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30 October 1982

FLEXIBLE RADIATOR SYSTEM

Executive Summary

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1.0 GENERAL DESCRIPTION

The flexible radiator panel is an advanced technology, high performance thermal radiator panel concept which has the potential of significantly reducing heat rejection subsystem weight, stowage volume and cost for future space vehicles and payloads. This technology has been developed to a high readiness level during the past 9 years by the Vought Corporation under the direction of NASA Johnson Space Center. A full scale prototype 1.1 kW panel has been designed, built and successfully tested in the thermal-vacuum environment. The technology is considered developed to the point of being ready for design and development for specific applications.

The flexible radiators were conceived to satisfy the needs of spacecraft and payloads which require deployed radiator area for heat rejection. They have performance and weight advantages over conventional rigid panels and radiators structurally integral with the vehicle skin. Flexible radiators are easily adapted to an existing vehicle since they can be stowed in compact units which are not susceptible to damage by dynamic loads during launch. The lightweight flexible panel can be integrated into a self contained fluid system which includes the equipment necessary to circulate the fluid, exchange the heat load to the fluid, and control the fluid temperatures to provide a Flexible Radiator Subsystem Module.

A full scale prototype flexible radiator panel has been designed, built and tested. The panel, shown in Figures 1 and 2, has approximately 173 ft^2 of radiating area (3.2 ft. wide by 27 ft. long, 2 sided) and is designed to reject 1.33 kW of heat to a $0^{o}F$ sink with a $100^{o}F$ fluid inlet. The panel is constructed from a flexible Teflon/silver mesh fin surrounding 1/8 inch Teflon tubes. The prototype panel is stowed on a 10 inch diameter by 4 foot wide drum. (It rolls up to a diameter of 17 inches when fully stowed.) Deployment of the soft tube prototype is via two four inch diameter Kevlar/Mylar inflation tubes with flat springs incorporated in each tube. Nitrogen is normally used for the deployment with approximately 1 psi required. The springs retract the panels when the inflation tubes are deflated. Another method of deployment available for the soft tube flexible is a motor driven deployable boom. This eliminates the need for expendables when the panel area is varied during the mission for heat load control. The soft tube panel is designed for a 90% probability of no punctured tube in a 30 day mission. The acceptable working fluids for this soft tube flexible are Coolanol 15, Coolanol 20 and Glycol/water (a eutectic mixture).

2.0 PANEL DESIGN

The flexible radiator panel is constructed from four basic components: (1) the flexible fin, (2) panel flow tubes, (3) fluid manifolds, and (4) the stowage drum. Principal to the capability of the panel to reject heat is the fin material. The fin material is fabricated by hot rolling a 40 x 67 silver wire mesh into 3 Mil FEP Teflon film. Figure 3 shows a cross section of the fin laminate. Two of the three mil laminates are fusion bonded together with the flow tubes sandwiched in between as shown in Figure 4. The flow tubes are PFA Teflon (typically 1/8" O.D. x 1/16" I.D.) and are normally spaced 0.75" apart on the panel. Solar absorptance value the mesh/film laminate is 0.16. The emissivity of the fusion bonded laminate is 0.70.

