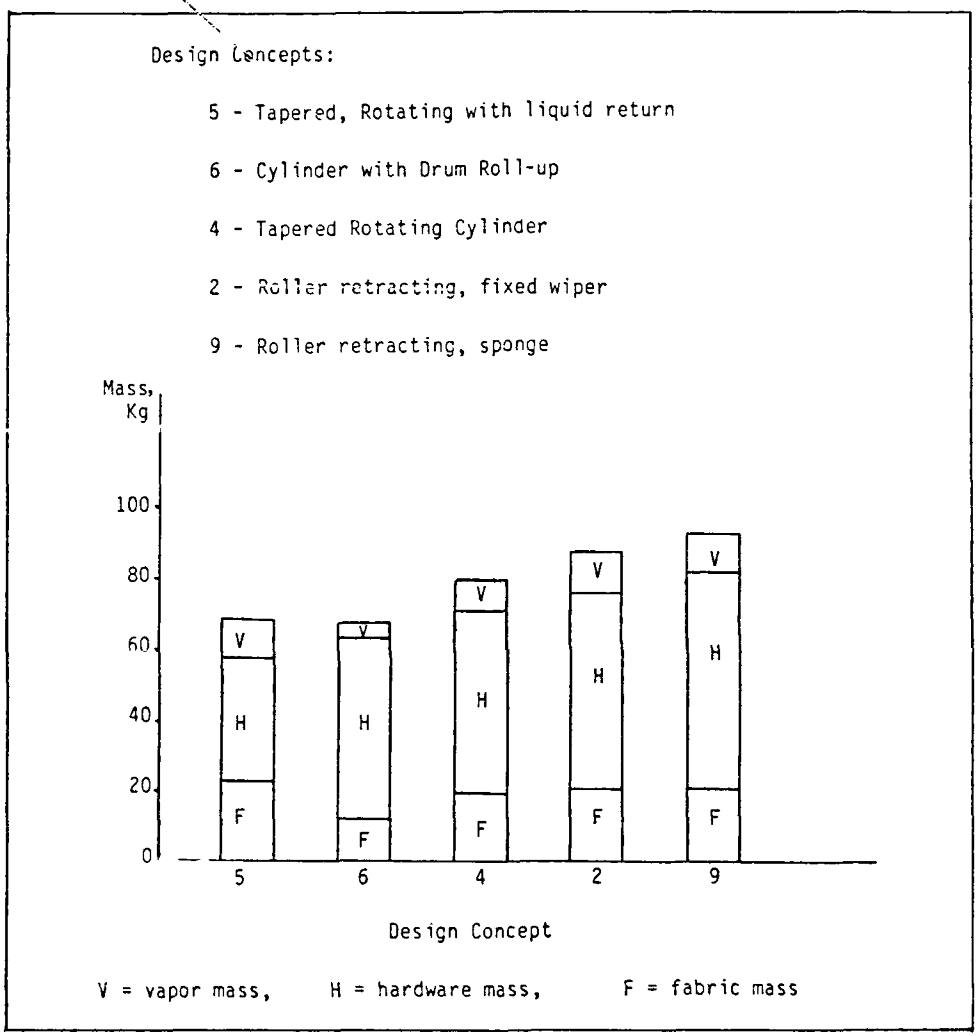


Figure 1. Mass Per Radiator (Standard Cylinders, 2.44m x 12.2m)

It is more meaningful to compare the design on the basis of 1 MW of heat absorption. Figure 2 below shows the total mass of radiator systems needed for 1 MW of heat with parameter of design concept and cylinder length. From a total mass viewpoint, design concept 8, the rotating sphere that retracts into a storage cylinder has the smallest mass for 1 MW power. Among the cylinders design concept 6, the drum roll-up cylinder, is least efficient because of the small cylinder diameter than can be rolled up on a take-up drum that will fit in the 2.44 m diameter circle for storage. The tapered rotating cylinder, design #4, becomes less efficient at 91.5 meter length because the far end tends to be a cone of small volumetric capacity.

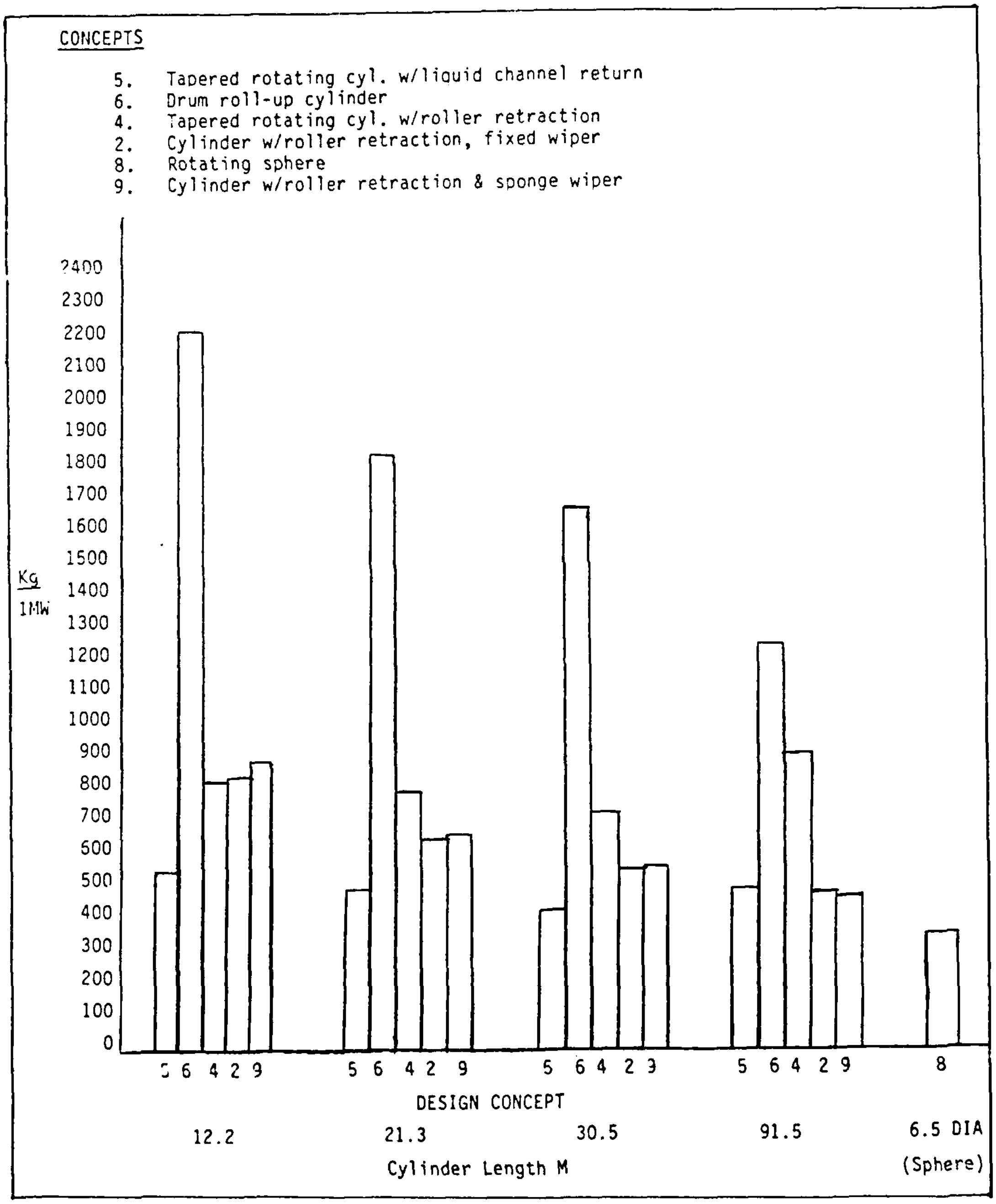


Figure 2. Total System Mass (Water) For 1 MW

Figure 3 illustrates the number of radiators per megawatt needed with the several design concepts. Apparently the number needed with ethylene glycol is so large as to eliminate this material from consideration as a working fluid.

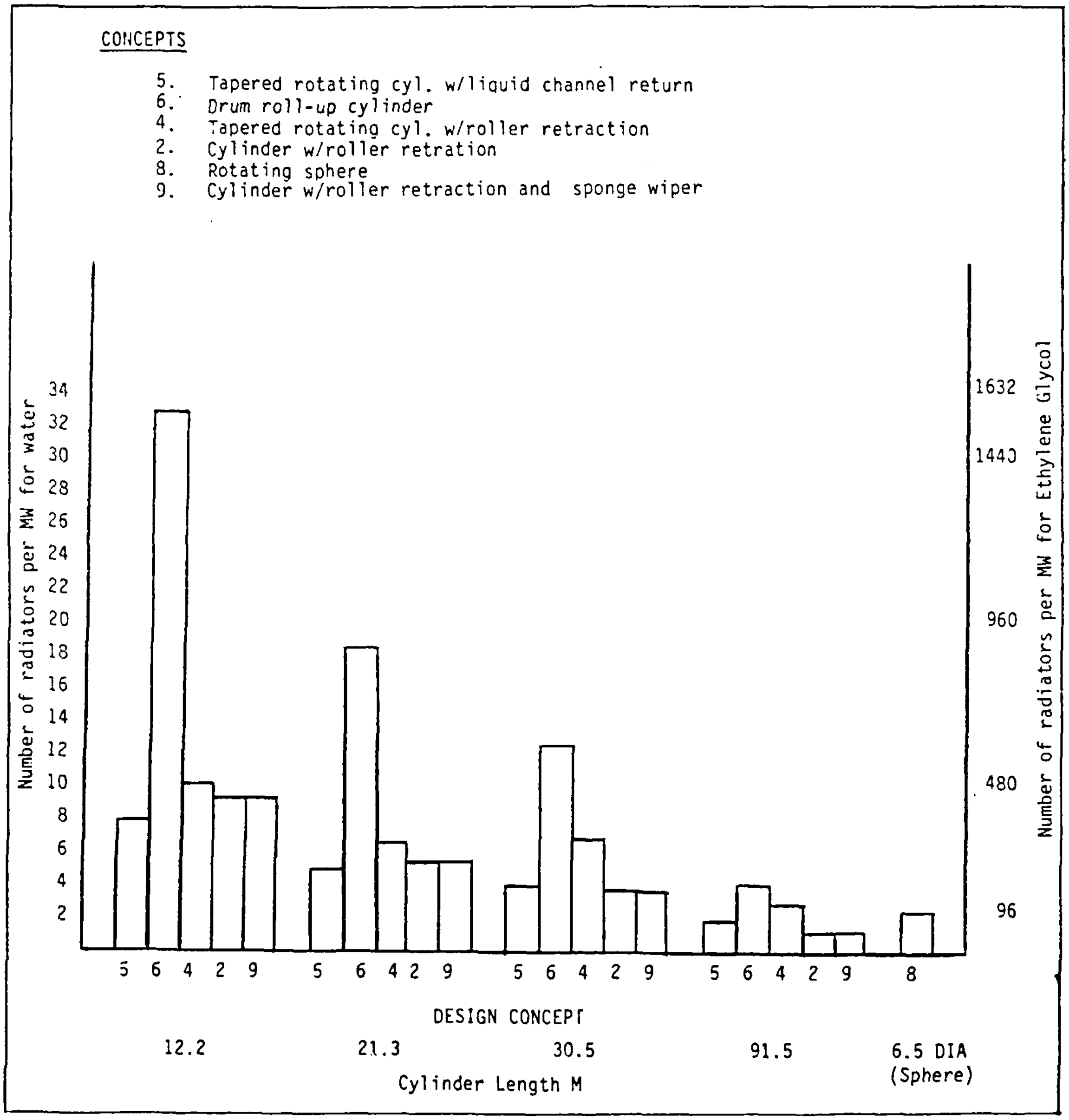


Figure 3. Total Number Units For 1 MW

E. Conceptual Designs

1. Rotating sphere - stored flattened.

This design is illustrated by Figure 4. This recovers water on a slightly larger circumference on the midpoint of its axis of rotation. It contracts by means of tethers pulled in by a central motor. A slip ring for an electrical interface is required, and a vapor tight mechanical seal is used.

A sphere of this type makes very inefficient use of the area of its base plate: thus a cylinder sticking out from the base plate could contain much more volume. For this reason the design was considered infeasible and a bill of materials is not presented. More efficient use of the spherical form is shown in design concept #8 in which the sphere expands out of an eight foot diameter cylinder attached to a base plate.

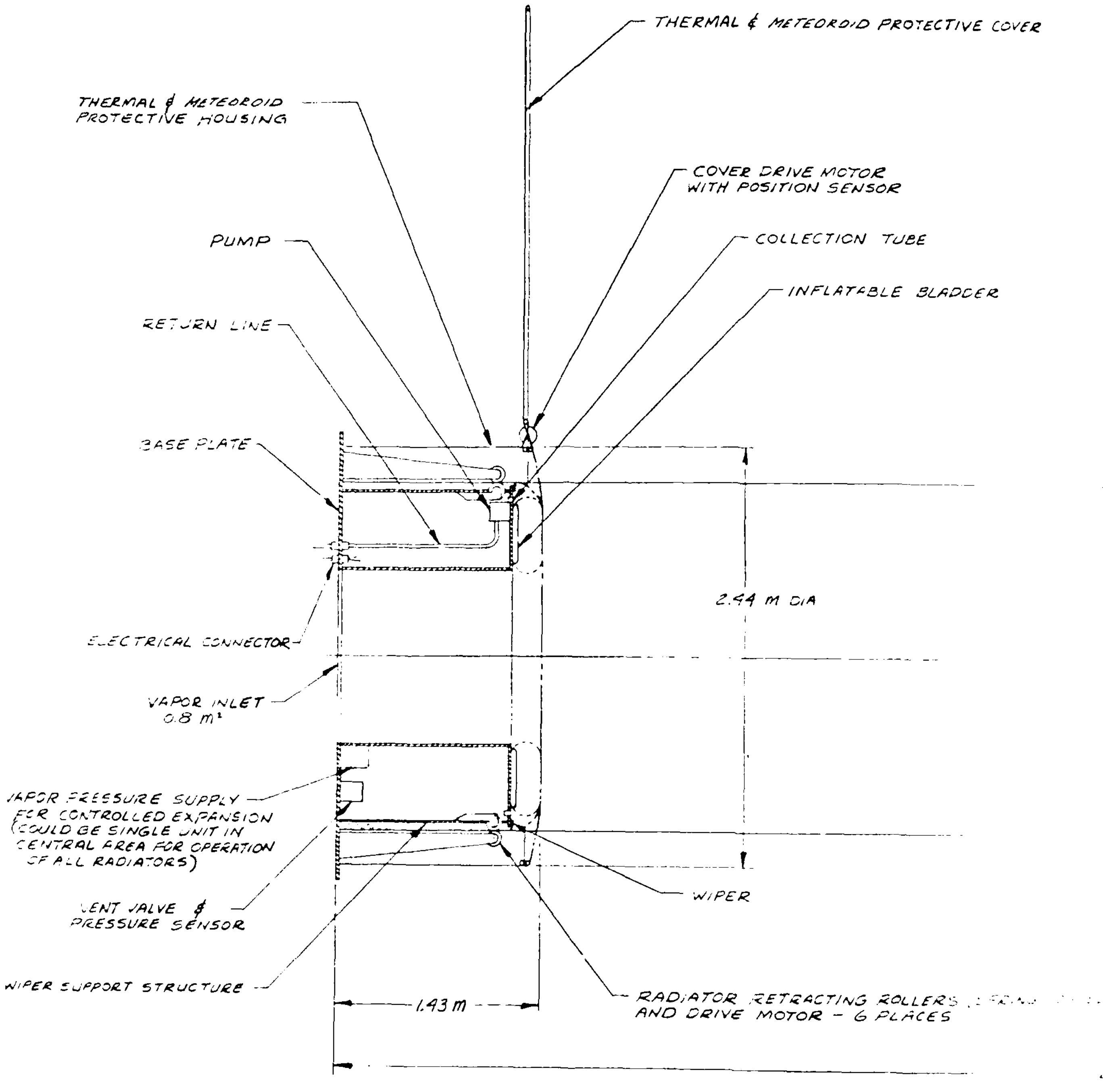
2. Roller - Retracting Cylinder - Fixed Wiper.

This has a circle of friction rollers (6 sets) which can feed the cylindrical radiator fabric out of its folded state at the base during inflation, and then draw it into storage during contraction. See Figure 5. These motorized rollers are spring loaded to press against the fabric and yet adjust to the space needed for folded fabric. As the fabric is rolled in, it is wiped by a fixed wiper to skim the condensed liquid toward the recovery pump inlets.

When the fabric has been drawn in to the maximum extent there is still a considerable volume of open space in which condensate may collect. To push this liquid toward the pump inlets inflatable bladders expand displacing the liquid to the collection system. An improved version of this system in which a sponge is used as a wiper was developed as design concept #9.

The disadvantage of the friction roller take-up is that the fabric may become wrinkled under the rollers. Excessive flexing and tight folding of Kevlar can reduce the fabric strength and destroy the bond between the fabric and coating. Experiments with a cylindrical fabric and roll will be needed to establish a workable system.

All of these designs operate with saturated vapor at 75°C, which has an equilibrium vapor pressure of 5.72 psia, for water. This allows the use of Kevlar 49 fabric Style 500 (Hi-Pro-Form Fabrics) which has a tensile strength of 560-600 pounds per lineal inch. For ethylene glycol, with a far lower vapor pressure, the lightest Kevlar available, Style 120 at 270 pounds strength per lineal inch, is adequate. For the Bill of Materials of there design, the coating mass on the Kevlar is not included since the weight of the coating has not been determined.