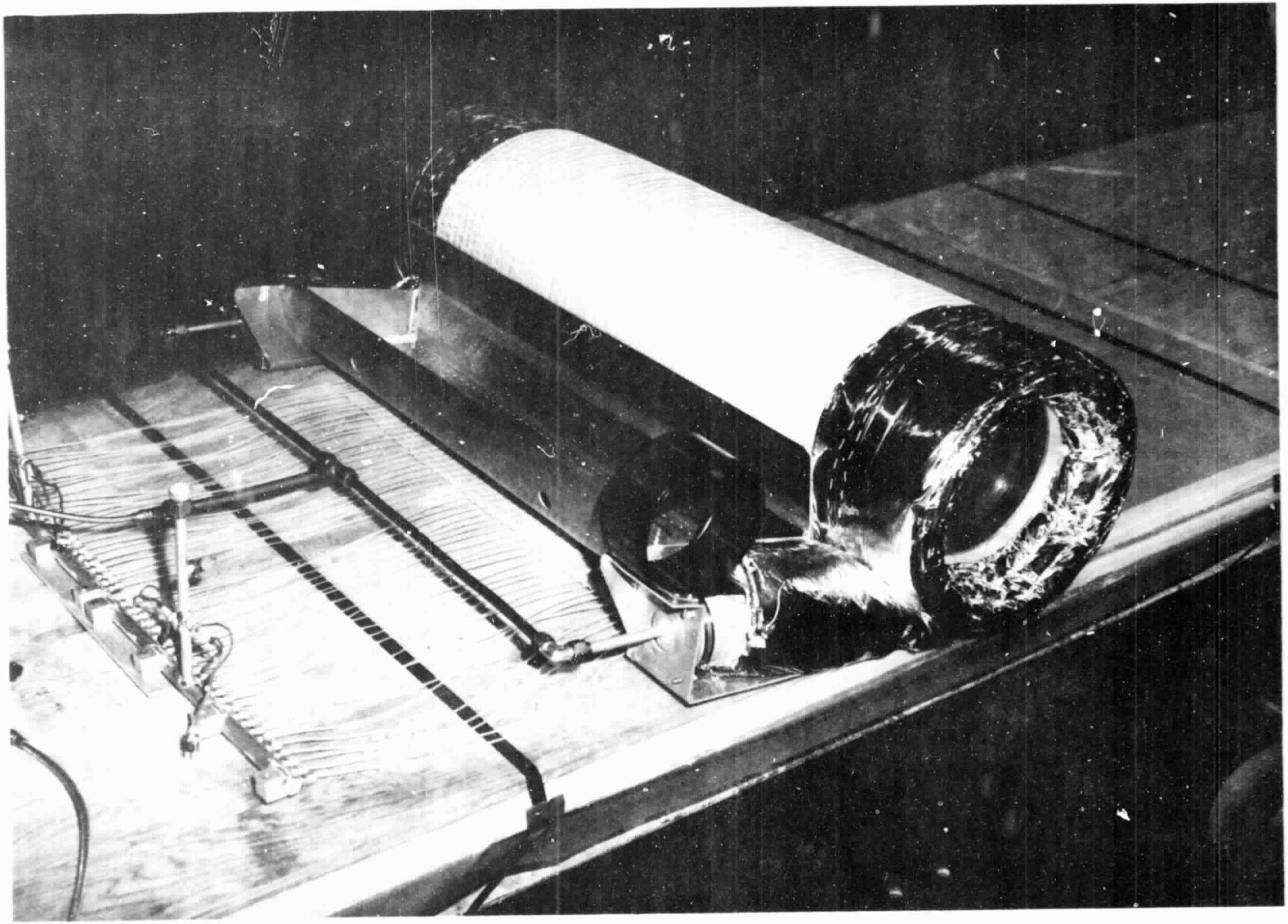

Figure 1 Prototype Flexible Radiator Panel

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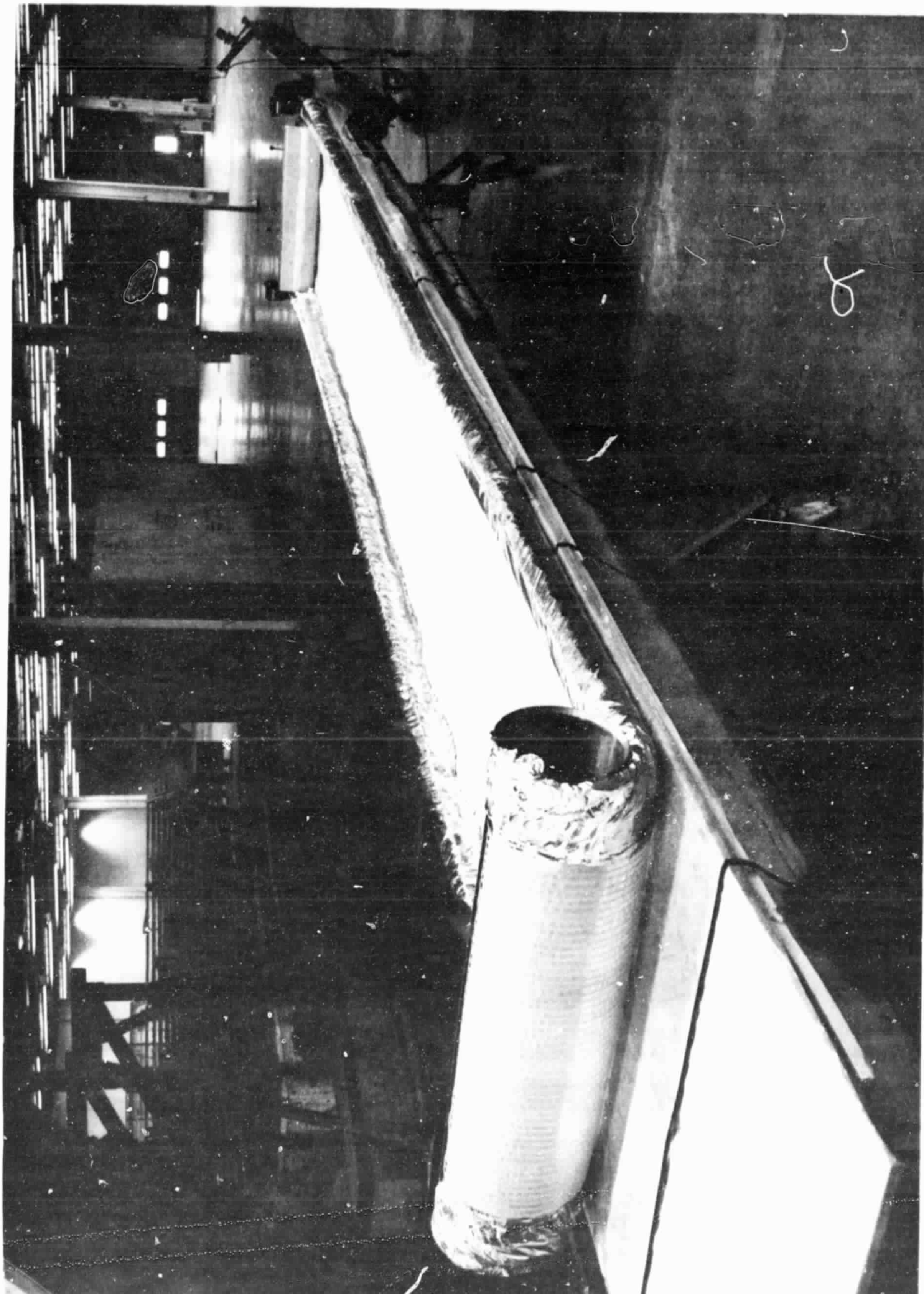

Figure 2 Prototype Flexible Radiator Panel

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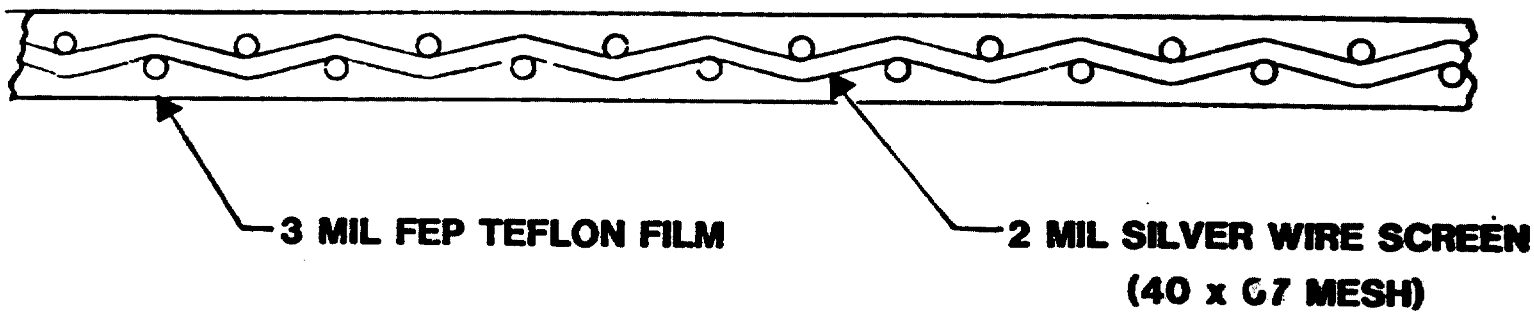
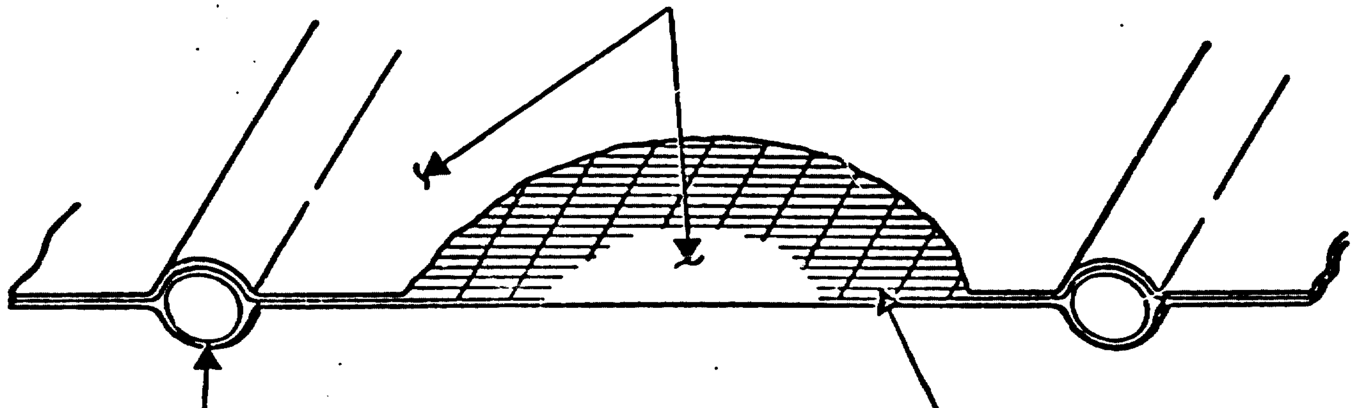


NOTE: ONE LAYER OF TWO-LAYER LAMINATE SHOWN

FIGURE 3 FLEXIBLE RADIATOR FIN MATERIAL



<u>TWO-SIDED RADIATOR DESIGN</u>

- TRANSPORT FLUID : GLYCOL/WATER, COOLANOL 15 OR COLLANOL 20
- RADIATOR PANEL AREA : 173 FT^2
- TUBE SPACING : 0.75 IN.
- PROJECTED TUBING AREA : 16.6%
- SILVER WIRE MESH : 5% FIN CONDUCTION AREA
  23% PROJECTED RADIATION AREA
- WEIGHTS : PANEL + FLUID - 47.3
  POWER PENALTY - 3.3
  50.6 lb.