RADIATOR (K
BASE PLATE
THERMAL PROT
ROLLER & SUP
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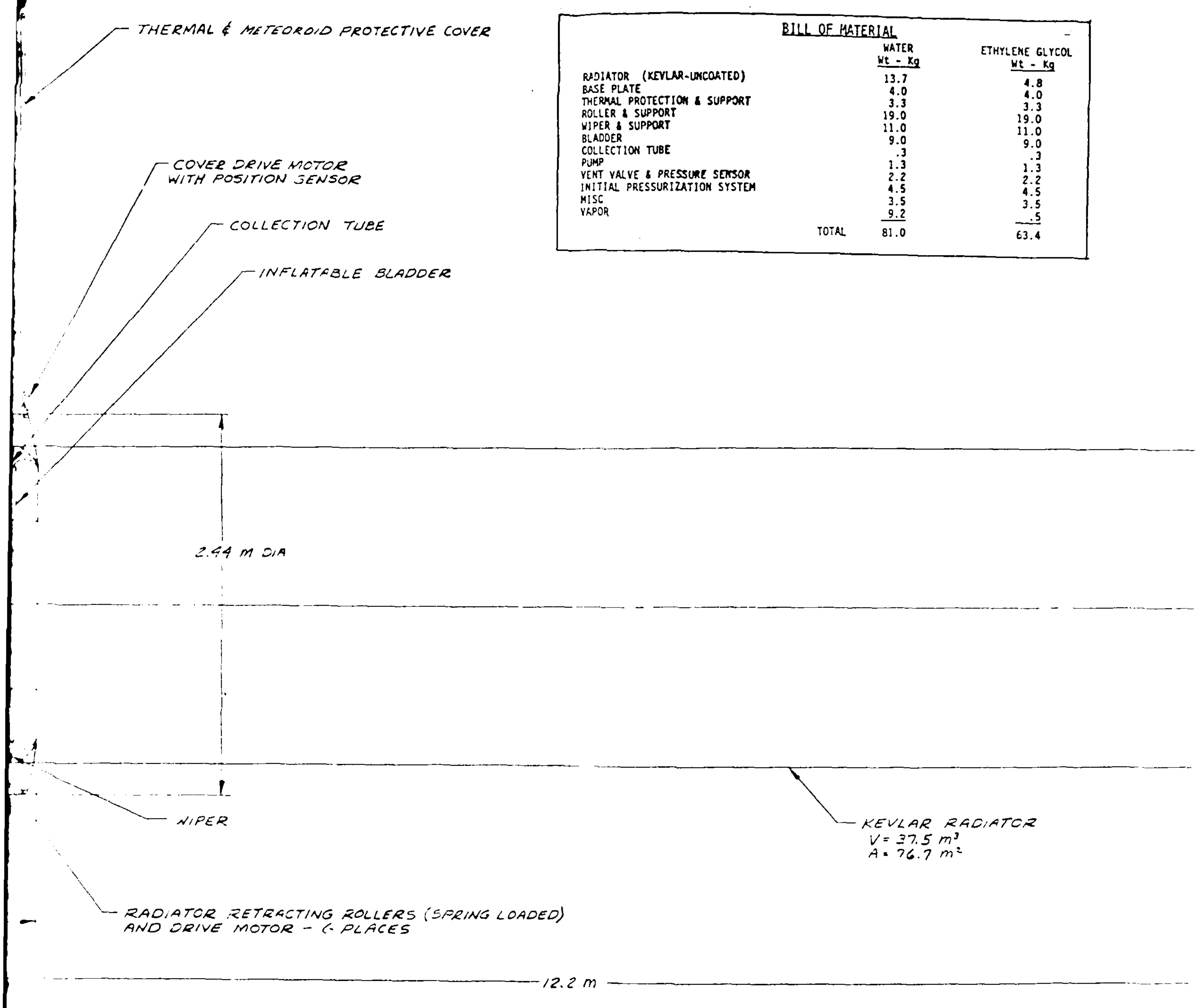

BILL OF MATERIAL

	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	13.7	4.8
BASE PLATE	4.0	4.0
THERMAL PROTECTION & SUPPORT	3.3	3.3
ROLLER & SUPPORT	19.0	19.0
WIPER & SUPPORT	11.0	11.0
BLADDER	9.0	9.0
COLLECTION TUBE	.3	.3
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
MISC	3.5	3.5
VAPOR	9.2	.5
TOTAL	81.0	63.4

QTY REQD	CODE IDENT	PART OR IDENTIFYING NO

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE:
FRACTIONS ± DECIMALS .XX ± .XXX ± ANGLES ±

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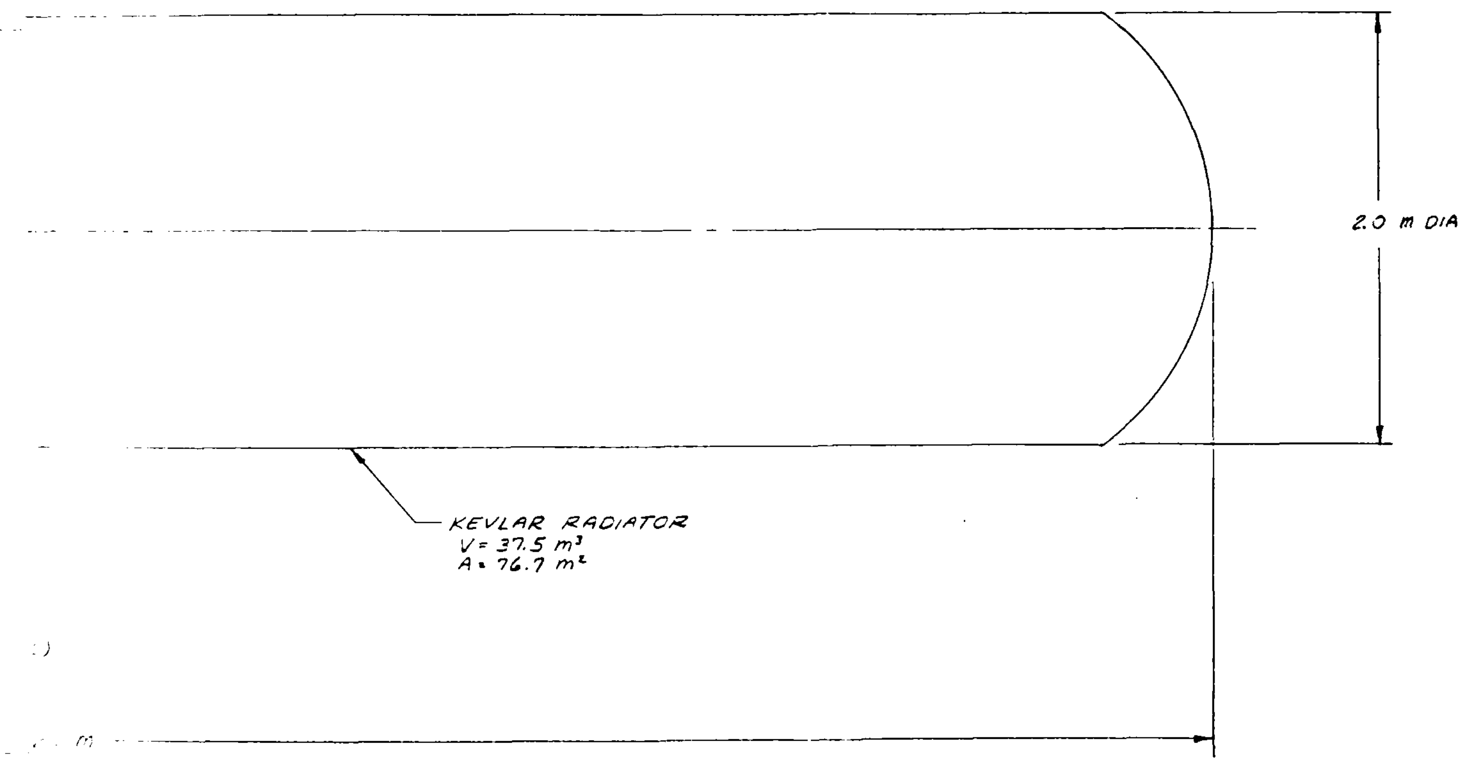
REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED

BILL OF MATERIAL

	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	13.7	4.8
BASE PLATE	4.0	4.0
THERMAL PROTECTION & SUPPORT	3.3	3.3
ROLLER & SUPPORT	19.0	19.0
WIPER & SUPPORT	11.0	11.0
BLADDER	9.0	9.0
COLLECTION TUBE	.3	.3
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
MISC	3.5	3.5
VAPOR	9.2	.5
TOTAL	81.0	63.4



QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION

PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE.
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MATERIAL

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EXPANDABLE RADIATOR, CYLINDER-ROLLER RETRACTING (2.44 m DIA)

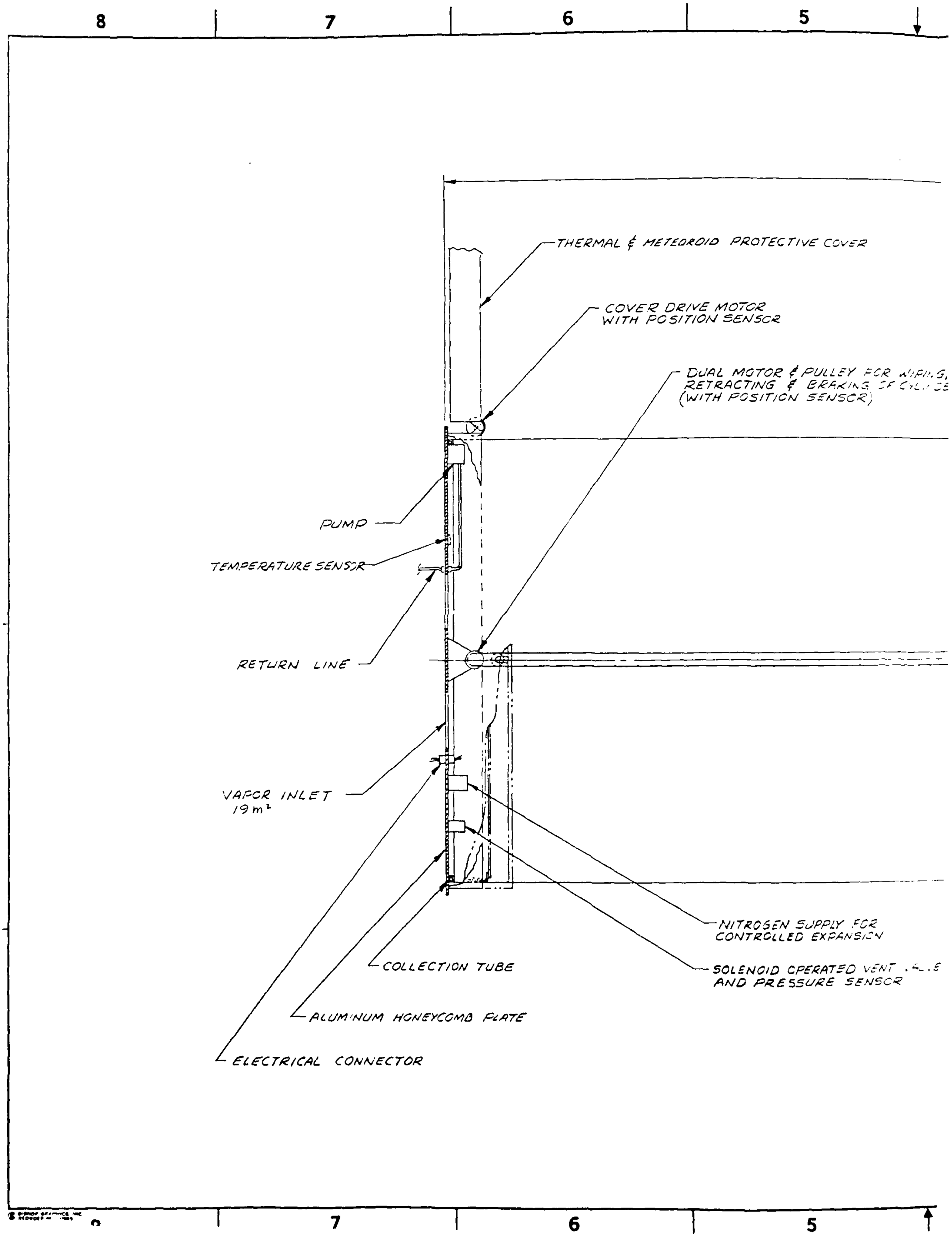
SIZE D | CODE IDENT NO | DRAWING NO. Figure 5. | 20

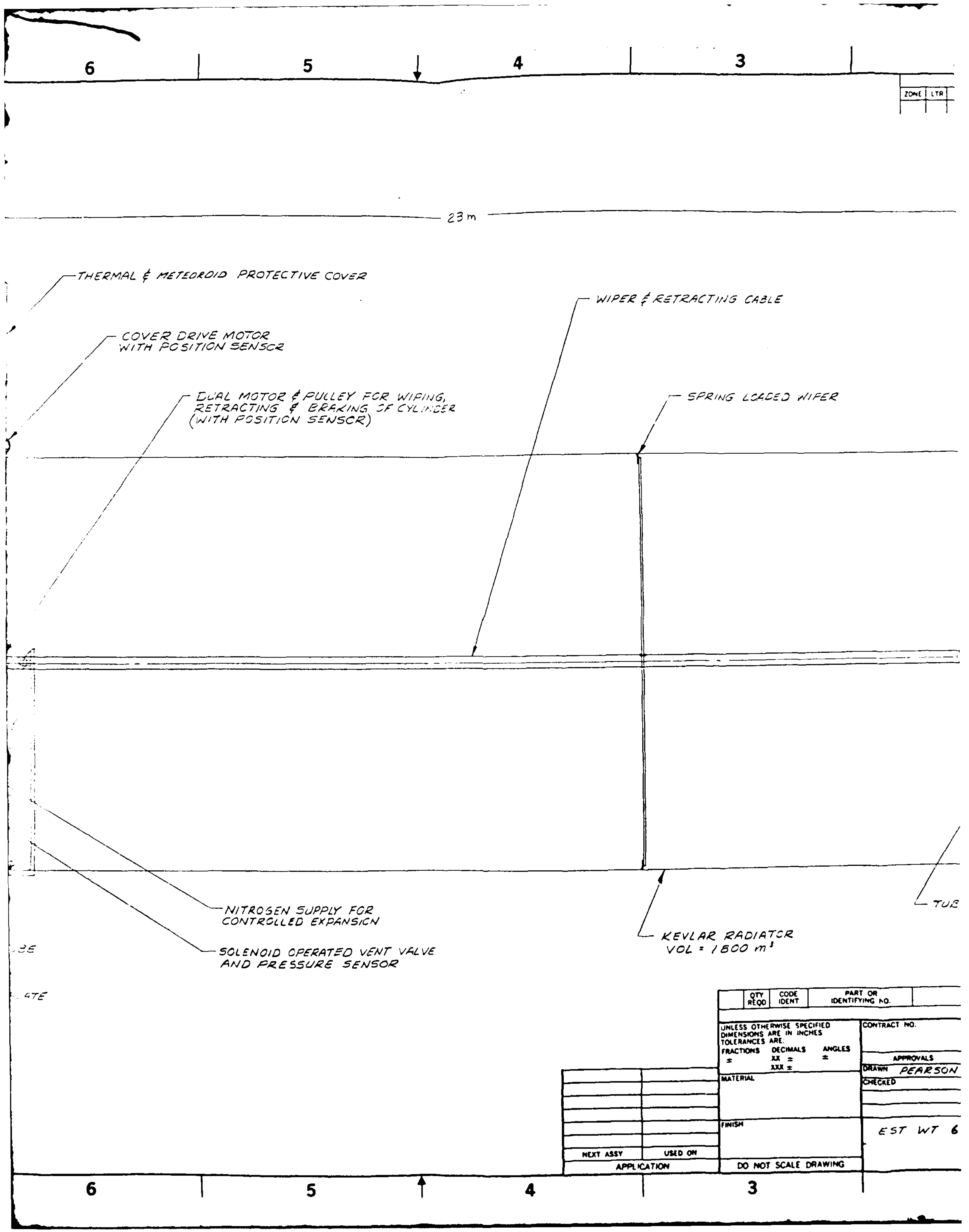
SCALE | SHEET | OF

3. Cylinder With Movable Wiper.

This early design is shown in Figure 6. It uses a diameter of 10 meters, as done initially. The movable wiper is intended to skim the water from the inner circumference of the cylinder. The wiper is moved along the cylinder by a tether, which is also used to moderate the initial expansion of the cylinder, and to retract it later; rollers are eliminated.

It was felt that it would not be possible to keep such a circular wiper in uniform contact with the fabric surface. It would tend to cant and skip areas of the cylinder. The fixed wiper near the base of the cylinder, as used in some other design concepts, was thought to be more practical and therefore work on this design was stopped.


8
7
6
5
THERMAL & METEOROID PROTECTIVE COVER
COVER DRIVE MOTOR
WITH POSITION SENSOR
DUAL MOTOR & PULLEY FOR WIPING,
RETRACTING & BRAKING
(WITH POSITION SENSOR)
PUMP
TEMPERATURE SENSOR
RETURN LINE
VAPOR INLET
19 m²
NITROGEN SUPPLY FOR
CONTROLLED EXPANSION
SOLENOID OPERATED VENT
AND PRESSURE SENSOR
COLLECTION TUBE
ALUMINUM HONEYCOMB PLATE
ELECTRICAL CONNECTOR
7
6
5



6
5
4
3
ZONE
LTR
23 m
THERMAL & METEOROID PROTECTIVE COVER
WIPER & RETRACTING CABLE
COVER DRIVE MOTOR WITH POSITION SENSOR
DUAL MOTOR & PULLEY FOR WIPING, RETRACTING & BRAKING OF CYLINDER (WITH POSITION SENSOR)
SPRING LOADED WIPER
NITROGEN SUPPLY FOR CONTROLLED EXPANSION
SOLENOID OPERATED VENT VALVE AND PRESSURE SENSOR
KEVLAR RADIATOR VOL = 1800 m³
QTY REQD
CODE IDENT
PART OR IDENTIFYING NO.
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE:
FRACTIONS ±
DECIMALS .XX ± .XXX ±
ANGLES ±
CONTRACT NO.
APPROVALS
DRAWN PEARSON
CHECKED
MATERIAL
FINISH
EST WT 6
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING

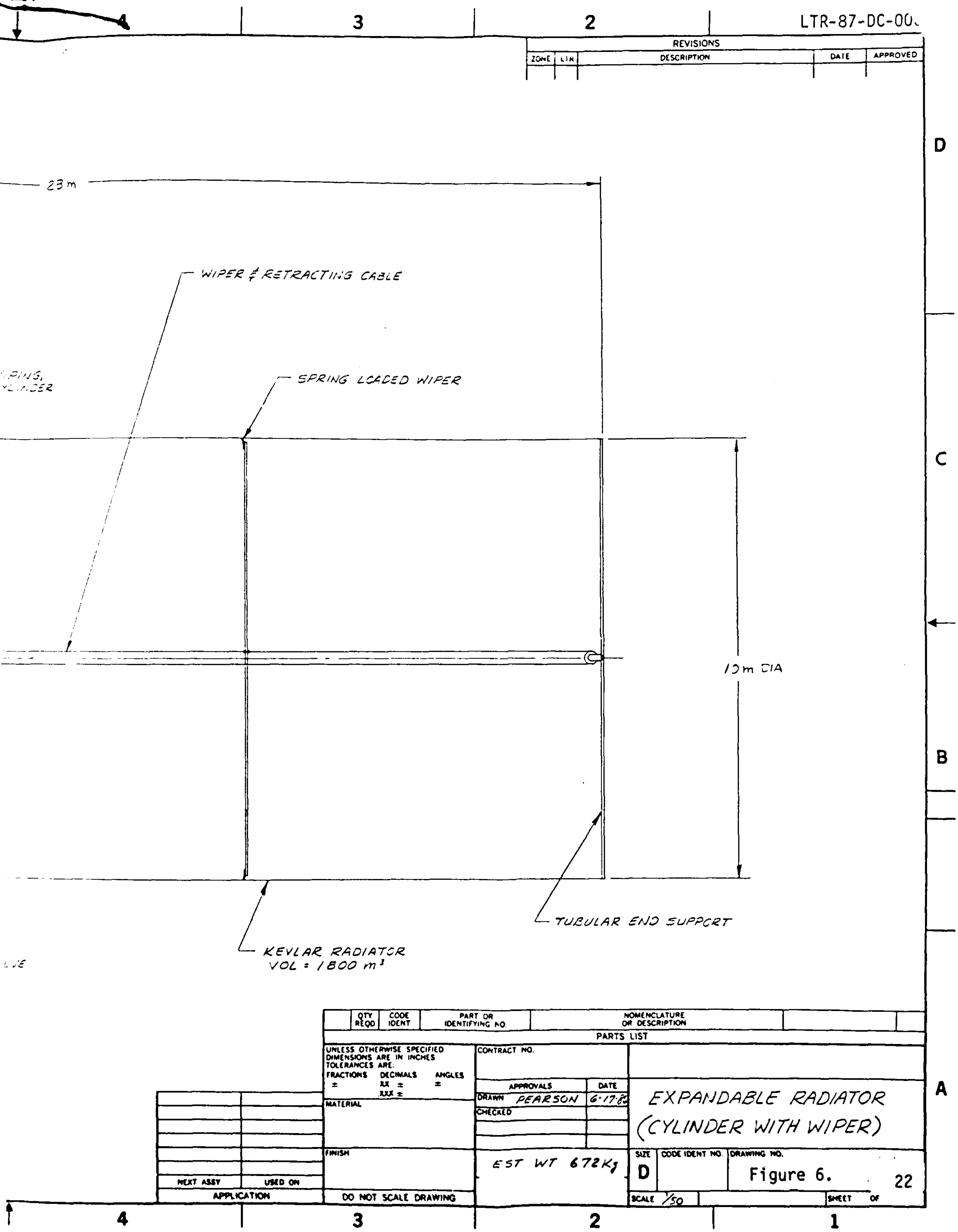

REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
23 m
WIPER & RETRACTING CABLE
SPRING LOADED WIPER
10 m DIA
TUBULAR END SUPPORT
KEVLAR RADIATOR
VOL = 1800 m³
QTY REQD
CODE IDENT
PART OR IDENTIFYING NO.
NOMENCLATURE OR DESCRIPTION
PARTS LIST
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE:
FRACTIONS
DECIMALS
ANGLES
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
CONTRACT NO.
APPROVALS
DATE
DRAWN PEARSON
CHECKED
EST WT 672 Kg
EXPANDABLE RADIATOR
(CYLINDER WITH WIPER)
SIZE D
CODE IDENT NO.
DRAWING NO.
SCALE 1/50
SHEET
OF

Figure 6.

4. Tapered Rotating Cylinder. See Figure 7.

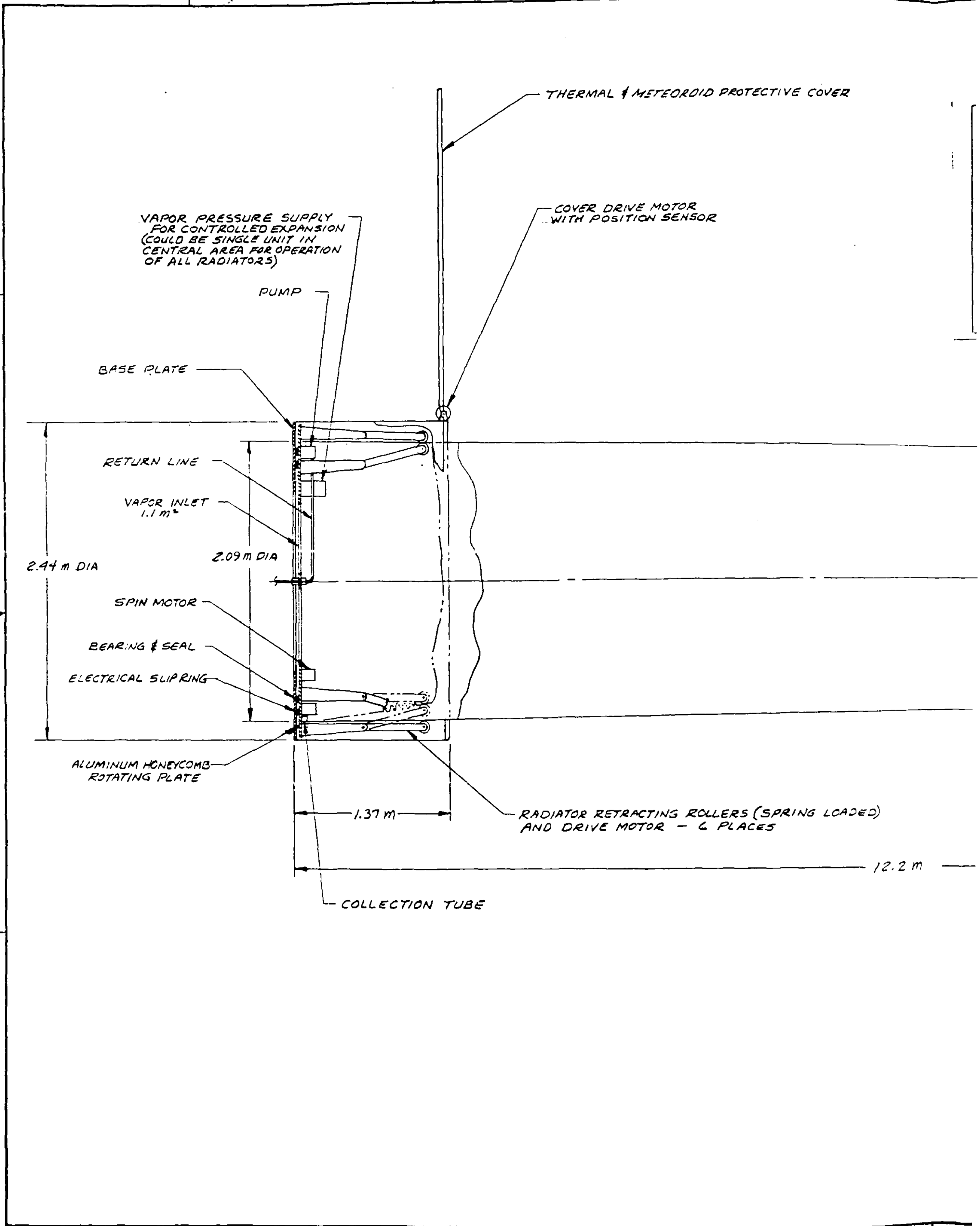
The concept uses spring loaded motorized rollers to retract the radiator and to brake its motion on expansion. It rotates so that the liquid is forced to the slightly larger base circumference, where it enters the pump inlets.

The taper used was 0.75^{0} for designs 30 meters long or less, but was decreased to 0.50^{0} for designs beyond this length, as the radiator otherwise approaches a cone, and the outer part has little volume for vapor.

There are problems associated with this or any rotating system:

1. Large diameter rotating vapor seals and electrical contacts must be used.

2. The cylinder may not have adequate stiffness to prevent sideways motion or coning.



THERMAL & METEOROID PROTECTIVE COVER
COVER DRIVE MOTOR WITH POSITION SENSOR
VAPOR PRESSURE SUPPLY FOR CONTROLLED EXPANSION (COULD BE SINGLE UNIT IN CENTRAL AREA FOR OPERATION OF ALL RADIATORS)
PUMP
BASE PLATE
RETURN LINE
VAPOR INLET 1.1 m²
2.44 m DIA
2.09 m DIA
SPIN MOTOR
BEARING & SEAL
ELECTRICAL SLIP RING
ALUMINUM HONEYCOMB ROTATING PLATE
1.37 m
RADIATOR RETRACTING ROLLERS (SPRING LOADED) AND DRIVE MOTOR – 6 PLACES
12.2 m
COLLECTION TUBE

6 5 4 3

DWG. NO.

ZONE REV

THERMAL & METEOROID PROTECTIVE COVER

COVER DRIVE MOTOR
WITH POSITION SENSOR

BILL OF MATERIAL

	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	13.5	4.7
BASE PLATE	3.2	3.2
ROTATING PLATE	4.0	4.0
ELECTRICAL SLIP RING	1.9	1.9
BEARING	5.9	5.9
THERMAL PROTECTION & SUPPORT	4.0	4.0
COLLECTION TUBE	.3	.3
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
ROLLER & SUPPORT	21.0	21.0
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
SPIN MOTOR	.9	.9
MISC	3.1	3.1
VAPOR	8.6	.5
TOTAL	74.4	57.5

KEVLAR RADIATOR
$V = 35.0\ m^3$
$A = 75.0\ m^2$
TAPER 0.75°

RADIATOR RETRACTING ROLLERS (SPRING LOADED)
AND DRIVE MOTOR – 6 PLACES

12.2 m

QTY REQD	FSCM NO.	PART OR IDENTIFYING NO.	

PARTS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ARE:
FRACTIONS DECIMALS ANGLES
± .XX ± ±
.XXX ±

CONTRACT NO.

APPROVALS	DATE
DRAWN PEARSON	7-11-86
CHECKED	
ISSUED	

MATERIAL

FINISH

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APPLICATION	

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6 5 4 3 2

LTR-87-DC-006

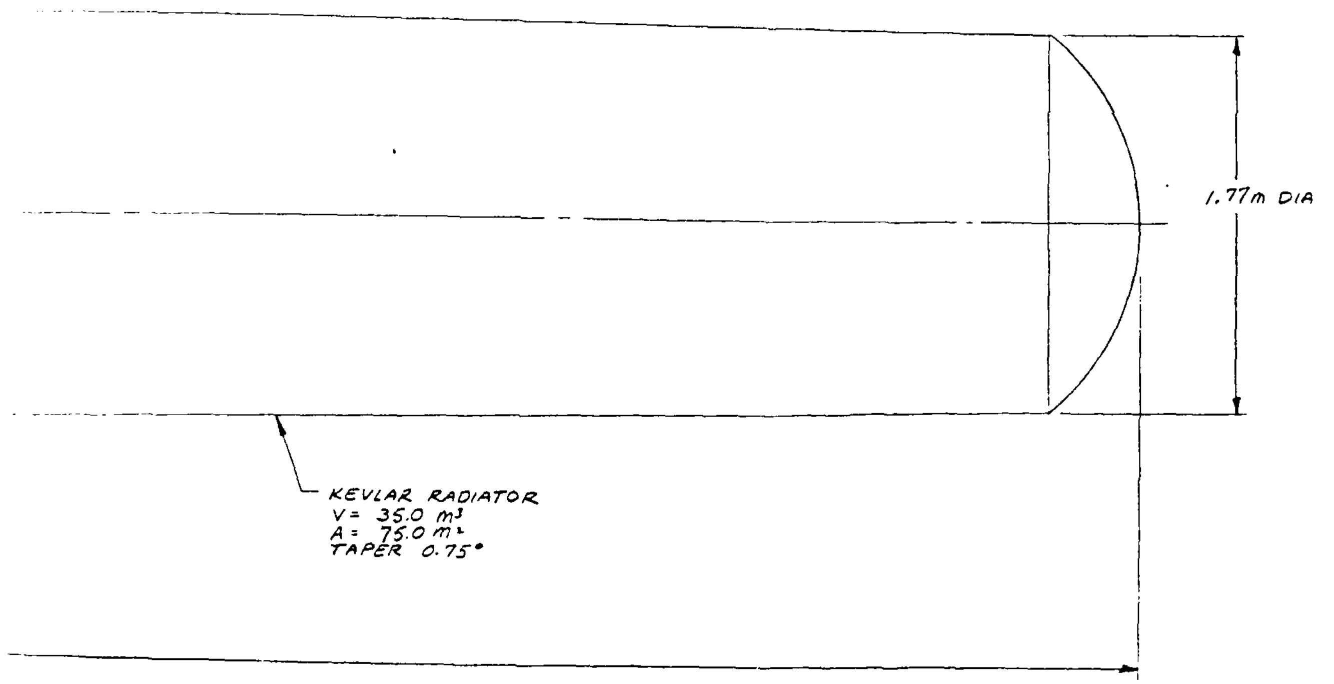
DWG. NO. | SH | REV.

REVISIONS

ZONE	REV.	DESCRIPTION	DATE	APPROVED

BILL OF MATERIAL

	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	13.5	4.7
BASE PLATE	3.2	3.2
ROTATING PLATE	4.0	4.0
ELECTRICAL SLIP RING	1.9	1.9
BEARING	5.9	5.9
THERMAL PROTECTION & SUPPORT	4.0	4.0
COLLECTION TUBE	.3	.3
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
ROLLER & SUPPORT	21.0	21.0
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
SPIN MOTOR	.9	.9
MISC	3.1	3.1
VAPOR	8.6	.5
TOTAL	74.4	57.5



QTY REQD	FSCM NO.	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION

PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE: FRACTIONS ± DECIMALS .XX ± .XXX ± ANGLES ±

CONTRACT NO.

APPROVALS | DATE

DRAWN PEARSON | 7-11-86

CHECKED

ISSUED

FINISH

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

EXPANDABLE RADIATOR, TAPERED ROTATING CYLINDER W/ ROLLER RETRACTION (2.44 m DIA)

SIZE D | FSCM NO. | DWG. NO. | REV.

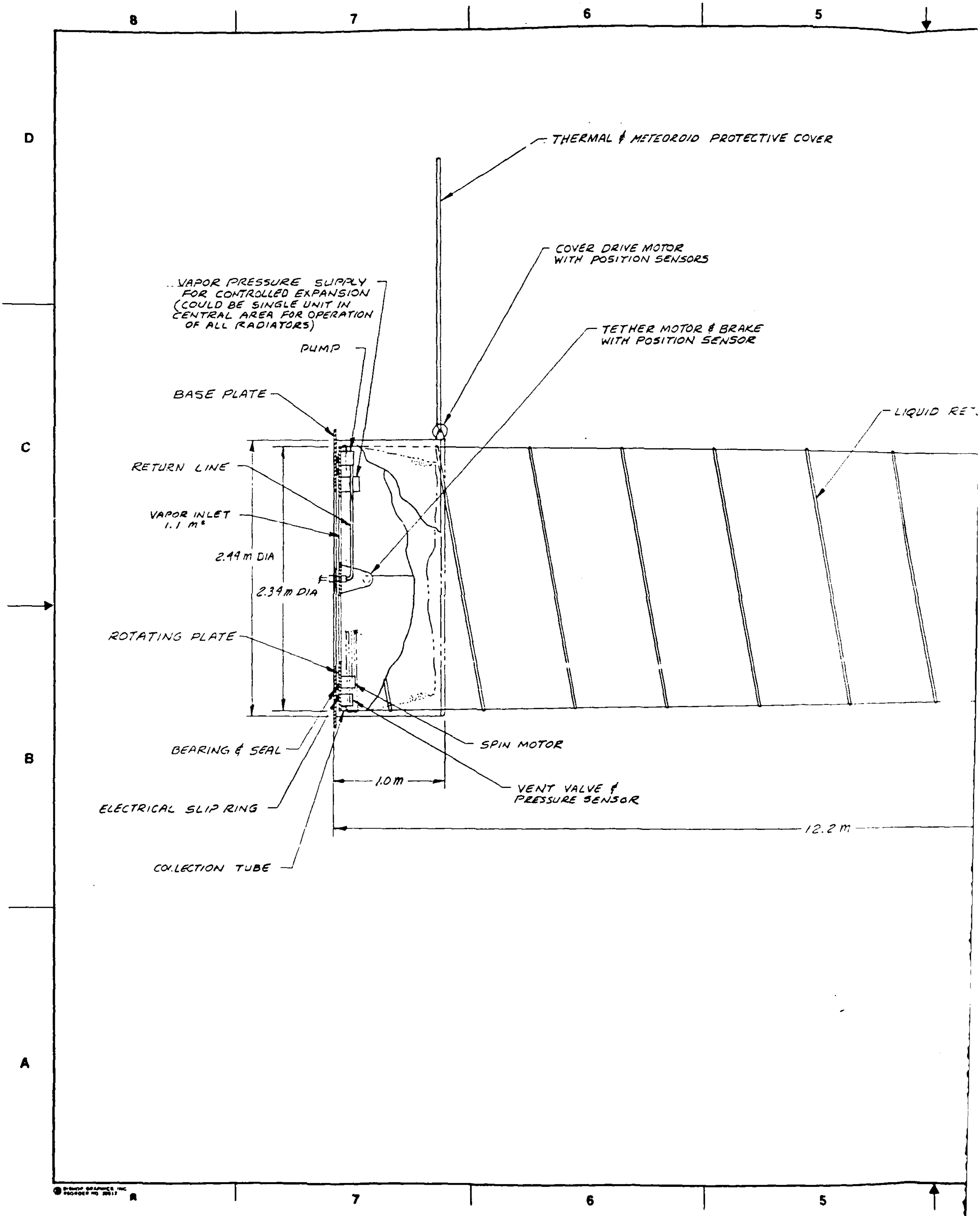
SCALE | SHEET

Figure 7.

5. Tapered Rotating Cylinder With Liquid Return Channel.

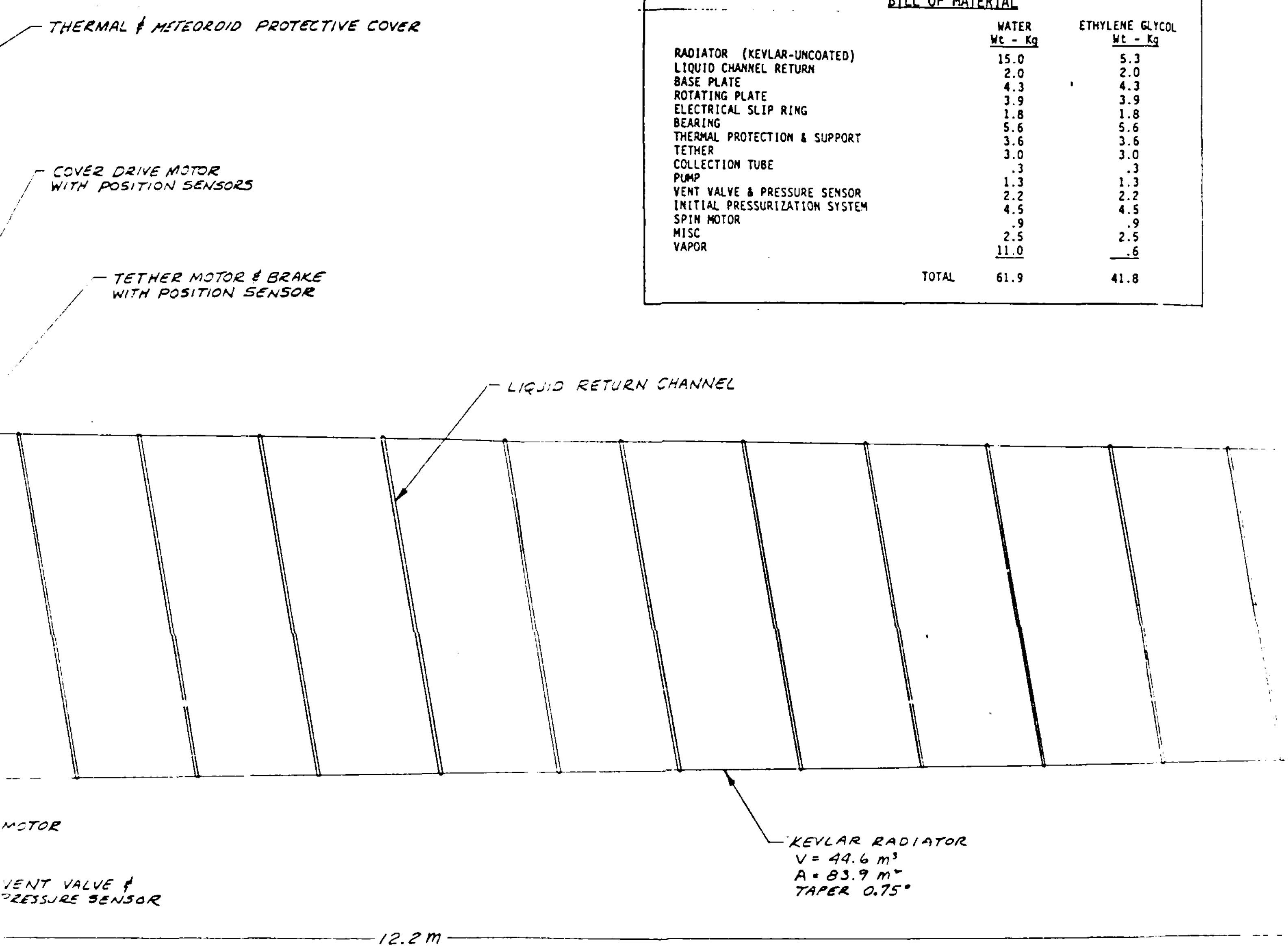
As shown in Figure 8, this is similar in shape to design concept #4. However, a liquid return channel forms a spiral on the outside of the tapered cylinder. As the cylinder rotates liquid would pass through holes in the fabric into the larger circumference of the return line. This channel can also be used to control the folding of the fabric, since the diameters of the spiral channel will be fixed. Because of the stability imparted by the channel, it is felt that the contraction can be done with a tether line with adequate control.

The channel should also give the extra stiffness needed to resist waggling of the cylinder in rotation; however, a dynamic analysis is needed to evaluate this.