FIGURE 4 FLEXIBLE RADIATOR PANEL LAYUP

The PFA Teflon flow tubes distribute the heat from the transport fluid over the panel area. These flow tubes run parallel to the long dimension of the radiator panel and connect to aluminum manifolds. The tube-to-manifold connections are made with standard Swagelok fittings, an adhesive (3M EC2216) and tube inserts which allowed the fittings to capture the soft tube without collapsing the tube wall. These connections have been tested for extended periods and have been shown to be leak free.

The fluid manifolds distribute the flow to the panel such that half the flow tubes receive inlet flow. At the deployed end of the radiator, a second manifold collects the flow and directs it into the other half of the flow tubes on the return leg back along the panel into the outlet manifold. The outlet manifold collects the transport fluid from the radiator and directs it back into the environmental control system.

The radiator panels were optimized using existing Vought radiator optimization computer routines for two working fluids identified as the best candidates in the fluid trade study: Ethylene-Glycol/water (60%/40%) and Coolanol 15. A comparison of radiator designs for Glycol/water and Coolanol 15 as working fluids is shown in Table 1. While the optimum tube inside diameter was determined to be 0.075 inches for Glycol/water and 0.080 for Coolanol 15 (see Figures 5 and 6), a value of 0.0625 inches was selected for the prototype design. This selection was made because of the availability of standard fitting sizes which limit the tube inside diameter to 0.0625 or 0.125. The larger value would cause a four fold increase in bending moment around the 10 inch drum, as shown in Figure 7.

3.0 PERFORMANCE

3.1 HEAT REJECTION PERFORMANCE

The heat rejection performance of the soft tube radiator is a function of the fluid temperatures (inlet and outlet), the radiation sink temperature and the physical panel configuration (tube spacing, tube diameter, and composite fin design). The heat rejection performance is shown parametrically in Figures 8 through 10 for the prototype panel configuration discussed in Section 2.0. The performance is shown in terms of heat rejected per unit radiation area vs inlet, outlet and sink temperatures. The performance is approximately the same for each of the three acceptable fluids (Coolanol 15, Coolanol 20 or Glycol/water). Thus, the curves can be used to determine the panel area required, regardless of the fluid used.

Flow stability restricts the panel outlet temperature for low sink temperature conditions the minimum allowable outlet temperature for a given fluid is a function of the inlet temperature, as discussed in Section 5.1 . The minimum allowable outlet temperatures for Glycol/water, Coolanol 20 and Coolanol 15 are shown on Figures 8 through 10. The heat load turn down ratio (high load to low load ratio) can be estimated from the curves if inlet temperatures and maximum and minimum sink temperatures are known. If, for instance, the high load fluid temperatures are 140°F in and 40°F out, and a sink temperature of -40°F, the maximum Q/A is 45 BTU/hr-ft^2. If the minimum inlet temperature is 60°F, and the minimum sink temperature is -180 F, the minimum Q/A is 41 BTU/hr-ft^2 for Glycol/water. Thus, the turn

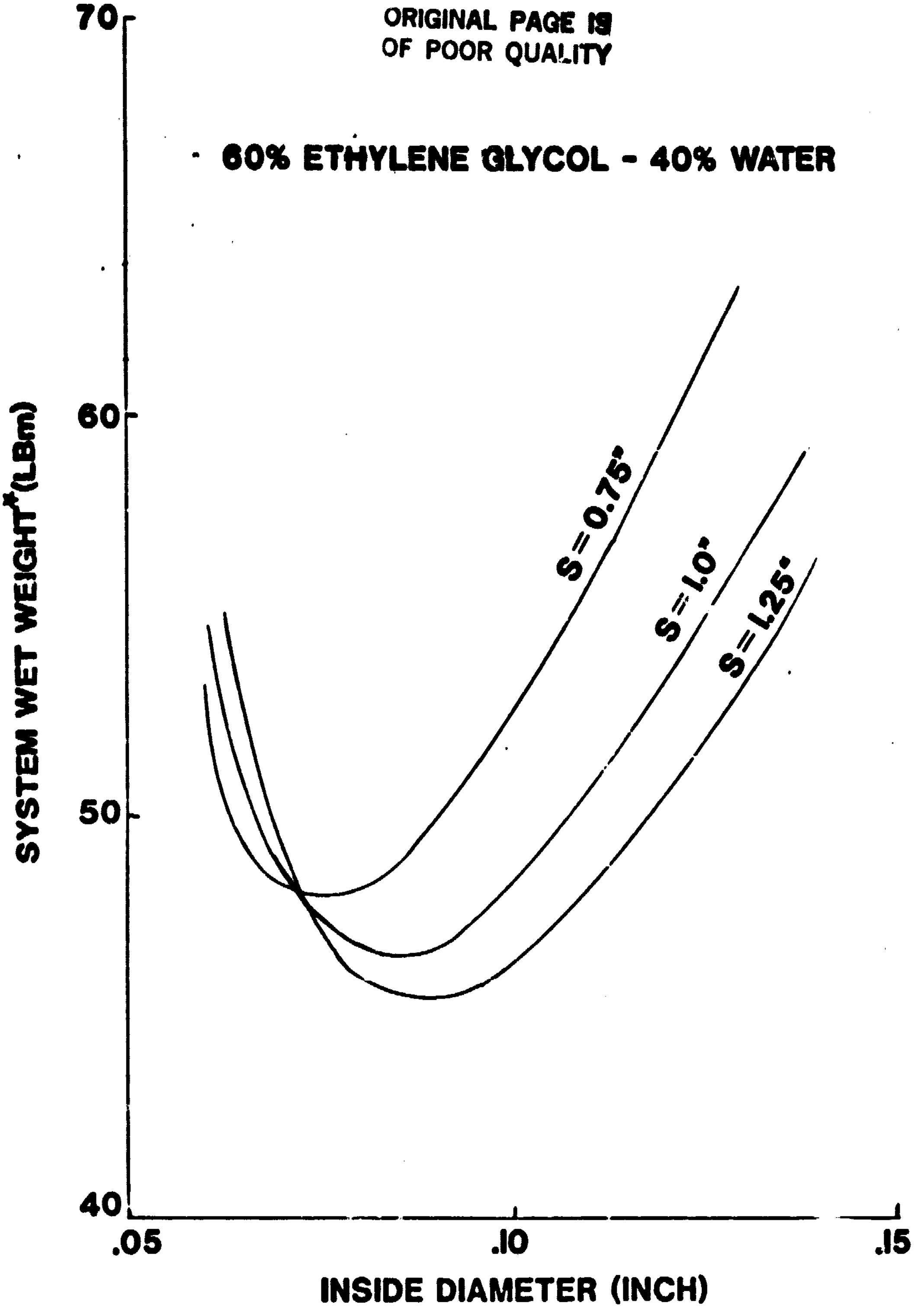


FIGURE 5 SYSTEM WEIGHT FOR RS-89a

*Weight includes manifolds, drum, retraction springs, transport tubing and fittings, fluid, radiator fins and pumping penalty

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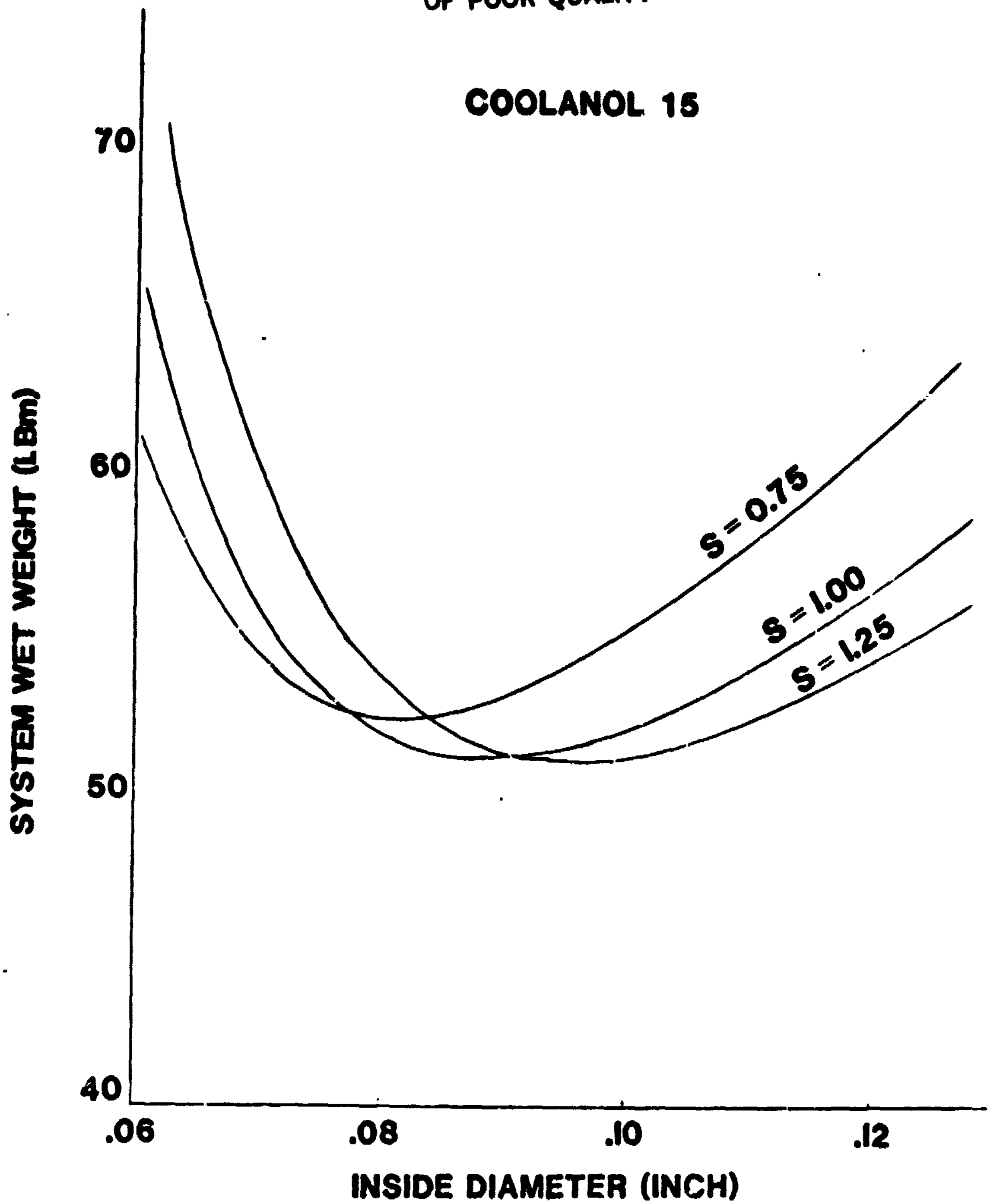

FIGURE 6 SYSTEM WEIGHT FOR COOLANOL 15

* Weight includes manifolds, drum, retraction springs, transport tubing and fittings, fluid, radiator fins and pumping penalty