8
7
6
5
D
C
B
A
THERMAL & METEOROID PROTECTIVE COVER
COVER DRIVE MOTOR WITH POSITION SENSORS
VAPOR PRESSURE SUPPLY FOR CONTROLLED EXPANSION (COULD BE SINGLE UNIT IN CENTRAL AREA FOR OPERATION OF ALL RADIATORS)
TETHER MOTOR & BRAKE WITH POSITION SENSOR
PUMP
BASE PLATE
LIQUID RE
RETURN LINE
VAPOR INLET 1.1 m²
2.44 m DIA
2.34 m DIA
ROTATING PLATE
SPIN MOTOR
BEARING & SEAL
1.0 m
VENT VALVE & PRESSURE SENSOR
ELECTRICAL SLIP RING
12.2 m
COLLECTION TUBE

DWG NO

ZONE | REV



BILL OF MATERIAL

	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	15.0	5.3
LIQUID CHANNEL RETURN	2.0	2.0
BASE PLATE	4.3	4.3
ROTATING PLATE	3.9	3.9
ELECTRICAL SLIP RING	1.8	1.8
BEARING	5.6	5.6
THERMAL PROTECTION & SUPPORT	3.6	3.6
TETHER	3.0	3.0
COLLECTION TUBE	.3	.3
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
SPIN MOTOR	.9	.9
MISC	2.5	2.5
VAPOR	11.0	.6
TOTAL	61.9	41.8

QTY REQD	FSCM NO.	PART OR IDENTIFYING NO

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE: FRACTIONS ± DECIMALS .XX ± .XXX ± ANGLES ±

CONTRACT NO

APPROVALS	DATE
DRAWN PEARSON	7-10-
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FINISH

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

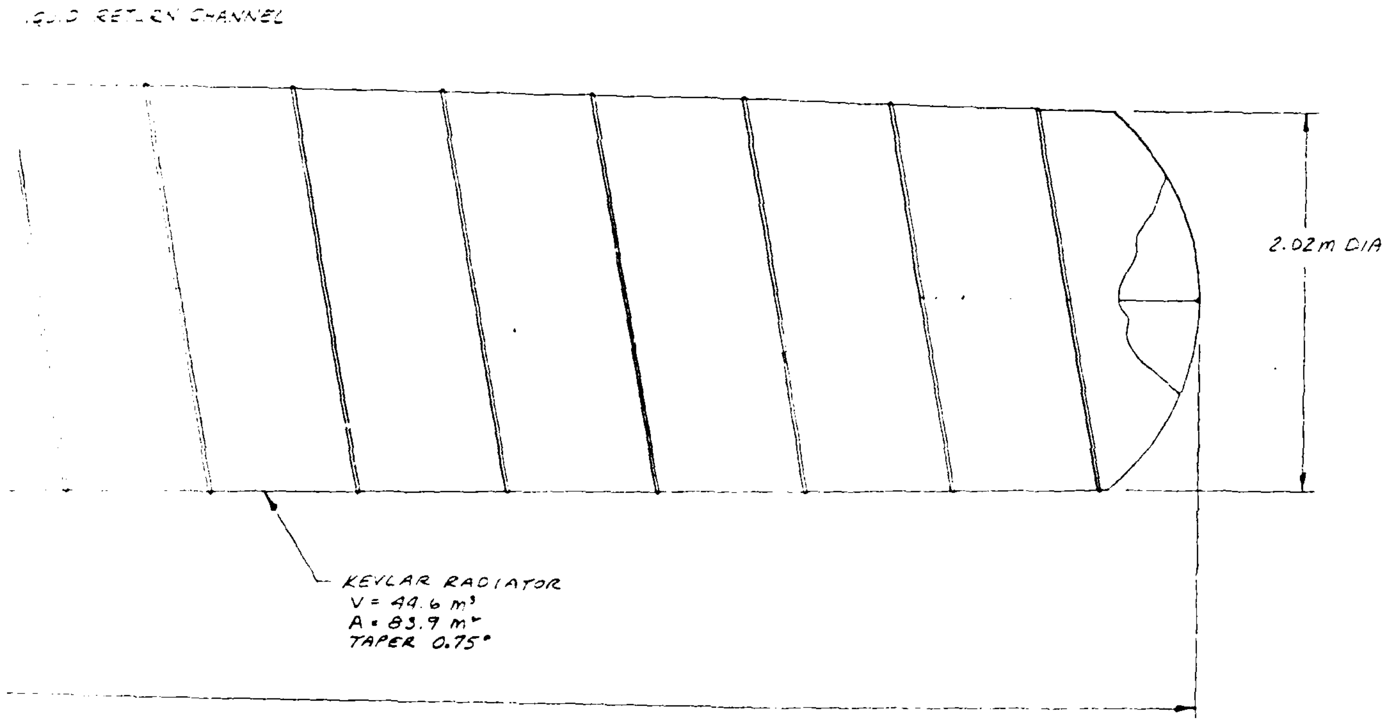
DWG. NO | SH | REV

REVISIONS

ZONE	REV	DESCRIPTION	DATE	APPROVED

BILL OF MATERIAL

	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	15.0	5.3
LIQUID CHANNEL RETURN	2.0	2.0
BASE PLATE	4.3	4.3
ROTATING PLATE	3.9	3.9
ELECTRICAL SLIP RING	1.8	1.8
BEARING	5.6	5.6
THERMAL PROTECTION & SUPPORT	3.6	3.6
TETHER	3.0	3.0
COLLECTION TUBE	.3	.3
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
SPIN MOTOR	.9	.9
MISC	2.5	2.5
VAPOR	11.0	.6
TOTAL	61.9	41.8



QTY REQD	FSCM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION

PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE
FRACTIONS DECIMALS ANGLES
.XX ±
.XXX ±

[redacted]

FINISH

CONTRACT NO

APPROVALS	DATE
DRAWN PEARSON	7-10-86
CHECKED	
ISSUED	

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

EXPANDABLE RADIATOR, TAPERED ROTATING CYLINDER W/LIQUID CHANNEL RETURN (2.44 m DIA)

SIZE D | FSCM NO. | DWG. NO. | REV

Figure 8.

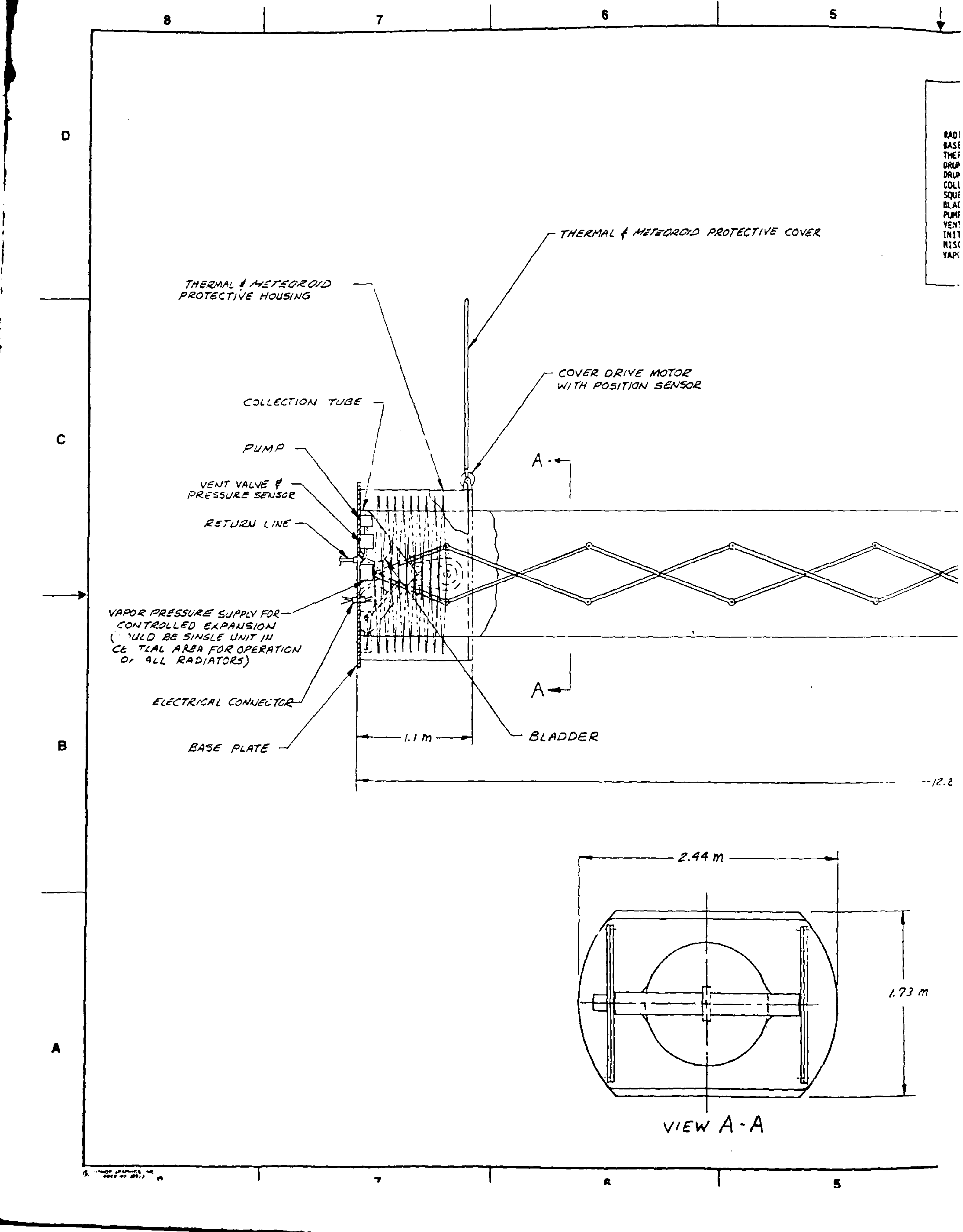
SCALE | SHEET

6. Cylinder With Drum Roll-Up.

Figure 9 illustrates this design concept which is a vapor holding cylinder with a motorized drum at the extended end, supported by a scissor linkage mounted to the base plate. As the pressure increases in the cylinder during expansion, the fabric is supplied by unrolling from the drum; this also serves as a brake to prevent too rapid expansion. When the cylinder retraction is called for, the drum rolls up the radiator fabric. Wringer rolls squeeze the water ahead toward the base of the radiator.

As shown in the Figure, the main drawback of this unit is that the radiator fabric must flatten from a cylinder causing the rolled up width to be more than 1.5 times the cylinder diameter, and the scissor linkage is outside of this. For a fixed stowed diameter, the cylinder diameter is less than one half as large -- creating a very low volume container while the weight is very high because of the linkage required.

If we abandon the concept of storing the radiator in an 8 foot circle (to fit in the shuttle bay), but allow it to have an oblong shape to be placed crossways in the shuttle bay, then the volume contained by the drum roll-up design could be increased from 11 m^3 to 45 m^3 for a 12.2 m length system. The system mass has not been estimated for this alternative.


THERMAL & METEOROID PROTECTIVE COVER
THERMAL & METEOROID PROTECTIVE HOUSING
COVER DRIVE MOTOR WITH POSITION SENSOR
COLLECTION TUBE
PUMP
VENT VALVE & PRESSURE SENSOR
RETURN LINE
VAPOR PRESSURE SUPPLY FOR CONTROLLED EXPANSION
ELECTRICAL CONNECTOR
BASE PLATE
BLADDER
A
A
1.1 m
2.44 m
1.73 m
VIEW A-A

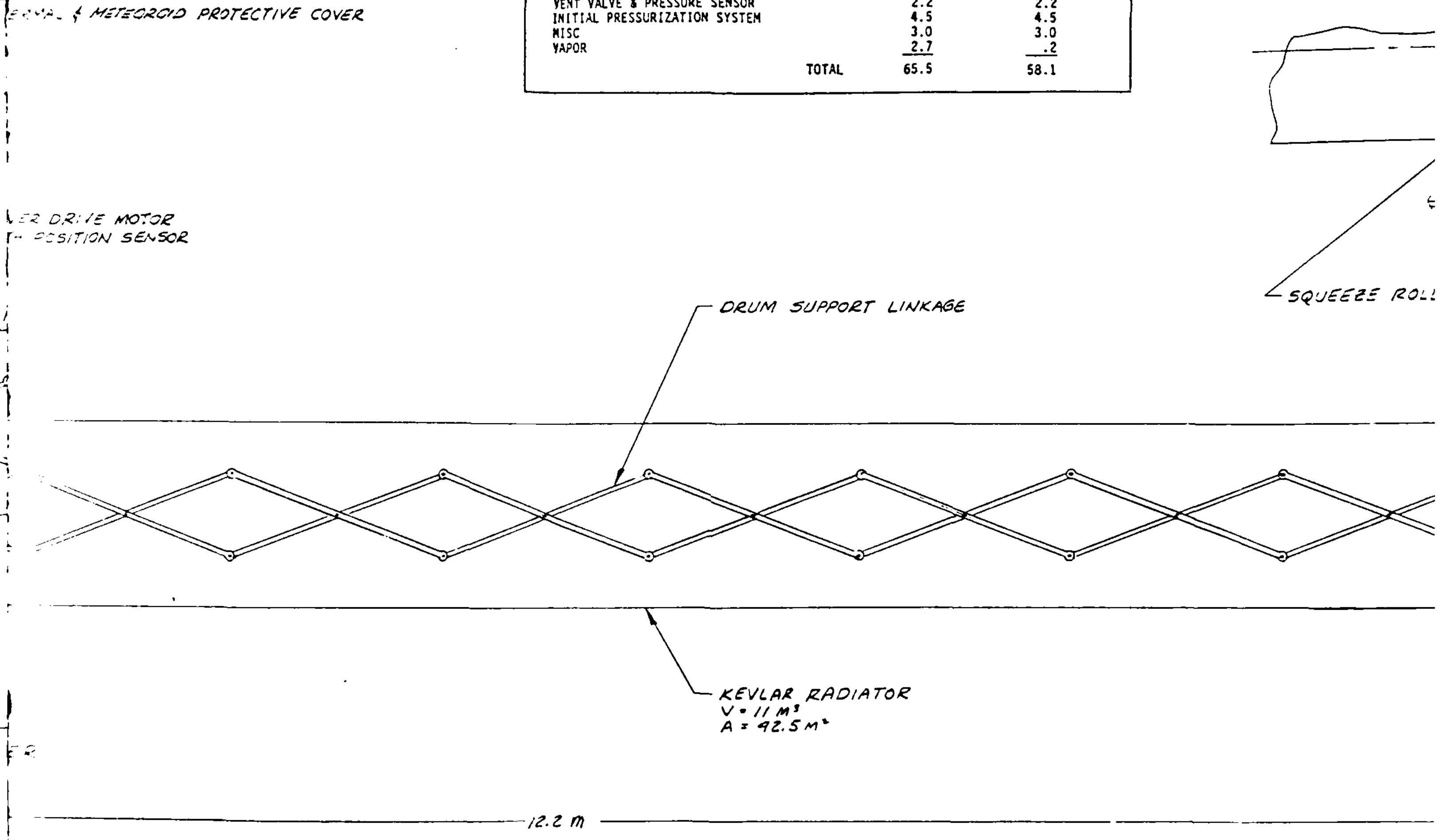
6	5	4	3

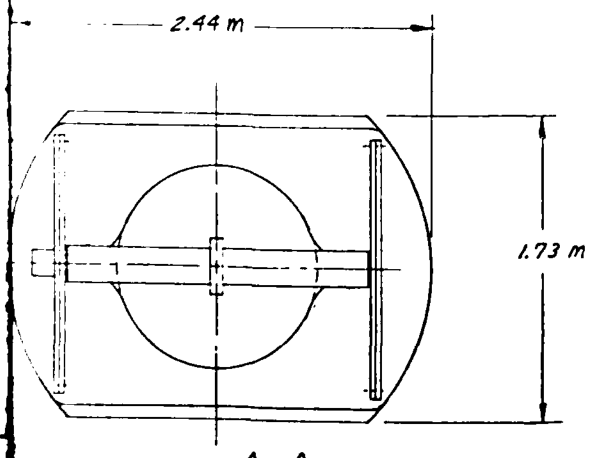
DWG. NO.

ZONE | REV.

BILL OF MATERIAL

	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	7.6	2.7
BASE PLATE	3.7	3.7
THERMAL PROTECTION & SUPPORT	3.6	3.6
DRUM SUPPORT LINKAGE & HARDWARE	23.6	23.6
DRUM & MOTOR	9.3	9.3
COLLECTION TUBE	.2	.2
SQUEEZE ROLLERS & HARDWARE	2.6	2.6
BLADDER	1.2	1.2
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
MISC	3.0	3.0
VAPOR	2.7	.2
TOTAL	65.5	58.1





VIEW A-A

QTY REQD	FSCM NO.	PART OR IDENTIFYING NO.	

PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ARE:
FRACTIONS ± DECIMALS .XX ± .XXX ± ANGLES ±

MATERIAL

FINISH

CONTRACT NO.

APPROVALS	DATE
DRAWN PEARSON	7-24-86
CHECKED	
ISSUED	

NEXT ASSY | USED ON

APPLICATION

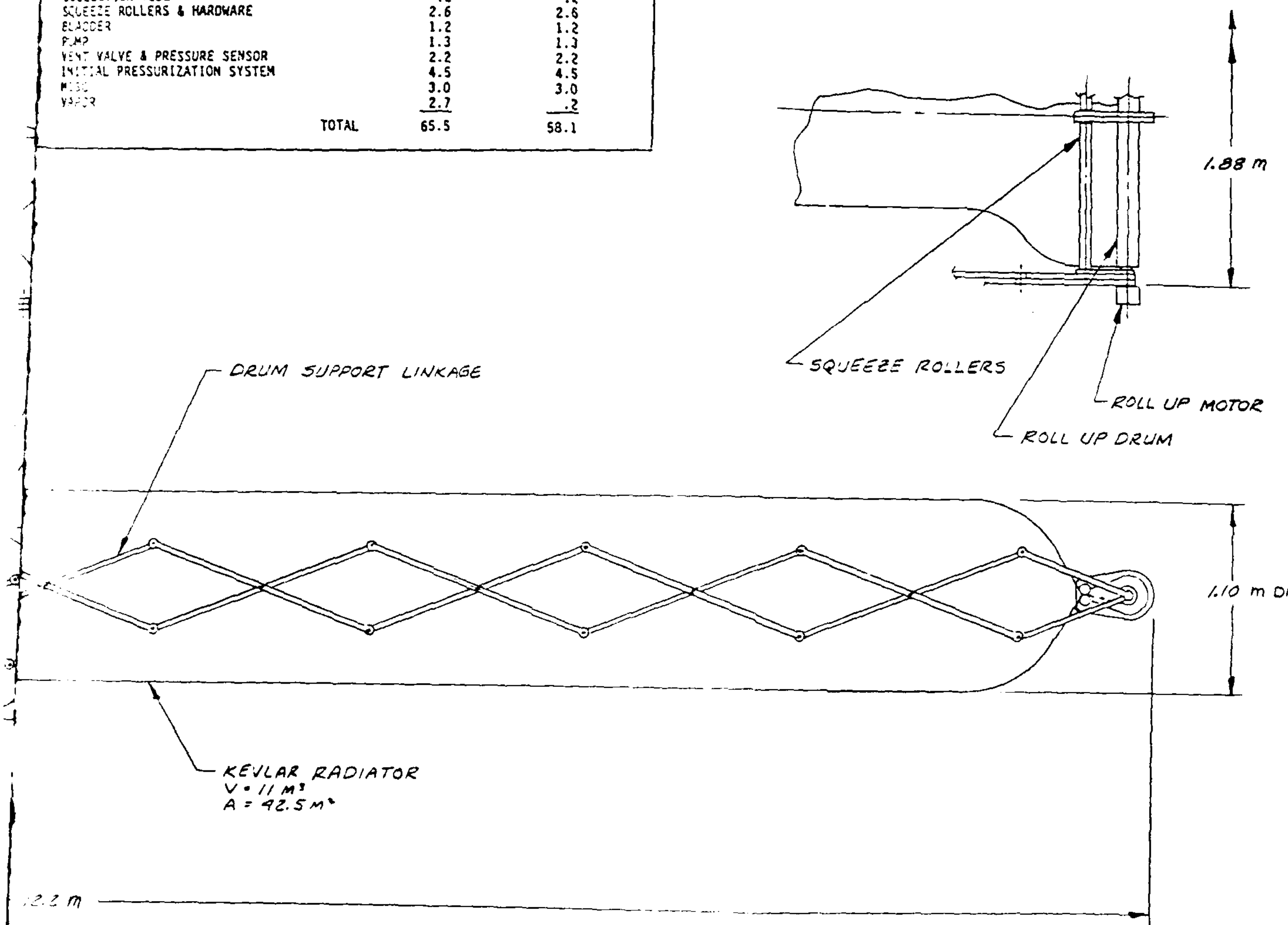
DO NOT SCALE DRAWING

SIZE D

6	5	4	3

BILL OF MATERIAL

	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	7.6	2.7
BASE PLATE	3.7	3.7
THERMAL PROTECTION & SUPPORT	3.6	3.6
DRUM SUPPORT LINKAGE & HARDWARE	23.6	23.6
DRUM & MOTOR	9.3	9.3
COLLECTION TUBE	.2	.2
SQUEEZE ROLLERS & HARDWARE	2.6	2.6
BLADDER	1.2	1.2
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
MISC	3.0	3.0
VAPOR	2.7	.2
TOTAL	65.5	58.1



DRAWN	PEARSON	7-24-86

EXPANDABLE RADIATOR, DRUM ROLL UP (1.10 m DIA)

Figure 9.

DO NOT SCALE DRAWING

7. Sock-Type Cylinder.

This concept would require a tangential elasticity in the fabric since the diameter of the donut formed in rolling up a sock increases with rolled up length. The strong Kevlar fabric however has very little elasticity - perhaps 3-6% at break. Therefore it was determined that this contraction design was not compatible with the high strength needed for this application. No design work was done.

8. Rotating Sphere - Stowed in Cylinder.

As illustrated in Figure 10, this is a sphere-cylinder combination. In storage the cylindrical part is stored in folds near the base plate, and the sphere is stored inside a solid cylindrical structure 2.44 m x 12.0 m. Because the large volume sphere is supported away from the region of the baseplate, the volume that can be contained by this system is much larger than with design concept #1. The cylinder volume also contributes to the volumetric capacity of the radiator.

Motorized tethers are used to collapse the system. The internal beam construction will allow this to be done in a controlled way. The stiffness of this structure should also resist waggling during rotation.

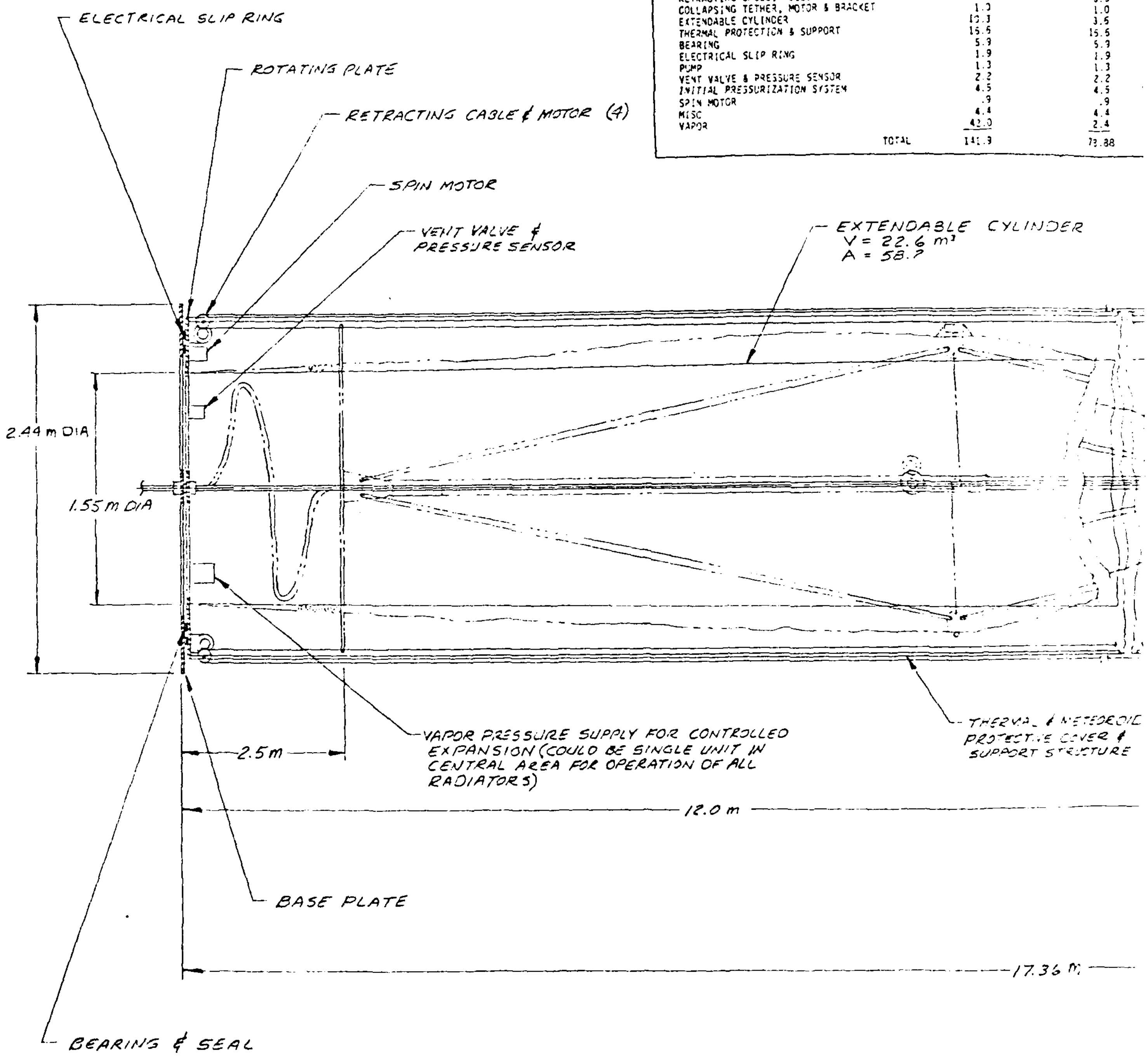
As with other rotating designs, a centrifugal force pulls the liquid to the largest circumference at the equator of the sphere. The cylinder is designed to be tapered larger toward its junction with the sphere so that its condensate can also be collected.

The expandable cylinder will not be as effective as a radiator since it is shielded by the cylinder support structure, however since it will cool less the resulting higher vapor pressure will force material into the sphere to be condensed.

Rotating vapor seals and electric slip rings remain a problem as with any rotating system.

BILL OF MATERIAL

	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	25.8	9.1
TELESCOPING BEAM	2.1	2.1
COLLAPSING BEAM	2.7	2.7
FITTINGS	4.6	4.6
COLLECTION TUBE	1.5	1.5
RETURN TUBE	1.2	1.2
SUPPORT PLATE	3.3	3.3
ROTATING PLATE	3.4	3.4
BASE PLATE	2.7	2.7
RETRACTING CABLE, PULLEY & MOTOR	3.5	3.5
COLLAPSING TETHER, MOTOR & BRACKET	1.0	1.0
EXTENDABLE CYLINDER	10.3	3.5
THERMAL PROTECTION & SUPPORT	15.5	15.5
BEARING	5.9	5.9
ELECTRICAL SLIP RING	1.9	1.9
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
SPIN MOTOR	.9	.9
MISC	4.4	4.4
VAPOR	42.0	2.4
TOTAL	141.9	73.88



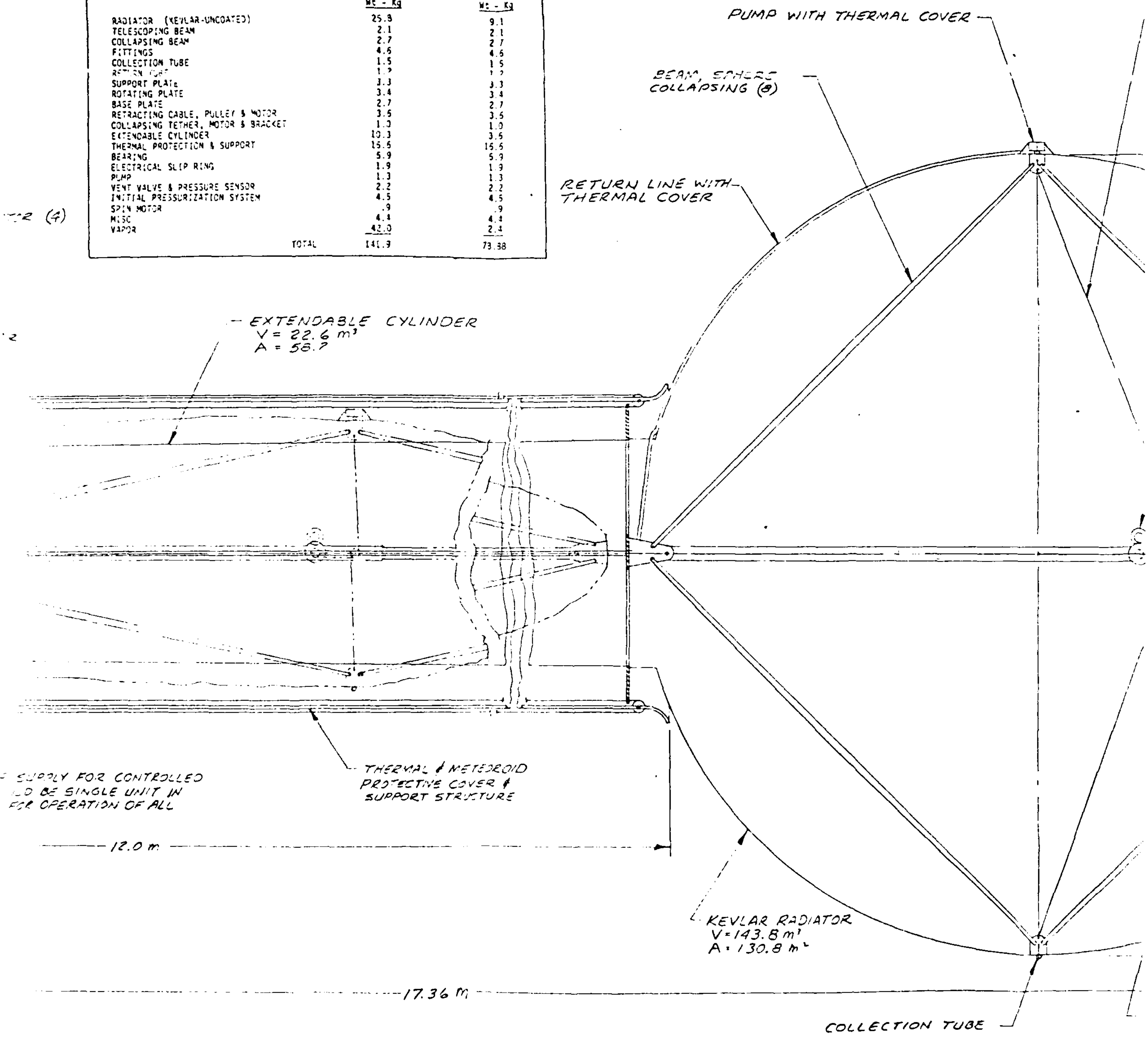
6 | 5 | 4 | 3

DWG NO

ZONE | REV

BILL OF MATERIAL

	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	25.8	9.1
TELESCOPING BEAM	2.1	2.1
COLLAPSING BEAM	2.7	2.7
FITTINGS	4.6	4.6
COLLECTION TUBE	1.5	1.5
RETURN TUBE	1.2	1.2
SUPPORT PLATE	3.3	3.3
ROTATING PLATE	3.4	3.4
BASE PLATE	2.7	2.7
RETRACTING CABLE, PULLEY & MOTOR	3.6	3.6
COLLAPSING TETHER, MOTOR & BRACKET	1.0	1.0
EXTENDABLE CYLINDER	10.3	3.6
THERMAL PROTECTION & SUPPORT	15.6	15.6
BEARING	5.9	5.9
ELECTRICAL SLIP RING	1.9	1.9
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
SPIN MOTOR	.9	.9
MISC	4.4	4.4
VAPOR	42.0	2.4
TOTAL	141.9	73.38



QTY REQD | FSCM NO | PART OR IDENTIFYING NO

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE FRACTIONS DECIMALS ANGLES .XX: .XXX:

CONTRACT NO

MATERIAL

APPROVALS | DATE

DRAWN PEARSON 7-2.

CHECKED

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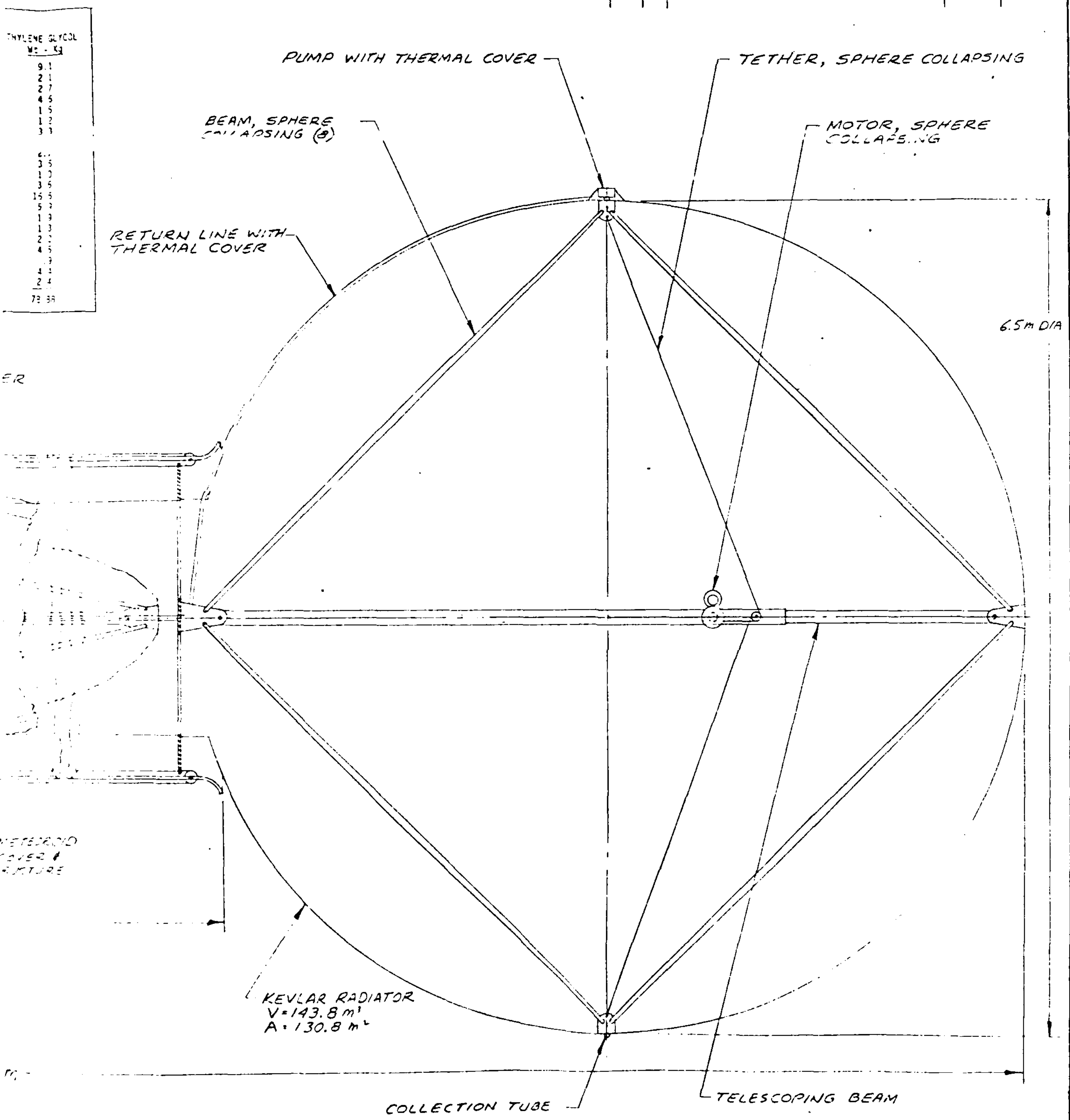
ISSUED

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING



PARTS LIST

EXPANDABLE RADIATOR, ROTATING SPHERE (STOWED IN 2.44 m DIA)

DRAWN PEARSON 7-23-84

SIZE D

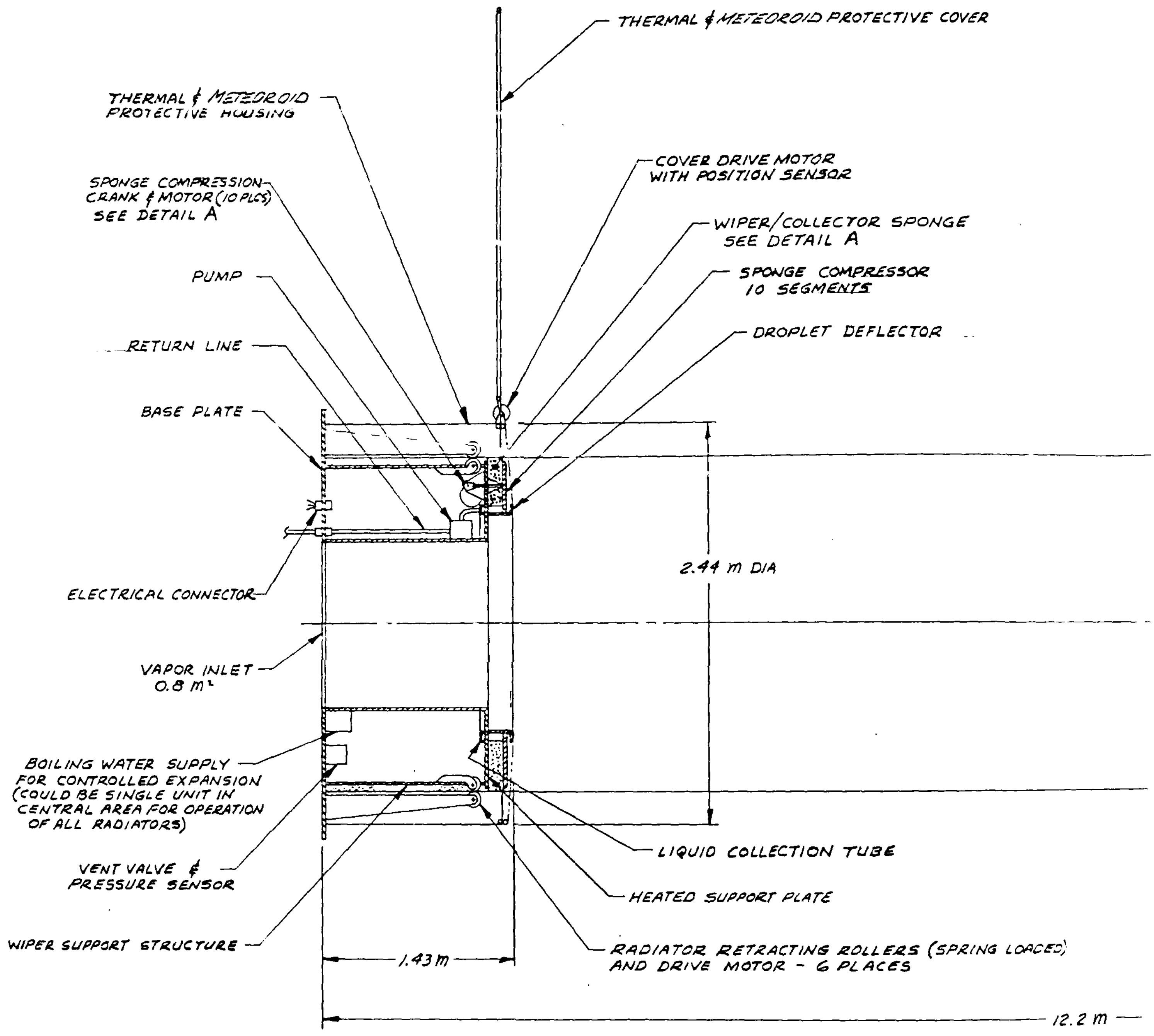
DO NOT SCALE DRAWING

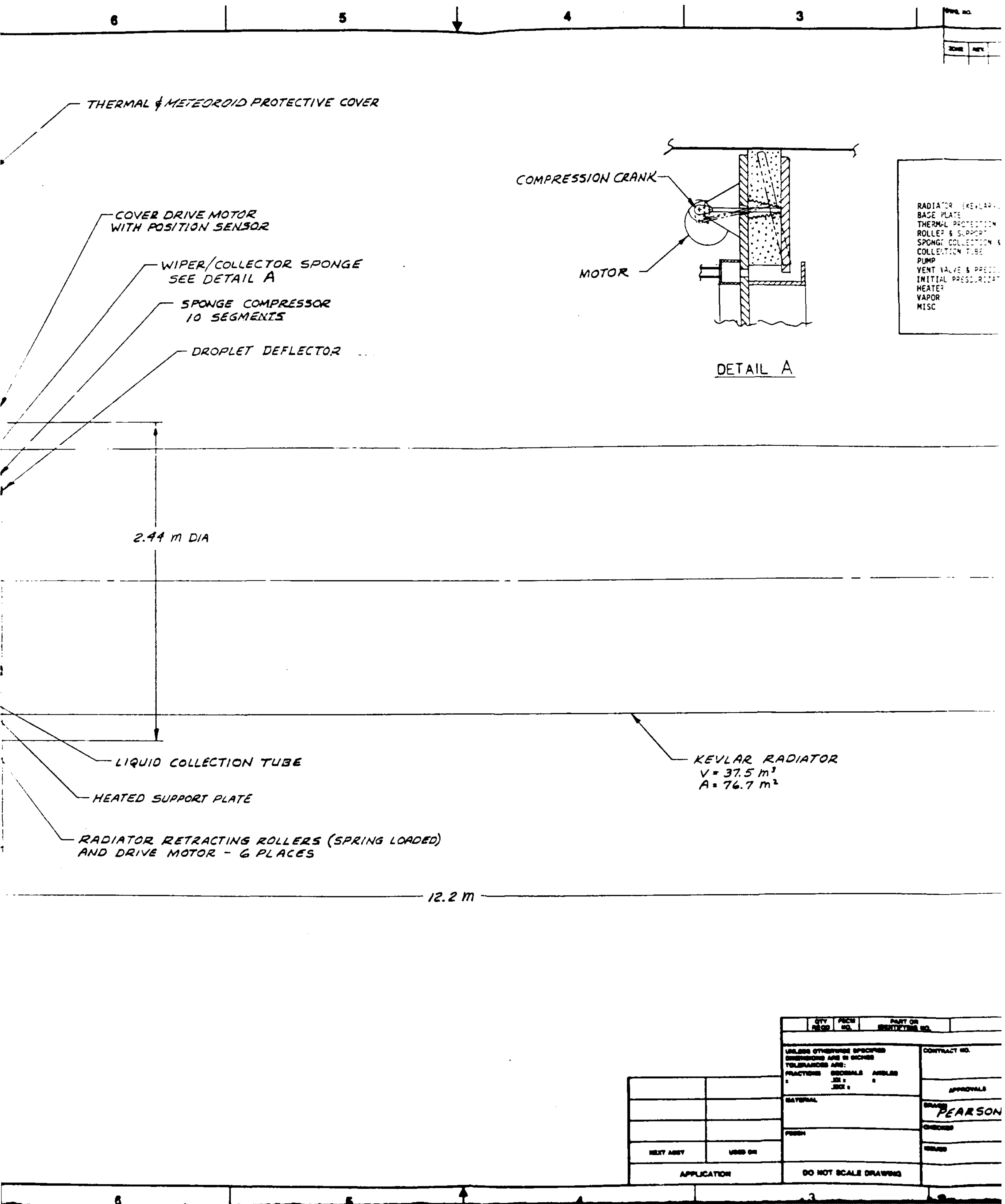
APPLICATION

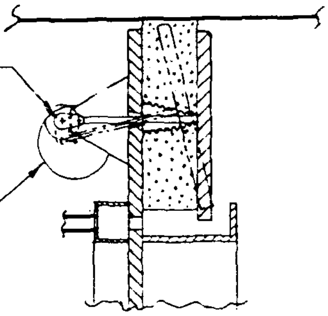
9. Roller Retracting Sponge with Squeeze Bar.