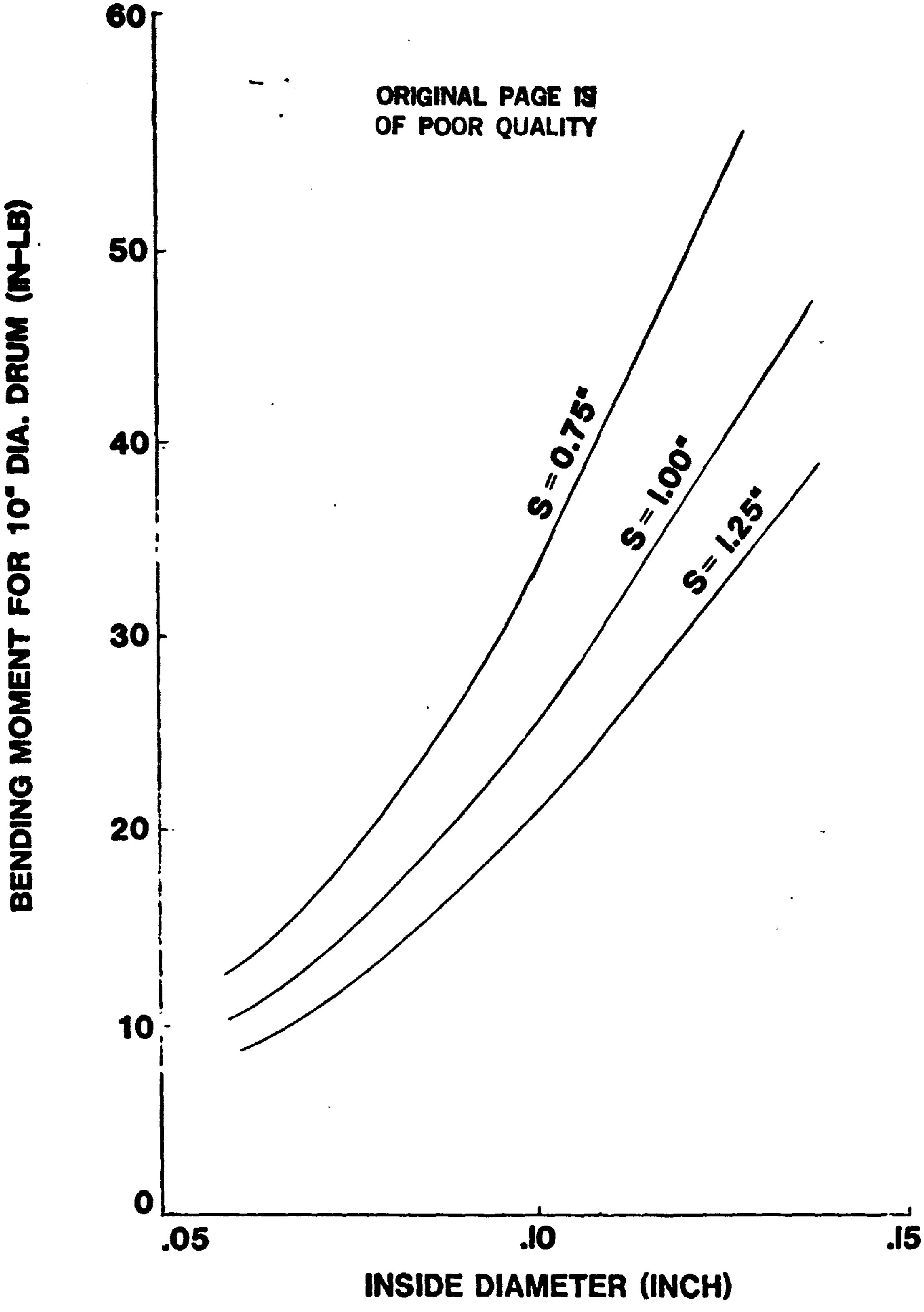

FIGURE 7 BENDING MOMENT REQUIREMENTS

TABLE I
COMPARISON OF FLEXIBLE RADIATOR DESIGNS

DESIGN VARIABLE	RS-89A *	COOLANOL 15
Radiator Panel Length	24.1'	25.7'
Radiator Panel Area	76.9 Ft^2	82.0 Ft^2
Radiator Panel Width	38"	38"
Number of Tubes	50	50
Tube Spacing	0.75"	0.75"
Tube Outside Diameter	0.125"	0.125"
Tube Inside Diameter	0.0625"	0.0625"
Relative Weight**	51.3 lb	58.3 lb
Pressure Drop	33.0 psi	25.5 psi
Bending Moment for 10" Dia Drum	14 in-lb	14 in-lb
Minimum Outlet Temp (100°F)	-20°F	-70°F
Radiator Fin Emissivity	0.71	0.71
Radiator Fin Efficiency	0.943	0.943
Spring Dimensions (5" Dia Mandrel)	.0167"x3"x29'	.0167"x3"x31'

*60/40% Mixture of Ethylene-Glycol/Water

**The relative weight includes manifolds, the deployment drum, retraction springs, transport tubing and fittings, transport fluid, radiator fins, and the weight penalty for fluid pressure drop.

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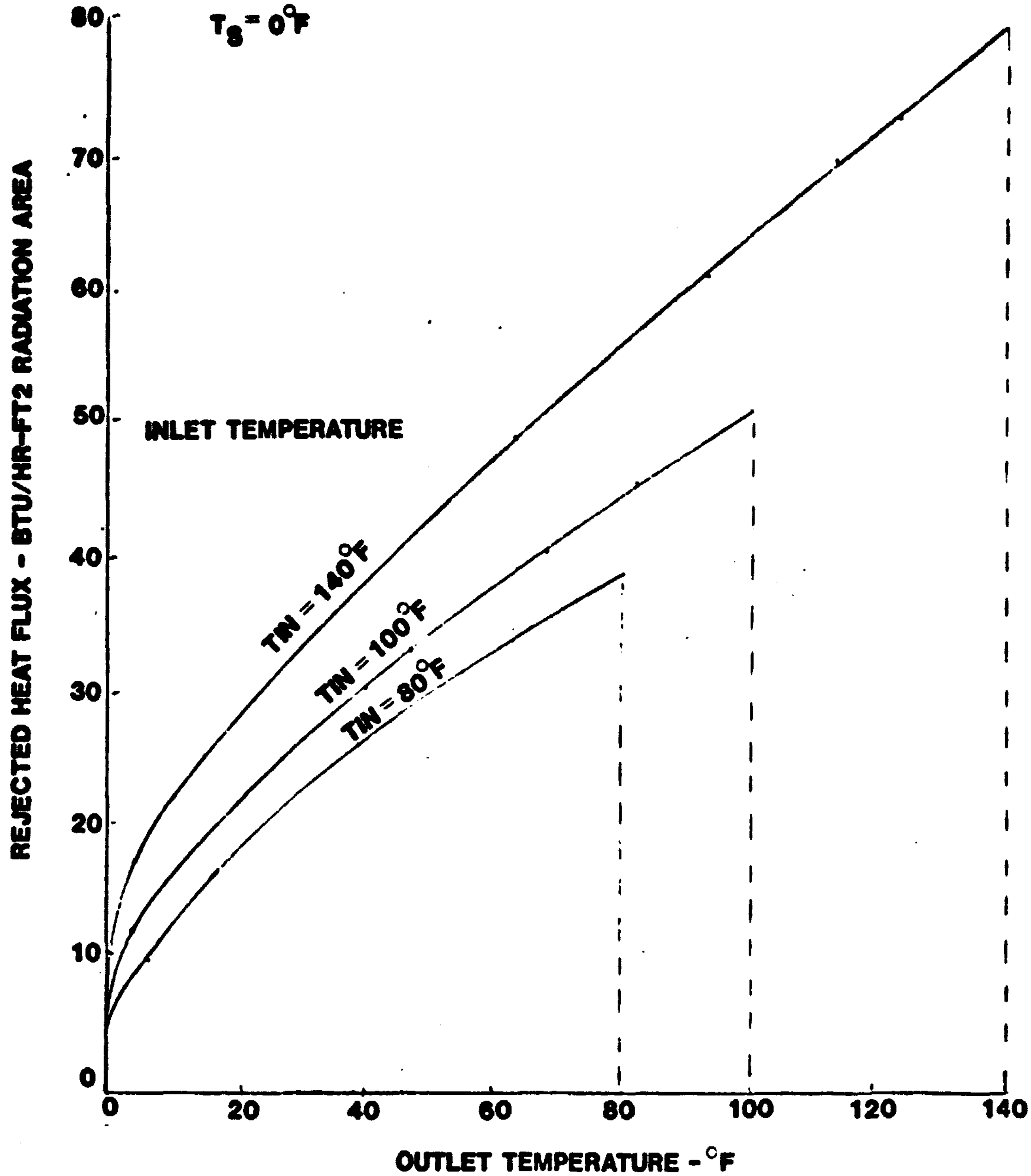