This is similar to design concept #2 except that the fixed wiper incorporates a sponge. When pressed against an uneven fabric the sponge will be able to collect liquid more efficiently than an incompressible wiper. A mechanical system is included, as shown in Figure 11, to squeeze liquid out of the sponges into the pump inlets.

This system is probably the most effective design - the main uncertainty being the take-up of fabric by the friction rollers. This will need to be studied experimentally.

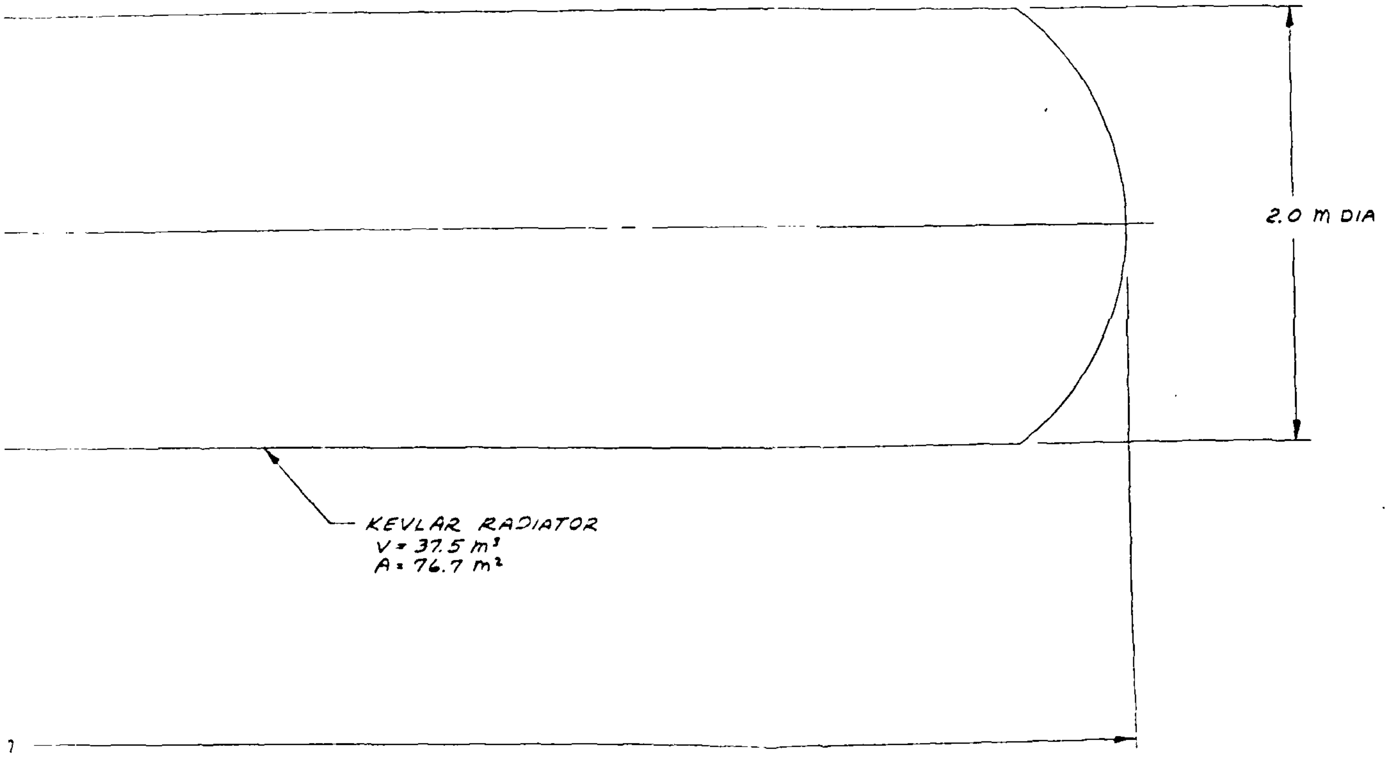

THERMAL & METEOROID PROTECTIVE COVER
THERMAL & METEOROID PROTECTIVE HOUSING
COVER DRIVE MOTOR WITH POSITION SENSOR
SPONGE COMPRESSION CRANK & MOTOR (10 PLCS) SEE DETAIL A
WIPER/COLLECTOR SPONGE SEE DETAIL A
SPONGE COMPRESSOR 10 SEGMENTS
PUMP
DROPLET DEFLECTOR
RETURN LINE
BASE PLATE
2.44 m DIA
ELECTRICAL CONNECTOR
VAPOR INLET 0.8 m²
BOILING WATER SUPPLY FOR CONTROLLED EXPANSION (COULD BE SINGLE UNIT IN CENTRAL AREA FOR OPERATION OF ALL RADIATORS)
LIQUID COLLECTION TUBE
VENT VALVE & PRESSURE SENSOR
HEATED SUPPORT PLATE
WIPER SUPPORT STRUCTURE
RADIATOR RETRACTING ROLLERS (SPRING LOADED) AND DRIVE MOTOR - 6 PLACES
1.43 m
12.2 m


6
5
4
3
THERMAL & METEOROID PROTECTIVE COVER
COVER DRIVE MOTOR WITH POSITION SENSOR
WIPER/COLLECTOR SPONGE SEE DETAIL A
SPONGE COMPRESSOR 10 SEGMENTS
DROPLET DEFLECTOR
COMPRESSION CRANK
MOTOR
DETAIL A
RADIATOR
BASE PLATE
THERMAL
ROLLER
SPONGE
COLLECTION TUBE
PUMP
VENT VALVE
INITIAL
HEATER
VAPOR
MISC
2.44 m DIA
LIQUID COLLECTION TUBE
HEATED SUPPORT PLATE
RADIATOR RETRACTING ROLLERS (SPRING LOADED) AND DRIVE MOTOR - 6 PLACES
KEVLAR RADIATOR
V = 37.5 m³
A = 76.7 m²
12.2 m
QTY REQD
PART OR IDENTIFYING NO.
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ARE:
FRACTIONS
DECIMALS
ANGLES
CONTRACT NO.
APPROVALS
MATERIAL
DRAWN
PEARSON
CHECKED
FINISH
ISSUED
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING



DETAIL A

BILL OF MATERIAL	WATER Wt - Kg	ETHYLENE GLYCOL Wt - Kg
RADIATOR (KEVLAR-UNCOATED)	13.7	4.8
BASE PLATE	4.0	4.0
THERMAL PROTECTION & SUPPORT	3.3	3.3
ROLLER & SUPPORT	19.0	19.0
SPONGE COLLECTION & SUPPORT	25.0	25.0
COLLECTION TUBE	.4	.4
PUMP	1.3	1.3
VENT VALVE & PRESSURE SENSOR	2.2	2.2
INITIAL PRESSURIZATION SYSTEM	4.5	4.5
HEATER	2.0	2.0
VAPOR	9.2	.5
MISC	3.8	3.4
TOTAL	88.4	70.4



PARTS LIST

DRAWN PEARSON 10-1-86

EXPANDABLE RADIATOR, CYLINDER-ROLLER RETRACTING WITH SPONGE (2.44 m DIA)

SIZE D

Figure 11.

DO NOT SCALE DRAWING

APPLICATION

3.0 COATED FABRIC TESTING

A. Introduction

The purpose was to evaluate coated fabrics that might be used to construct the expandable radiator. The requirements were:

1. A very high strength to mass ratio is needed. The fabrics best in this respect are Kevlar, the duPont polyaramid, and Allied Chemical's Spectra, a polyolefin. On discussing Spectra with custom coaters they agreed that it was very difficult to get an adherent coating on this unreactive surface. Although this fiber is 50% stronger than Kevlar, it is also very new and coaters do not yet know how to coat it. Therefore, it was decided to use only Kevlar at this time.

2. A fabric coating is needed that is water vapor impermeable at 75°C, which is the proposed maximum operating temperature of the system. This coating depends somewhat on what is available for Kevlar, since it has also proved difficult to coat in the past. (There are no off-the-shelf coated Kevlar products available. Samples of previously coated materials are hard to obtain in amounts large enough for testing.) Discussions with custom coaters who were experienced with Kevlar showed that the following coating materials were available:

    a. Polyurethane. Since this has rather poor water vapor permeability characteristics, it was not used.

    b. Teflon. Samples of a cast PTFE film laminated to 2 oz./sq.yd. Kevlar were received too late in the project to test. These were supplied by Chemfab Corporation of Buffalo, New York. These materials are used for the fabric roofs of inflated stadiums, and are very resistant to water and radiation. They would be good candidates for future study.

    c. Silicone. L'Garde sent a sample of Kevlar 745 fabric to R.M. Products of North Charleston, South Carolina. This was coated with silicone rubber and is one of the principal materials evaluated here.

d. Neoprene. The Chemprene Division of Witco in Appleton, N.Y., coated neoprene rubber on Kevlar 745 for our evaluation. Neoprene was also coated on our Kevlar by Flexfirm Products of South El Monte, CA, but the samples were not large enough for our testing program.

e. EPDM. This is a rubber compound which consists of an ethylene propylene terpolymer with a nonconjugated diene that can be crosslinked. A compound of this type was applied to a sample of Kevlar 745 for L'Garde by R.M. Products, and this material was used in our testing program.

f. Butyl. This rubber is known to have excellent water vapor resistance, and therefore, L'Garde wanted to include it in the testing program; however, our sample arrived too late in the project for testing.

3. Another requirement is that strong, water vapor tight seams can be made with the coated material. Both adhesive and sewn seams were tried.

4. Since the expandable radiator must be folded in its contracted form, and may be expanded and contracted several times, the fabric must not lose strength or water vapor resistance in this process.

5. The outside surface of the Kevlar will be exposed to the full strength of sunlight. An evaluation is needed of the strength loss due to this radiation, and the possibility of protective coating.

B. DESCRIPTION OF THE TESTS AND RESULTS

1. Sample Weight and Thickness

Table 6 shows the weights and thicknesses of the three coated fabrics tested in this project. The EPDM and silicone were coated on both sides of the fabric and the neoprene on one side.

In use for the radiator only one side needs to be coated with the vapor barrier. Therefore the increase in fabric weight might be only 25 to 50% due to the coating, as illustrated by the thin side coats in the table. Because of the roughness of the fabric these thin coats are close to being

TABLE 6. COATED KEVLAR WEIGHT AND THICKNESS

Material		Fabric Oz/Yd^2	Weight %	Fabric Thickness, Mils
EPDM (R.M. Products)	Thick side	17.2	45.	24.
	Fabric	14.5	38.	25.
	Thin side	6.8	17.	10.
	Total	38.5	100.	54.
Silicone (R.M. Products)	Thick side	15.7	40.	15.
	Fabric	14.5	37.	25.
	Thin side	8.7	23.	12.
	Total	38.9	100.	44.
Neoprene (Chemprene)	Coating	4.7	25.	6.
	Fabric	14.5	75.	25.
	Total	19.2	100.	31.

NOTE: Thicknesses do not always add properly since stripped material seems thicker than when coated.

discontinuous, if not applied with great care. Further testing needs to be done to establish the water vapor permeability as a function of coating thickness for each feasible type of coat, so that the coating weight can be minimized while retaining adequate water resistance.

(Note that a lighter Kevlar fabric could be used for the eight-foot diameter expandable radiator as designed in the previous section; these designs were based on Kevlar 49, Style 500 from Hi-Pro-Form Fabrics, Inc., of Newark, Delaware. However, when test fabrics were ordered at the beginning of this project, it was thought that the standard design would be based on a 10-meter diameter system which would require much greater strength. Therefore, Kevlar 29, Style 745, was ordered from Hi-Pro-Form, and that has been coated to produce test materials. Most of the findings in this project are independent of the differences in these materials.)

2. Fabric Tensile Strength

The mechanical designs are done using the vendor specified tensile strength of the Kevlar fabric. For an uncoated fabric this strength measurement is generally done by ASTM Test Method D1682, and for coated fabrics by the essentially similar ASTM Test Method D751. The fabric is cut into strips one inch by six inches in the direction of pull. The fabric ends are held by vise-like grips, and the material is pulled to obtain a stress-strain curve, and the breaking strength.

When this was attempted with Kevlar 745 fabric, the fabric pulled out of the grips every time. In fact, if this happens at all it invalidates the stress-strain curve since the strain recorded by the tester is partly due to slippage, rather than an actual material strain. It happened so badly with Kevlar 745 that we were not able to apply more than 200 pounds per linear inch stress, although the Kevlar was rated by the vendor at 1800-1900 pli breaking strength.

In response to this problem, L'Garde designed special one-inch grips to hold the Kevlar strips. These are shown gripping a one-inch Kevlar strip, coated on one side with neoprene in Figure 12. The essential parts of the grip are two stainless steel bars that are machined into facing half cylinders. The fabric end is placed between the two half cylinders which are then tightly screwed together. The fabric is wound one full turn around the cylinder, and the grip is dropped into a cradle that is attached to the pulling mechanism. Figure 12 shows the setup in our Monsanto Tensometer 10 testing machine. The full turn around the split cylinder distributes the stress evenly and uses the friction against the surface of the cylinder to help hold the fabric.

When these grips were used for uncoated fabric it did not pull out of the grips, and the results shown in Table 7 were obtained.

The results in the "standard" row of the table, obtained as described above, are very significantly less than the vendor specifications. When repeated testing determined that this difference was real, and did not appear to be a function of the L'Garde grips, we called Hi-Pro-Form Fabrics to determine how the tensile test data reported in their literature was obtained. At last, we learned that Kevlar is tested by ASTM Test Method D579, Standard Specification for Greige Woven Glass Fabrics. By this time the project was scheduled to be completed, so we did not try D579. However, the results of our method are self-consistent, so some important results can be developed as shown below.

For example, we developed a flexing method based on the deMattia flex tester used in ASTM D430. The L'Garde tester was modified with a speed reducer to run at 10 cycles per minute, instead of the 250 cpm which is used for rubbers in ASTM D430. The tester with a 4-inch wide piece of coated fabric in the jaws is shown in Figure 13.

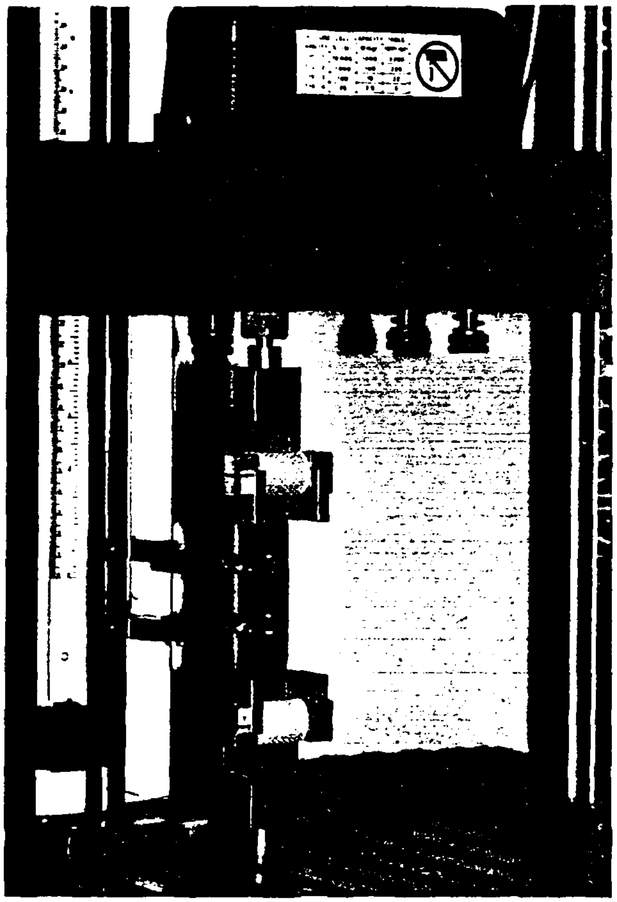


Figure 12. Neoprene Coated Kevlar in Tensometer

Previous flex testing of Kevlar (1) had established that the tensile strength of Kevlar begins to deteriorate after 1000 flex cycles. However, the results depend on the nature of the weave being tested. Our tester with six strips of one-inch wide uncoated Kevlar 745 is shown in Figure 14. The machine was adjusted to close its jaws to a 100 mil clearance. The loops of Kevlar were then creased tightly between the platens jutting forward in Figure 14.

Because the application of the Kevlar in the expandable radiator will not require a very high number of flexes, our tests used 100 flexes as shown in Table 7. The tensile strengths obtained from flexed strips, considering the variability of the data, are not significantly less than for unflexed strips. (Six replicates were used for each in ASTM Test D751.) Although these results seems to show that Kevlar 745 is not affected in its tensile strength by 100 flexes, each weave may differ in

TABLE 7. UNCOATED KEVLAR 745 TENSILE STRENGTH

ASTM D751 lbs/in.	Warp Direction	Fill Direction
Standard	908.	1470.
Flexed 100 times	854.	1380.
Vendor Specification	1800.	1900.
Creased Strips	---	1428.

Notes:

1. There is not a significant effect of flexing on tensile strength.
2. Fill is significantly stronger.
3. Vendor specifications are based on ASTM D579 "Test for Greige Woven Glass Fabrics"
4. No strength loss in crease test. Two pound pressure on strip folded with three creases.

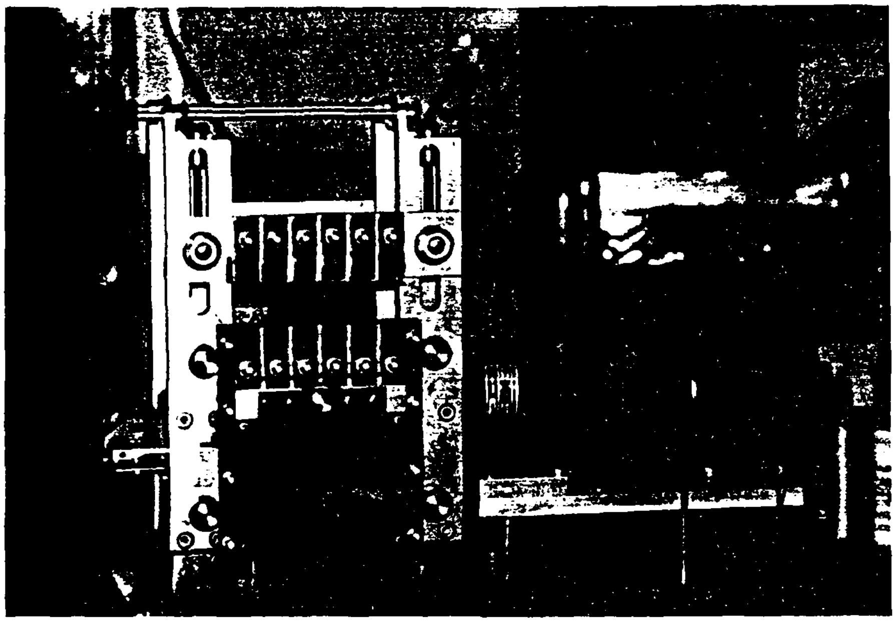


Figure 13. Modified de Mattia Flex Tester with 4 Inch Wide Piece of Coated Fabric.

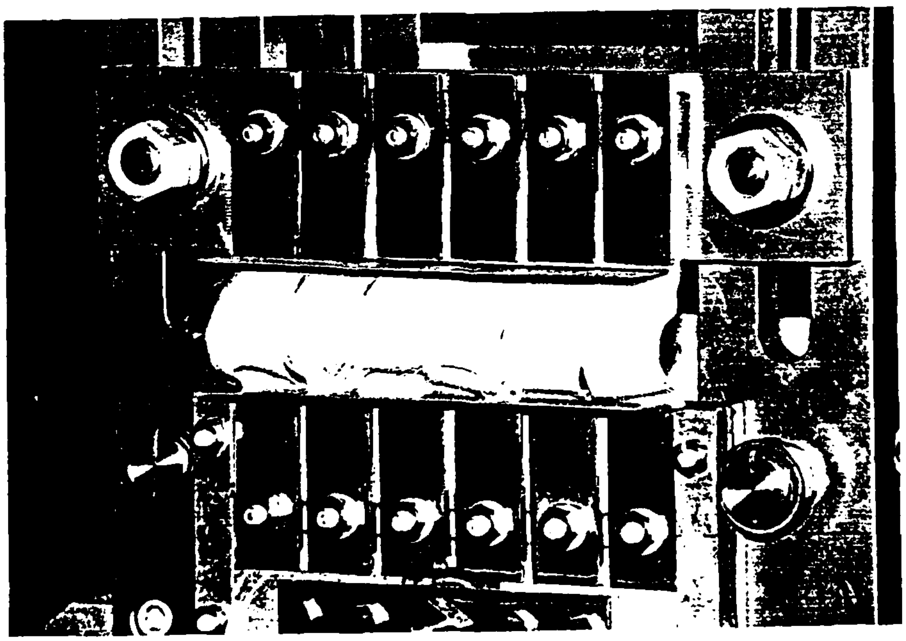


Figure 14. Flex Testing One Inch Strips of Uncoated Kevlar

this respect, so the actual material to be used in an expandable radiator must be tested.

Table 7 also contains data on a crease test. This crease test, as described in a NASA report (2), consisted of folding a one-inch wide strip of Kevlar with three creases, one-inch apart, then six creased strips were pressed for 24 hours under a weight corresponding to two pounds force on each strip. The tensile test results obtained after that showed no significant difference from uncreased strips. However, it is interesting to note that the break in the Kevlar strip always occurred where the crease had been made.

Since it is claimed that coating can change the strength of fabrics, even when the coating itself is very weak, we attempted tensile tests on coated fabrics. With silicone and EPDM coatings, even with the special L'Garde grips, the Kevlar fabric slid on the coating, leaving the latter in the grip. With the neoprene, coated on only one side as shown in Figure 12, it was possible to get tensile test results as shown in Table 8.

TABLE 8. KEVLAR 745 TENSILE STRENGTH EFFECT OF NEOPRENE COATING

ASTM D751 lbs/in.	Warp Direction	Fill Direction
Uncoated	908.	1470.
Neoprene Coated	1404.	1206.

Notes:

1. Neoprene coating has improved tensile strength in the warp direction.

2. Strength in the fill direction is significantly better in uncoated fabric.

These results show that neoprene coated Kevlar 745 was very significantly stronger in the warp direction. Surprisingly, there was a small, but significant, decrease in strength in the fill direction due to neoprene coating. These results were reproducible for neoprene; however, it is not known if this is a general phenomenon. Obviously it will be necessary to measure the effects of coating completely in future work.

L'Garde's results in tensile testing were verified by work done by our instrument vendor, Monsanto (3). On uncoated Kevlar, Monsanto attempted the "One Inch Raveled Strip Method" from ASTM D1682, which is similar to our one-inch tensile tests. Their results were that the fabric pulled out of all the various types of grips that they had. We concluded that the L'Garde grip is an improvement over commercially available grips for this test.

Monsanto then attempted the "Modified Grab Test", also described in ASTM D1682, which uses a three inch wide strip of Kevlar. In the central part of the strip the fibers in the pull direction are cut in a two inch segment on both sides, leaving only one inch of uncut fibers in the pull direction. The cut fibers are raveled out from the transverse fibers. The idea of this is to put stress on a one inch strip, but to eliminate unrepresentative stresses at the edges of the fabric, which would be present in the standard one-inch strip. The ends of the strips were gripped by 1 in. x 2 in. vise jaws with the 2 inch length in the direction of pull. Monsanto claims these tests were satisfactory; however, the Kevlar 745 breaking strengths observed were only about 520 pli, much less than the 1800 pli claimed by the vendor. Also the Kevlar broke many yarns in the region of the grip, usually considered to be a failed test. We concluded that this test is not suitable as a measure of Kevlar fabric strength.

Finally Monsanto tried the grab test with uncut 3 inch wide Kevlar 745 strips, gripping with 1 in. x 2 in. vise grips having the 2 inch length in the pull direction. The fabric was looped around a 3/8 inch diameter by 5 inch long pin at the top of the grip, with the loose end put back in the grip. The results here show strengths of around 1700 pli. However, closer examination of the data show elongation at break of 80%. This should be only 3 to 6% in a fabric that has not pulled out at the grips. Inspection of the actual test samples after pulling shows that there is no actual fabric break between the grips rather the fabric has pulled and broken entirely at the grips - invalidating these results.

We conclude that measurement of the tensile strength of Kevlar is very difficult, even for a manufacturer of test equipment like Monsanto. Any of these test methods can only be used in connection with a calibration to actual test cylinders stressed with internal pressure.

Construction of test cylinders and development of a calibration to a tensile test should be part of a future project.

3. Blocking of Coated Fabric

When coated fabrics are pressed together, especially at high temperature, some surface sticking is likely to occur. This is called "blocking". The standard test for blocking is Federal Test Method Standard 191A, Method 5872. In summary, the steps in this method are:

a. An 8-in. x 8-in. piece of coated fabric is folded 2 ways to 4-in. x 4-in. This results in areas of front-to-front and back-to-back surface contact.

b. The folded piece is heated at 82°C in an oven under a four pound weight for 30 minutes.

c. It is removed from the oven, and allowed to cool for 5 minutes. Then it is slowly unfolded while observing for any sign of adhering or peeling of the surface coating.

The results of tests of three samples each of neoprene, EPDM, and silicone coatings on Kevlar 745 showed no adhering tendency at all. Long duration tests would be recommended before a final decision on a coating could be made.

4. Water Vapor Permeability

The purpose of this test is to evaluate the water vapor loss through the coated fabric under conditions that are like those encountered by the expandable radiator in use. The usual ASTM test method is E96, "Water Vapor Transmission of Materials." This test consists of enclosing a weighed amount of water inside a container so that the only water exit path is through a flat side of stretched, coated fabric. The container is placed in a controlled environment so that the temperature and water vapor pressure on the open side of the fabric are constant. Then the water in the container vaporizes and the water vapor passes through the coating and fabric by diffusion. The experimentor measures the weight loss of the container every few hours or days to measure the rate of vapor transmission, which can then be combined with the known exposed area of the fabric to obtain the diffusion flux in units such as $gm/hr\text{-}cm^2$. When steady state operation is achieved, this flux will be a reproducible function of only the temperature, the humidity in the controlled environment, the type of coating and fabric, and of course the diffusing vapor, water in our case.

To simulate the conditions of the expandable radiator, we needed to use the test at 75°C which could be done by putting the container in a 75°C oven. Then the pressure inside the enclosure is the atmospheric pressure plus the water vapor pressure at 75°C, or about 14.7 + 5.8 psi. The pressure outside the container is about 14.7 psi, of which a negligible part is water vapor pressure. Therefore, to a close approximation the pressure driving force for water transmission through the coated fabric is 5.8 psi, the same as would be present if there were no air, as in space.

From a practical viewpoint, however, the total pressure on the inside of the container is 5.8 psi more than on the outside. For a 2-7/8-inch circular opening, as in the cup actually used in these experiments, the total force pushing the fabric toward the outside is $(2.875)^2(\pi/4)(5.8) = 37.6$ pounds. This tends to bow the fabric out, pulling it out at the edges from its support. The edges become loose, and the water vapor escapes through them instead of through the coated fabric.

The vapor cup developed to prevent vapor leakage around the edges is shown in Figure 15.

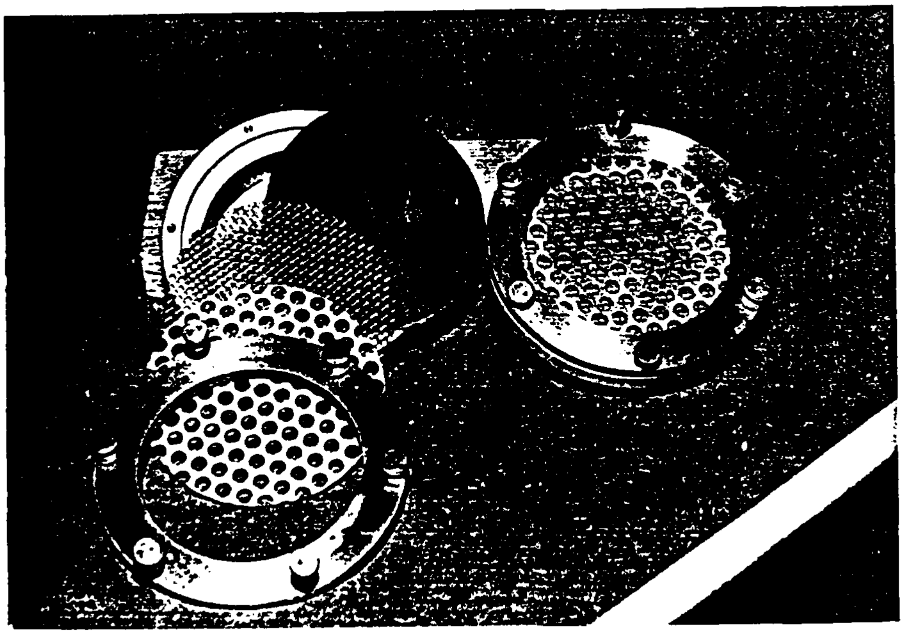


Figure 15. Vapor Permeability Cups

The closed cup is on the right in the photograph. The parts are stacked at the left, and will be described with the assembly sequence:

a. The vapor cup on the bottom is filled with 30 cubic centimeters of water before use.

b. The circle of coated fabric is set on the inner flange of the cup. Not shown in this photograph is a thin layer of General Electric RTV 106 silicone rubber spread on the inner flange of the vapor cup, and on the edge of the coated fabric. The purpose of the RTV 106 is to try to assure that the water vapor passes through the coated fabric and not through openings at the edges.

c. Light aluminum window screen is used next to hold the fabric down, while shielding the minimum area from diffusion.

d. Perforated aluminum sheet is the next layer. It holds the window screen down and has adequate strength to resist the water vapor pressure. This sheet is intended to prevent the fabric from unsealing at the edges during heating.

e. The aluminum flange is put on finally and screwed down evenly.

These cups were used in the sequence:

a. After assembly the cups were weighed.

b. They were then heated in an oven at 75^{o}C with good air circulation for 23 hours.

c. The cups were removed from the oven and cooled for 1/2 hour.

d. The cups were weighed again.

e. Return to step b.

The weight differences can be used to find the rate of loss of water in grams/hour.

The water vapor permeability results can be described as follows:

a. Results were plotted as shown in Figure 16, with water loss rate in milligrams per hour as ordinate and the date as abscissa.

b. Six vapor cups in all were used for each material. On occasion, one of the cups in a test would show a much higher rate of loss than the others, and this was ascribed to leakage around the edge. That data was discarded.

c. The rate of loss stabilized after 1 or 2 days. After that, variability was observed, as shown in Figure 16, but it is felt that the average rates from six cups are meaningful. The summary results are presented in Table 9.

TABLE 9. WATER VAPOR PERMEABILITY THROUGH COATED FABRICS

		EPDM			NEOPRENE	
		Permeation From 17.2 oz/yd^2 Side	Permeation From 6.8 oz/yd^2 Side		Permeation Through 4.7 oz/yd^2 Coating	
		Not Flexed	Flexed	Not Flexed	Flexed	Not Flexed
Rate of Water Loss, mg/hr	No. of Points	86	84	40	66	66
	Mean	5.6	10.1	13.8	35.5	33.3
	Standard Deviation of Mean	0.2	0.3	0.5	0.5	0.4
Rate of Water Loss for 8' x 40' Radiator, Kg/hr		0.36	.72	.93	2.28	2.14
Percent of Radiator Fill Lost per Hour		2.6	5.2	6.7	16.5	15.5

NOTE: Silicone was not done in these tests when it was learned that it is not considered to have good water vapor barrier properties.

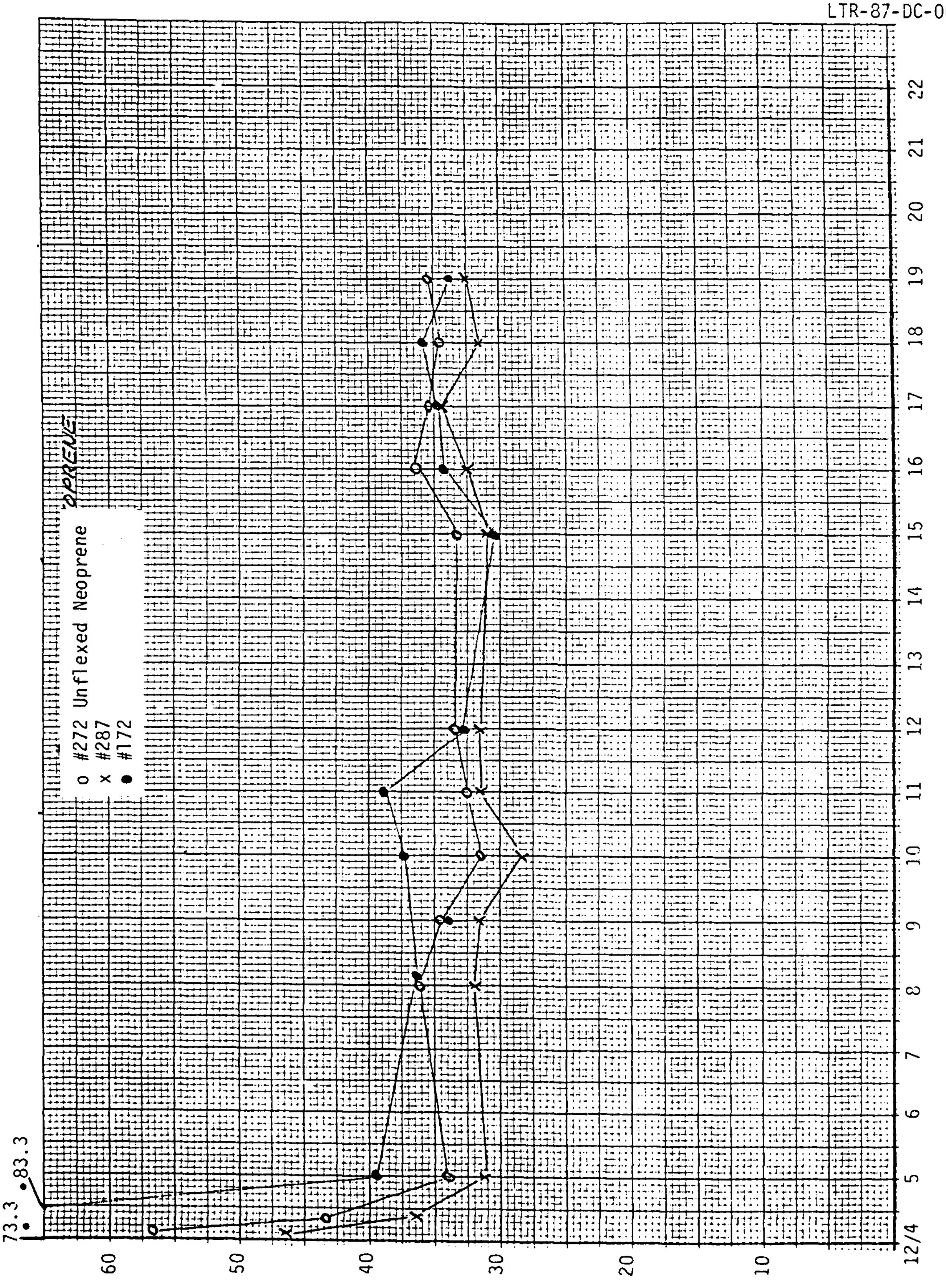


Figure 16. Water Vapor Permeability of Unflexed Neoprene

The table gives data for the fabrics flexed and not flexed. The former designation means that a 4-inch square of coated fabric was flexed 100 times in the modified de Mattia tester described in Section 3B-2. Figure 17 shows the fabric in place in the tester. After flexing a 2-7/8-inch circle was cut from the flexed sample for use in the water vapor permeability test.

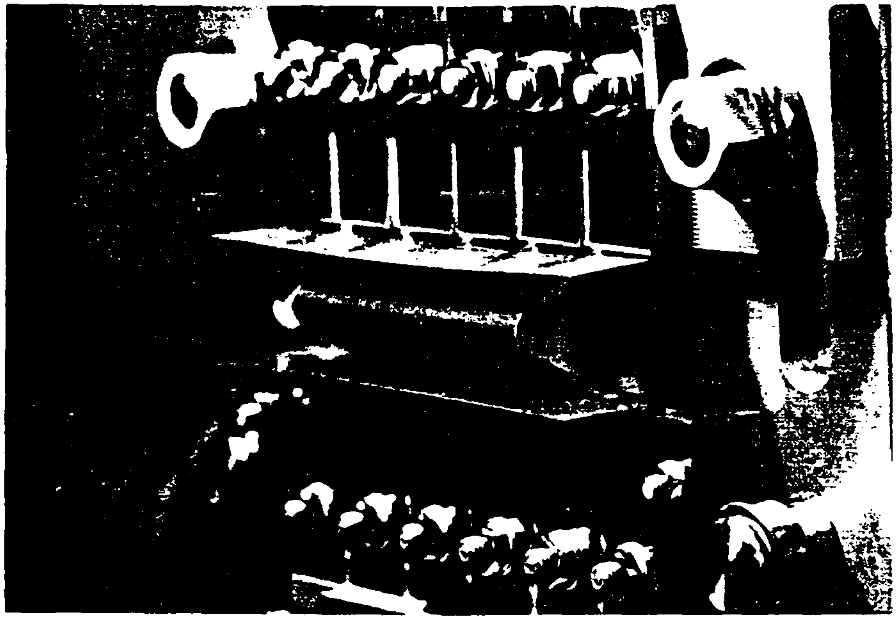


Figure 17. Closeup of de Mattia Testor with 4 Inch Wide Piece of Coated Fabric

Conclusions from the water vapor permeability tests are:

a. Water vapor losses around the edges of the fabric are not significant since:

   1.) All six cups used for a given experiment were in reasonable agreement.

   2.) Rates of loss were measured with the sealing procedure using a 2 mil thick aluminum disk instead of a fabric. Observed losses of about 1 mg/hr were negligible.

b. For neoprene the rates of 33-35 mg/hr mean that 15-16% of the radiator fill would be lost in one hour of use if this neoprene coating were to be used. However, flexing of the fabric did not appear to make much difference in the rate of loss. A thicker coat of neoprene might be satisfactory. If there were any pinholes in the coatings tested, the improvement in permeability would be greater than linear.

c. EDPM was less permeable than neoprene, losing only 3-6% of the radiator fill per hour with our samples. There are two anomalous results, however:

1.) Data for the samples not flexed had a larger rate of loss. With the number of points available, one can show that this is a highly significant difference statistically. We currently have no explanation for these experimental results, since our hypothesis about flexing was that it would crack the coating and increase the rate of loss.

2.) The fabric was coated on 2 sides: one side had 17.2 oz. coating/yd^2, and the second had 6.8 oz. coating/yd^2. The normal hypothesis is that the water vapor passes through both coatings in escaping from the water cup. However, the results indicate that permeation was one half as great when the thick side was directly against the vapor compared to when the thin side was against the vapor. This would be consistent with a hypothesis that the coating against the vapor is the only barrier since when water reaches the fabric it is transferred laterally to the edges where it escapes. It would seem our attempts to seal the fabric edges with RTV 106 did not prevent this. In tests with fabric coated on just one side, as proposed for the expandable radiator, this does not matter.

In future work it will be necessary to test several thicknesses of coating to determine how thin it can be and still be an adequate vapor barrier.

5. Strength of Seams

Some very preliminary adhesive bonding results were obtained as shown in Table 10 for neoprene coated Kevlar 745.

TABLE 10. LAP-SHEAR ADHESIVE BONDING WITH COATED KEVLAR 745 AND ONE INCH LAP JOINTS WITH SYNTHETIC SURFACES 74D

MATERIAL	BREAK STRENGTH OF ADHESIVE BOND, LBS/IN.
EPDM	87.
NEOPRENE	67.
UNCOATED	65.5
NOTE:	Bonding with this adhesive is much weaker than fabric strength of 1200 - 1400 lbs/in.