FIGURE 8 SOFT TUBE FLEXIBLE RADIATOR REJECTION HEAT FLUX FOR 0°F SINK TEMPERATURE

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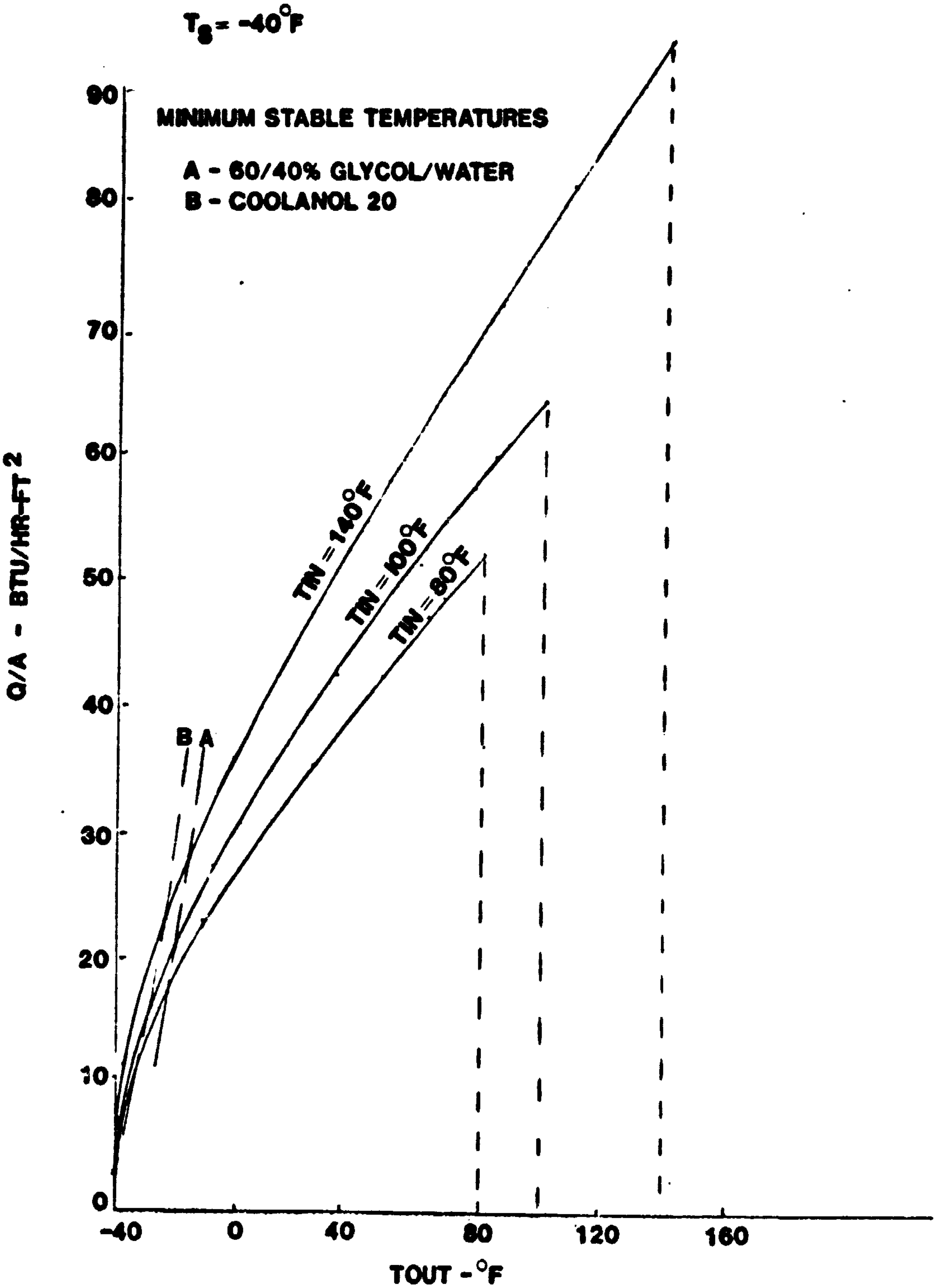

FIGURE 9 SOFT TUBE FLEXIBLE RADIATOR REJECTION HEAT FLUX FOR -40°F SINK TEMPERATURE

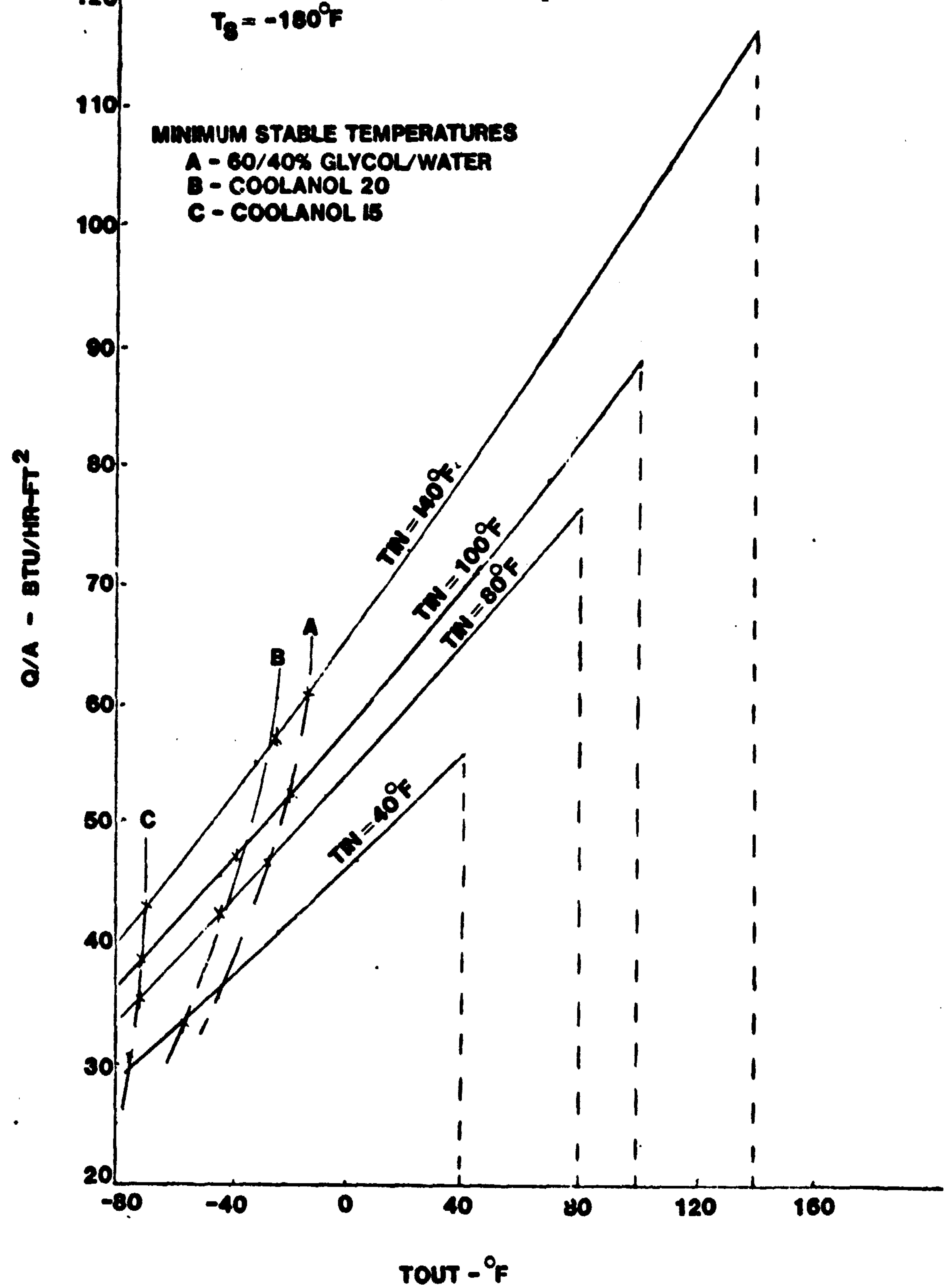

FIGURE 10 SOFT TUBE FLEXIBLE RADIATOR REJECTION HEAT FLUX FOR -180°F SINK TEMPERATURE

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down ratio is 1.1 to 1. Area modulation is necessary for heat load control because of this low turn down ratio. Methods for doing this are discussed in Section 4.0.