The bond strengths obtained with one inch lap joints were ver low compared to the strength of the fabric. More complex adhesive bonds should be tried. Also, the adhesive used should be chosen to be compatible with the coating used.

If a better adhesive or complex joint is used, it seems likely, although not certain, that the coating will separate from the Kevlar, since that bond must transmit the stress to the fabric which is probably the strongest link in the system. Therefore, we looked into sewn seams. We were able to obtain bonded Kevlar thread in samples from the Robinson Thread Co. of Worcester, MA. (Bonding is a surface treatment that enables the thread to slide easier against the needle and fabric. Kevlar thread does not necessarily come that way, but Stu Robinson was willing to prepare a sample for us in their lab.) Samples of Kevlar 745 were sewn for us at Santa Ana Canvas in one foot long seams which we planned to cut into one inch strips. On examination of the seams, we realized that one can get only 8-10 stitches per inch, so that when the one inch strips were cut, the end effects of broken stitches at the edges would weaken the seam and make the results invalid. The strength of sewn seams must be tested by a "grab" test as described in ASTM D1683. It is not clear that this method can be applied to Kevlar, since the "grab" tests attempted for us at Monsanto resulted in breaking of fabric at the grips. The experimentation needed to develop a method for pulling sewn Kevlar seams could not be done within the scope of this project.

6. Compatibility of Coated Kevlar and Water

Typical coated Kevlar samples were exposed to water to determine compatibility . The materials used were small pieces of light weight coated Kevlar obtained early in the project from vendors as shown below:

a. Yellow Polyurethane from Fabric Development
b. Red neoprene rubber from Fabric Development
c. Clear polyurethane from Fabric Development
d. Yellow polyurethane from Reeves Bros.
e. Red silicone rubber from Hitco
f. Black neoprene rubber from Witco

The first test was exposure to condensing steam at 75-80°C. the samples were suspended in condensing steam above boiling water for 4 hours. After this period they were examined for visual evidence of deterioration. The edges of these samples were not sealed so water could wick up into the fabric. Very little damage resulted from this test. The only observation was a very slight loosening of the fibers exposed at the edges.

The second test used pieces of the same fabric above. They were put in a small cup, submerged partially in water and allowed to stand in the dark for six months. Again, there was extremely little change in these samples when compared to controls kept dry. The only noticeable differences were very slight loosening of the fibers at the edges, and slight change in color of some samples. No growth of mold was observed.

A realistic test for materials in future work should include exposure to 75°C steam for 1 hour, followed by evacuation. After repeated applications of this cycle, the fabric strength, seam strength, and water vapor permeability should be measured.

C. Primers For Coating Kevlar

Early in the project much difficulty was encountered getting information on primers to be used to activate the Kevlar surface, so that we could coat the fabric. Finally, some progress was made working with duPont publications which were not found in the open literature (4), (5), and through the help of Fran Doherty (6) of duPont. This information was not located early enough in the project to enable L'Garde to coat Kevlar; in-house; however, it is presented here for future reference. The recommended procedure is:

1. Apply to the Kevlar a subcoat primer consisting of either:

   a. A water dispersible epoxy, duPont formula IPD-31; or

   b. A 3-10% toluene solution of PAPI-135 polyisocyanate (Upjohn). This penetrates the fabric better, but gives a stiffer final fabric.

2. An overdip primer of resorcinol/formaldehyde, such as duPont formula GV-25.

3. A 30-60 second exposure at 375-475^{o}F after applying both the subcoat and the overdip.

4. Then the EPDM elastomeric coating stock can be applied. A duPont formulation using Nordel 1040 is suggested for water and steam resistance. This could be applied either as a laminate, or from a naphtha/n-heptane solution.

Now that we have these specific suggestions, developed and tested by duPont, future work with EPDM can be done to develop Kevlar coated fabric suitable for the expandable radiator.

4.0 ENERGY TRANSFER CONSIDERATIONS

A. Impact On The End Of The Radiator During Filling

When the radiator which has been expanded at low pressure is later filled with vapor entering at 75°C and the water equilibrium pressure of 5.72 psi, there will be a substantial force on the radiator. To calculate this we can make a momentum balance on an idealized cylindrical radiator shown in Figure 18.

From p210, "Transport Phenomena" by Bird, Steward and Lightfoot, the macroscopic momentum balance is:

$$\frac{dP}{dt} = V_1W_1 - V_2W_2 + P_1S_1 - P_2S_2 - F + mg_0$$

(term 1) (terms 2) (terms 3) (term 4) (term 5)

This balance is on the control volume between planes 1 and 2. Term 1 is the rate of accumulation of momentum in the control volume. Terms 2 are the forces associated with the momentum carried by the fluid across surfaces 1 and 2. Terms 3 are the forces due to pressure at planes 1 and 2. Term 4 is the force of the fluid on the lateral surface of solid. Term 5 is the gravity force.

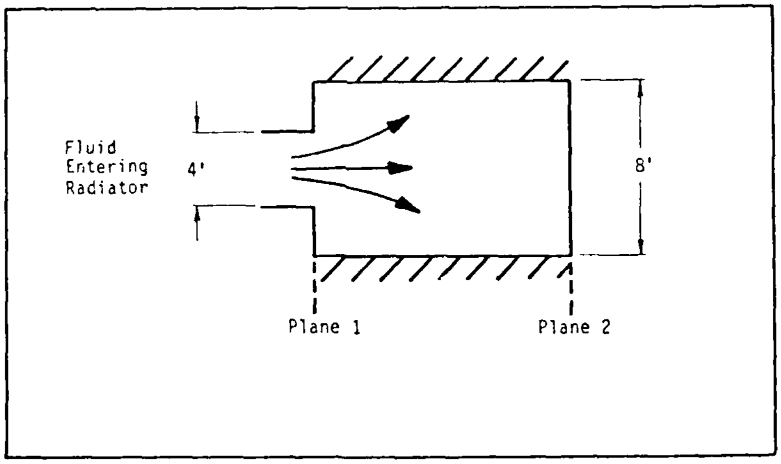


Figure 18. Fluid Entering Radiator

The assumptions are:

1. $mg_0 = 0$ in a weightless system

2. $V_2 = 0$ since nothing crosses plane 2

3. P_1 = vapor pressure of water at 75°C, or 39.4 Kpa

4. Storage of momentum in the control volume is negligible, so dP/dt = 0. This neglect will give the maximum force on the radiator.

5. The pressure on plane 2 and the force of the fluid on solid can be combined into a single force, $\mathcal{F}$, then

$$\mathcal{F} = F + P_2 S_2 = V_1 W_1 + P_1 S_1$$

On the basis of 1 Mw energy in steam at 75°C, the vapor rate is:

$$W_1 = (1(10)^6\ W) \times (0.432(10)^{-6}\ \frac{Kg}{J}) = 0.432\ \frac{Kg}{s}$$

The inlet area is 1/4 of the total cross sectional radiator area:

$$S_1 = 8^2 \cdot \frac{\pi}{4} \cdot \frac{1}{4} = 12.6\ ft^2 = 1.17 m^2$$

The inlet vapor velocity is:

$$V_1 = (0.432\ \frac{Kg}{s}) \times (0.837\ \frac{m^3}{Kg}) \times (\frac{1}{1.17 m^2}) = 0.309\ \frac{m}{s}$$

Then the force on the end of the radiator is:

$$\mathcal{F} = (0.309 \frac{m}{s}) \times (.432 \frac{Kg}{s}) + (39.4(10)^3 Pa) \times (1.17 m^2)$$

$$\mathcal{F} = 46{,}140 \text{ Newtons} = 10{,}370 \text{ pounds force.}$$

Note the following about this result:

1. The force calculated is conservative since for most expandable radiator configurations considered here, more than one radiator is needed per megawatt of stored energy.

2. The force contributed by fluid momentum (VW) is negligible.

3. This is the maximum initial force, and may be looked upon as the force projection from the area of the inlet, which is 1/4 of the radiator cross sectional area. When the radiator is fully pressurized, the force on the end is 4 times as great; therefore, there is no problem sustaining this initial force.

4. More detailed calculations were done treating the radiator as a shock tube; however, the result was still that the end of the radiator can sustain the anticipated initial force. When the actual vaporization rate is known, as well as the design of the manifold system proposed, a more complete force calculation can be made.

B. Resistance To Heat Transfer In The Condensation Process

The condensation process allows the heat stored in vapor during the radiator pressurization to be dissipated to space. Heat flows down a temperature gradient from the hot vapor at $75^{o}C = T_s$, through a condensate film to the liquid-fabric interface at temperature T_1, through the fabric to the fabric outer interface at temperature T_2, and finally by radiation from the fabric outer interface into space which is estimated to have an average temperature of T_0 = 250K. This is illustrated by Figure 19.

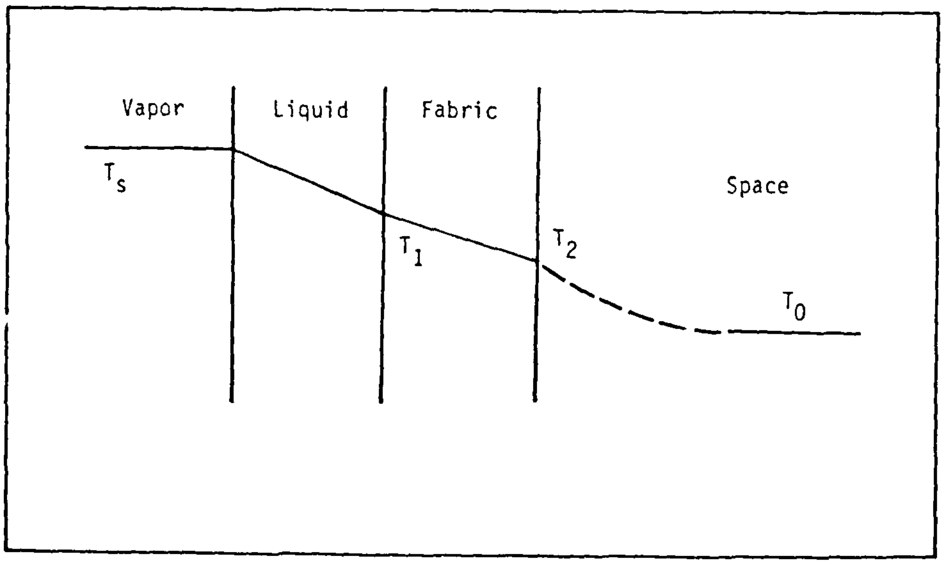


Figure 19. Temperature Profile in Condensation

At steady state the rate of heat loss through all the parts of the heat transfer path is q (W/M^2); the corresponding heat transfer equations are 4-1 through 4-3.

$$q = \sigma \epsilon \,(T_2^4 - T_0^4) \tag{4-1}$$

$$= \sigma \epsilon \,(T_2^3 + T_2^2 T_0 + T_2 T_0^2 + T_0^3)(T_2 - T_0)$$

$$= h_r \,(T_2 - T_0)$$

$$q = \frac{K\,(T_1 - T_2)}{D} \tag{4-2}$$

$$q = h_c \,(T_s - T_1) \tag{4-3}$$

where:

σ = the Stefan-Boltzmann constant

ϵ = the fabric outer surface emissivity

h_r = the heat transfer coefficient for radiation

$h_r = \sigma \epsilon \,(T_2^3 + T_2^2 T_0 + T_2 T_0^2 + T_0^3)$

K = the thermal conductivity of the coated kevlar fabric

D = the thickness of the coated fabric

h_c = the condensation heat transfer coefficient

Each of these three equations can be rearranged to solve for the temperature difference which is the driving force for heat transfer in that region. When these equations are added together, the intermediate temperatures are subtracted out, and the final form of the heat transfer relation becomes equation 4-4.

$$q = \frac{T_s - T_0}{\left[\frac{1}{h_r} + \frac{D}{k} + \frac{1}{h_c}\right]} \tag{4-4}$$

The three terms on the bottom are considered to be resistances to heat transfer. Their magnitudes may be compared to evaluate the relative importance of the radiation, conduction, and condensation resistances to heat transfer.

For example, the condensation resistance (7) is:

$$R_c = \frac{1}{h_c} = \frac{1}{1200\ W/M^2K} = .0008\ \frac{M^2K}{W}$$

An estimate of the conduction resistance is:

$$R_f = \frac{D}{K} = \frac{.045\ \text{inch}}{0.29\ W/\text{inch}\ K} \times \left(\frac{.0254M}{\text{inch}}\right)^2 = .0001\ \frac{M^2K}{W}$$

The radiation resistance is:

$$R_r = \frac{1}{h_r} = \frac{1}{\sigma\epsilon\left(T_2^{\ 3} + T_2^{\ 2}T_0 + T_2T_0^{\ 2} + T_0^{\ 3}\right)}$$

$$= \frac{1}{5.672(10)^{-8}\ \frac{W}{M^2K^4}\ (0.9)(340^3 + 340^2 \cdot 250 + 340 \cdot 250^2 + 250^3)}$$

$$R_r = 0.1864\ M^2K/W$$

Naturally the radiation resistance depends on the temperature of 340K chosen for T_2. That value assumes a reasonable 8K temperature drop through the liquid condensation film and fabric. The maximum value of 348K that could be chosen for T_2 would make the resistance only slightly smaller, so the conclusion would be the same -- that the radiation resistance to heat transfer is very much higher than the others, at least 100 times higher. This leads us to believe that the limiting step in the heat transfer process is radiation, so efforts to improve condensation, for example, would not be helpful.

Another heat transfer question which has been asked concerns condensation in the vapor space. This can happen if the vapor becomes supersaturated during pressurization of the radiator. There will be some tendency toward this because of the adiabatic expansion of the gas in this process. However, condensation for slightly supersaturated vapors requires an initial nucleus, such as dust, pollen or ice crystals, which are thought to be important in initiating rain. We have conflicting requirements in this respect: if we wish to promote vapor phase condensation, then some particulate matter should be present; on the other hand, such material will foul boiling surfaces and will probably need to be filtered out of the liquid system. It is probably best to keep this system clean and depend upon condensation on the radiator walls.

Determining when condensation will occur in a vapor phase system is an inquiry about a non-equilibrium phenomenon. Since the predictability of such phenomena is quite poor, experiment would need to be done to investigate it; however, considering the small degree of supersaturation achieved in the expandable radiator system, it is likely that no vapor phase condensation will occur. Neglecting vapor phase condensation is a conservative design assumption.

C. Temperature of the Expandable Radiator in Space

When water vapor is admitted into the expandable radiator it is intended to condense as a liquid on the inner walls. If the water should freeze on the walls either at the initial pressurization or during the time of contraction when the fabric is being gathered in and the liquid water is being collected off the inner surface, then the system would become inoperable.

To make a preliminary investigation of this we have looked at two cases, and determined the steady state temperatures for an idealized model of the standard radiator: 8 foot diameter cylinder, 40 feet long; radiator is not moving (or spinning), but one end is attached to a central structure.

Case 1: The sun and the earth shine on opposite lateral sides of the cylinder. The circular end and the side away from the earth radiate heat away to space. Using reasonable values of emissivity and solar and earthshine absorptivity, the equilibrium radiator temperature is 332K = 59°C.

Case 2: The sun shines on the circular end of the radiator. The earth is on the other side of the central structure, and therefore, does not shine on the radiator. The lateral sides of the radiator lose heat to space. The equilibrium temperature here is 172K = -101°C.

To make these approximate calculations it was assumed that the radiator was a solid body at a single constant temperature. In the more exact situation where heat is transferred by radiation and convection due to temperature differences across the inside of the radiator, the hot side of the radiator will be warmer than the figure given, and the cold side will be colder. Of course, these are equilibrium values. The actual transient temperatures would need to be calculated taking into account the system initial temperatures, weights, specific heats.

A spinning radiator would even out these temperatures somewhat, however, a careful thermal analysis will still be needed to determine the temperature history of the radiator as a function of time and of position relative to the sun.

5.0 RECOMMENDATIONS FOR FUTURE WORK

Additional problem areas that have been identified in materials science, mechanical design, and system implementation need to be resolved by future work. An overall plan can be also presented.

1. Coated fabric should be made in laboratory quantities by L'Garde. This should be feasible now that Kevlar primer information is available. The objective would be to produce EPDM coats in various thicknesses on Kevlar so that the weight of coating needed for water vapor containment can be determined. Neoprene and Butyl coatings are also feasible. Measurements of the unsteady state gain of water by the fabric are also of interest since the water contained by the saturated fabric will not be recovered later.

2. The problem of making strong seams in coated Kevlar must be studied. Because of the great strength of Kevlar fabric compared to that of the coatings and adhesives available, it seems likely that sewn seams will be needed. To test such seams L'Garde will need equipment that can pull wide samples of coated Kevlar.

3. The results of tensile tests on strips of fabric are not the same necessarily as those for balloons constructed of the materials. A correlation needs to be established between a tensile test method that can be done easily, and a performance test on an inflated balloon. Then the tensile test method can be used to evaluate various candidates for fabric and seams.

4. A careful thermal analysis is needed considering the effect of radiation from the earth and sun, and radiation to space on the temperatures in the radiator as a function of time and position.

5. Additional conceptual designs can be evaluated, such as:

   a) An inflated torus sticks out on inflated stalks from a central cylindrical waste heat producer. The whole system rotates to force water to the outermost radius of the torus, where it is collected. The fabric wraps around the outside of the central cylinder for storage, and is covered to protect from meteoroids.

b) A pleated bag can be constructed with permanent creases to be rolled up more efficiently than our Design #6.

c) Other designs similar to our Design #8 should be devised. The object in general is to remove the holding volume away from the base of the system to take advantage of the available volume which increases as the square of the radial distance from the center line. These designs could be various high-volume-to-surface shapes depending on ease of water collection.

6. The mechanical systems in our designs must have a detailed design, followed by prototype construction, and test operation. This would include the friction rollers to take up fabric, the sponge wiper system, and the rotating seals.

7. Table 11 provides an overview of the development cycle which would be expected for a device of this type. This follows closely the process which has evolved for inflatable solar collector systems being developed for AFRPL. The first two projects are currently funded or have been completed (note solid lines). All the other projects are not currently funded, nor to L'Garde's knowledge are they currently being planned (note dashed lines).

   The Thin Film Composite Materials (Phase 3) would use the results of this strictly to drive toward a preliminary design of a baseline system. It would address the loose ends of the current work and initiate materials development and lab/bench scale subsystems type testing efforts. The output would be the design to be used in the subsequent High Power Inflatable Radiator Ground Test Program (SBIR Phase II) where the development testing would be accomplished. The Design Update Program would take all this test/analysis effort and finalize a flight design.

   The flight tests could be planned in a separate SBIR Phase I study. A major issue would be booster assets: a dedicated launch vehicle (such as a sounding rocket), a seat on an expendable launch vehicle, a space shuttle/Get-Away Special assignment or possibly for later, full scale tests,

TABLE 11. EXPANDABLE RADIATOR DEVELOPMENT OVERVIEW

PROJECT TITLE	OBJECTIVES	VALUE	YEAR 0 2 4 6 8 10 12 14
Thin Film Composite Materials (Phase 1 and Phase 2)	o Establish feasibility/benefits o Identify key issues	$140K	
High Power Inflatable Radiator Study (SBIR Phase I)	o Plan a realistic ground test of an inflatable radiator	$ 60K	
Thin Film Composite Materials (Phase 3)	o Develop baseline preliminary design of a concept for ground test o Develop prototypical materials o Lab/bench testing	$300-500K	
High Power Inflatable Radiator Ground Test (SBIR Phase II)	o Perform development testing of baseline radiator system	$500K	
Design Update Program	o Use test/design data to finalize flight design	$300-500K	
Flight Test Plan (SBIR Phase 1)	o Plan a cost-effective flight test approach (i.e., Space Shuttle/Get-Away Special)	$ 70K	
Flight Test Programs	o Perform flight tests on (sub-scale) Inflatable radiator systems	$2-5M	
	o Perform full-scale engineering development tests on operational system (maybe using space station)	$20-30M	

use of the space station. The development cycle would come to fruition in the Flight Test program. This program is envisioned as a phased program involving 2-3 subscale systems tests followed by a similar number of full-scale engineering developpment tests.

Costs and program durations have been estimated from experience with current flight programs such as the Sounding Rocket Measurements Program (SRMP) being conducted for BMO/USASDC and from the solar collector development work being conducted for AFRPL.

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