3.2 WEIGHT ESTIMATES

The dry panel weight in pounds can be estimated as follows:

$$W_p = W_{manifold + fittings} + W_{tubes} + W_{fins}$$

$$W_p = .0674\,W + 8.86\,\frac{A}{S}\,(d_o^2 - d_i^2) + \left[.1397 + .080\,\frac{d_o}{S}\right] A$$

where:
- W = the width of the radiator panel in inches
- A = the panel projected area in ft^2
- S = tube spacing in inches
- d_o = outside tube diameter in inches
- d_i = inside tube diameter in inches

For the baseline design, $S = .75$ inches, $d_o = .125$ inches, $d_i = 0.062$ inches and $W = 38$ inches, and the length is 27 ft ($A = 85.5\ ft^2$)

This gives, for the baseline design

$$W_p = 2.56 + 0.139A + .153A$$

or

$$\frac{W_p}{A} = .32\ lb/ft^2 \text{ dry panel weight}$$

The fluid weight can be estimated by

$$W_f = \left[4.08\,\frac{A}{S}\,d_i^2 + .01\,W\right]\,\rho/\rho_{H_2O}$$

For $S = .75$, $d_i = .062$, $\rho = 67$ (Glycol/water) and $W = 38$ inches,

$$\frac{W_f}{A} = .028\ lb/ft^2$$

The inflation tube deployment system weight can be estimated by

$$W_D = .0195\,DW + 23\,tL$$

where:
- D = diameter of deployment drum in inches
- W = panel width in inches
- t = thickness of retraction springs in inches
- L = length of panel in feet

For the baseline panel, $D = 10$ inches, $W = 38$ inches, $t = .0167$ inches, and $L = 27$ ft.

$$W_D = 17.8\ lb$$

or

$$\frac{W_D}{A} = .208\ lb/ft^2$$

The pumping power weight can be estimated by

$$W_{pp} = 9.87 \times 10^{-17} \left(\frac{S \cdot L}{W \cdot d_i^4}\right) (\dot{m}^2) \frac{PP}{\eta}$$

For the baseline panel, S = .75 inches, L = 27 feet, W = 38 inches and d_i = .062 inches. Also, if we assume m = 100 lb/hr, PP = 350 lb/kW and a pump efficiency, η = 0.3:

$$W_{pp} = 3.33 \text{ lbs.}$$

or

$$\frac{W_{pp}}{A} \quad 0.039 \text{ lb/ft}^2$$

The total weight can be summarized as

$$\frac{W_t}{A} = \frac{W_p}{A} + \frac{W_f}{A} + \frac{W_D}{A} + \frac{W_{pp}}{A}$$

$$= (.32 + .028 + .208 + .039) \text{ lb/ft}^2$$

$$= .595 \text{ lb/ft}^2 \text{ of projected area}$$

$$= .298 \text{ lb/ft}^2 \text{ of radiating area}$$

If the pumping power weight is ignored (i.e., hardware weight only), the total wet hardware weight of the baseline system is

$$\frac{W_t}{A} = \frac{W_p}{A} + \frac{W_f}{A} + \frac{W_D}{A}$$

$$= (.32 + .028 + .208) \text{ lb/ft}^2$$

$$= .554 \text{ lb/ft}^2 \text{ of projected panel area}$$

$$= .277 \text{ lb/ft}^2 \text{ of radiating area}$$

3.3 PANEL HYDRAULIC PERFORMANCE

The pressure drop of the flexible radiator is a function of the panel flow geometry (number of tubes, tube I.D., and tube length) and the fluid thermophysical properties (which are a function of temperature distribution). The pressure drop can be calculated by the equation

$$\Delta P = 6.795 \times 10^{-10} \left(\frac{\mu}{\rho}\right) \left(\frac{L\ S}{W\ d_i^4}\right) \dot{m} + 3.4 \times 10^{-7} \left(\frac{1}{\rho}\right) \left(\frac{S}{W\ d_i^2}\right) \dot{m}^2$$

where
ΔP = panel pressure drop, psi
m = mass flowrate, lbm/hr
L = length of flow path, ft.
w = panel width in flow direction, inches
S = tube spacing, inches
d_i = internal diameter, inches
μ = fluid viscosity, lb/ft-hr
ρ = fluid density, lb/ft^3

Figure 11 summarizes the pressure drop estimates for the baselined (prototype) panel design. The geometric values used are:

$L = 58.5$ feet
$W = 18.75$ inches
$S = .75$ inches
$d_i = .0625/12$, feet

The thermophysical property values for the fluids used in predictions are summarized in Table II.

TABLE II
THERMOPHYSICAL PROPERTIES OF FLUIDS

	VISCOSITY, LB/HR-FT			DENSITY, LB/FT ^{3}		
TEMP, $^\circ$F	GLY/WATER	COOLANOL 15	COOLANOL 20	GLY/WATER	COOLANOL 15	COOLANOL 20
-50	700	28.6	58.1	69.4	59.0	59.9
0	76.0	10.5	15.7	69.6	57.4	58.0
50	18.0	5.42	6.97	67.6	56.0	56.2
70	12.0	4.19	5.46	67.2	55.4	55.2
100	7.25	3.21	4.06	66.6	54.5	54.3
150	3.65	2.26	2.57	65.4	53.0	52.4

4.0 DEPLOYMENT METHODS

Two basic approaches are candidates for deployment of the soft tube flexible radiator. These are the inflation tube/retraction spring deployment or pneumatic method and an extendable boom deployment method. These approaches are discussed below.

4.1 PNEUMATIC DEPLOYMENT

With the pneumatic inflation tube deployment/spring retraction concept, the flexible radiator panel, which is stored (wrapped) onto a cylindrical drum, is deployed into a near planar panel by inflating tubes on each side of the panel with nitrogen gas. The pressurizing of the tubes causes them to straighten against the retraction springs contained inside the tubes. Retraction is accomplished by deflating the deployment tubes, allowing the retraction spring to roll the flexible panel up around the drum.

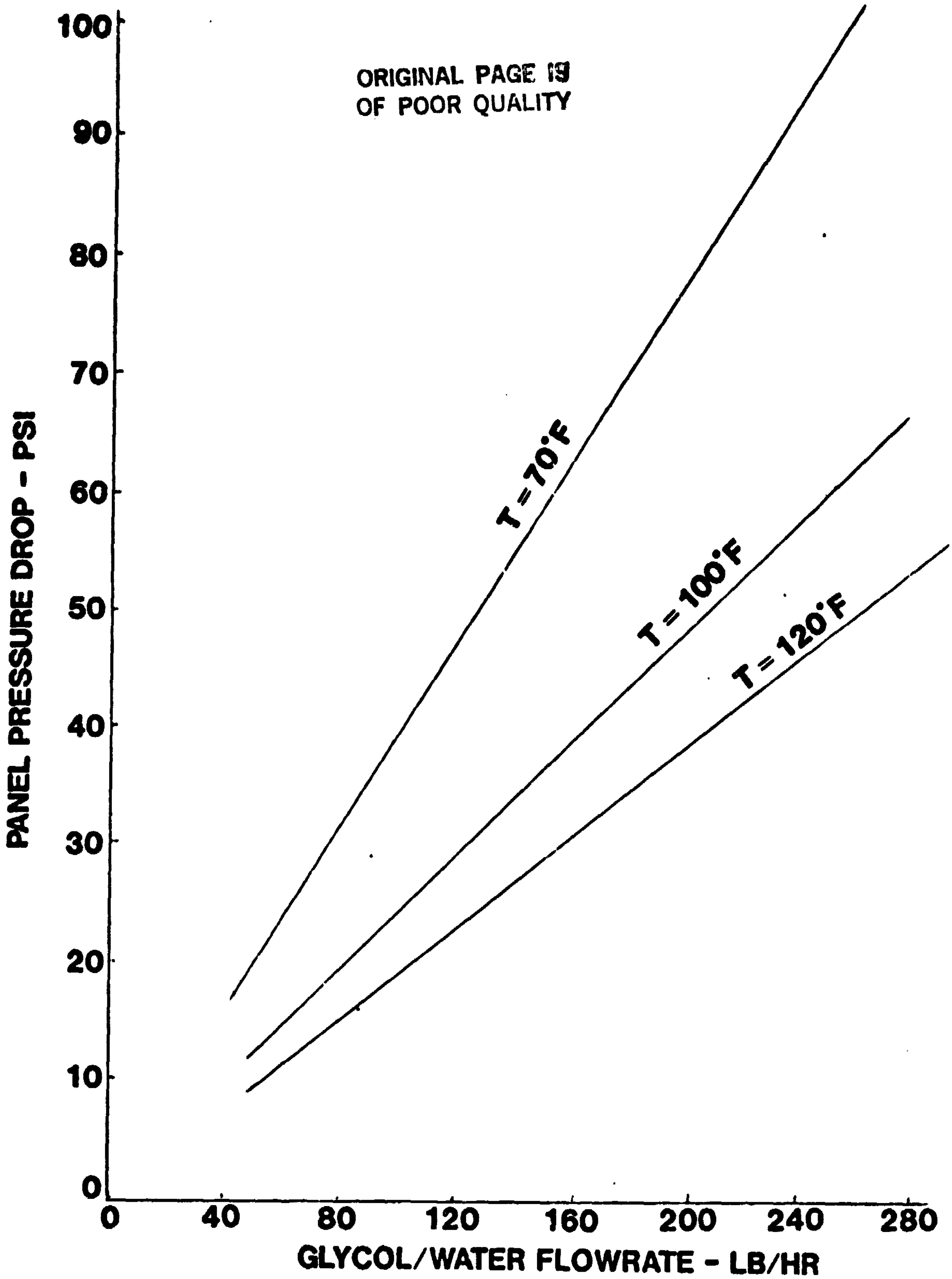

FIGURE 11 SOFT TUBE RADIATOR PRESSURE DROP TEST SUMMARY

Figures 12 through 15 illustrate the pneumatic deployment approach. Figures 1 and 2 show the prototype panel configuration which uses this method. In its design, a 4 inch diameter inflation tube is attached to each edge of the radiator panel. The tube is fabricated from .030" thickness of Kevlar/Mylar and a pocket is fabricated onto the inflation tube (on the drum side of the tube) into which the 3 inch wide by 0.016 inch thick flat steel spring is attached. The panel is stowed in approximately eight wraps on a 10 inch diameter by 30 inches wide stowage drum. The drum is deployed on the end of the panel as illustrated in Figure 12. The deployment is accomplished by supplying low pressure nitrogen (1 psig) to the inflation tube. The magnitude of the force exerted by the two retraction springs must be closely matched to effect a straight roll-up of the radiator panel onto the drum. A spring adjustment capability is designed into the spring hold-down to permit fine tuning of the panel retraction force.

Figure 13 shows a schematic of the nitrogen pressurization system interfaces with the inflation tube deployment approach. This nitrogen pressurization system is configured to permit active control of deployment length for heat load control. Deployment is accomplished by increasing nitrogen pressure in the inflation tubes. Retraction is accomplished by venting the tubes to reduce pressure. This method of deployed area control requires a sufficient supply of nitrogen gas to replace that expended. Also shown in Figure 13 is the deployment action as a function of radiator outlet temperature. The area control system attempts to maintain the radiator outlet temperature between 0^{o}F and 30^{o}F.

Figure 14 shows a drawing of a 4 kW heat rejection subsystem (3.4 kW with 0^{o}F sink temperature; 5.1 kW with a -40^{o}F sink temperature) with 110 F inlet temperature and 40^{o}F outlet temperature.

Figure 15 shows two 4 kW wings stowed in the cargo bay of the Shuttle Orbiter. Weight estimates for the 4 kW subsystem using the pneumatic deployment are shown in Table III. The total system weight is approximately 368 pounds.

4.2 EXTENDIBLE BOOM DEPLOYMENT/RETRACTION

The mechanically driven extendable boom is an attractive alternate to the pneumatic deployment system described in the previous section. As with the pneumatic deployment, the flexible panel is stowed on a cylindrical drum. The panel is deployed into a planar configuration by extending the extendable boom, thus unrolling the panel from the drum. The stowage drum can be either located at the outboard end of the panel, as shown in Figure 17, or at the panel base, as shown in Figure 16. When the drum is located outboard, no fluid swivels are required. However, the concentrated outboard mass (of the drum) adversely impacts the extendable boom design. When the drum is located inboard, fluid swivels or a flexible hose transfer device is required. Figure 18 illustrates the coiled flexible hose transfer device which has been built and tested at Vought.

The flex hose transfer device which was built will allow 5.8 revolutions and 250 cycles. Fluid swivels will do the same joe with much lower weight, less volume, less pressure drop, and less complexity. The baselined approach for the extendible boom deployment methoa is with drum at

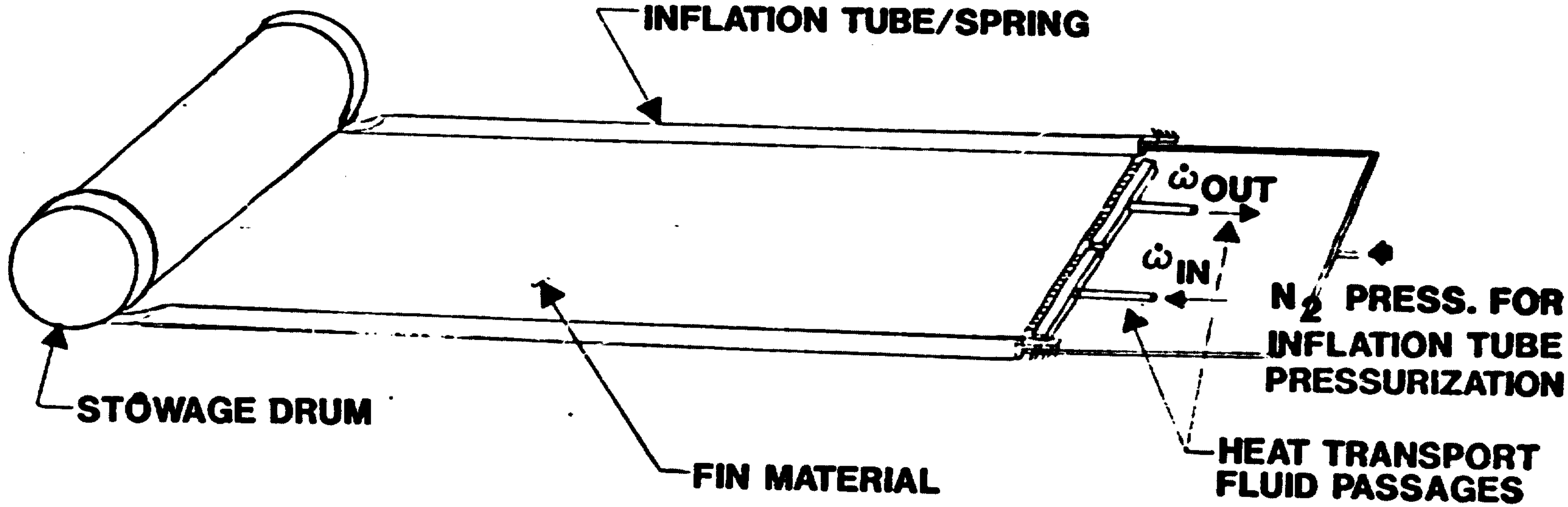

Figure 12 Flexible Radiator Panel with Pneumatic Deployment

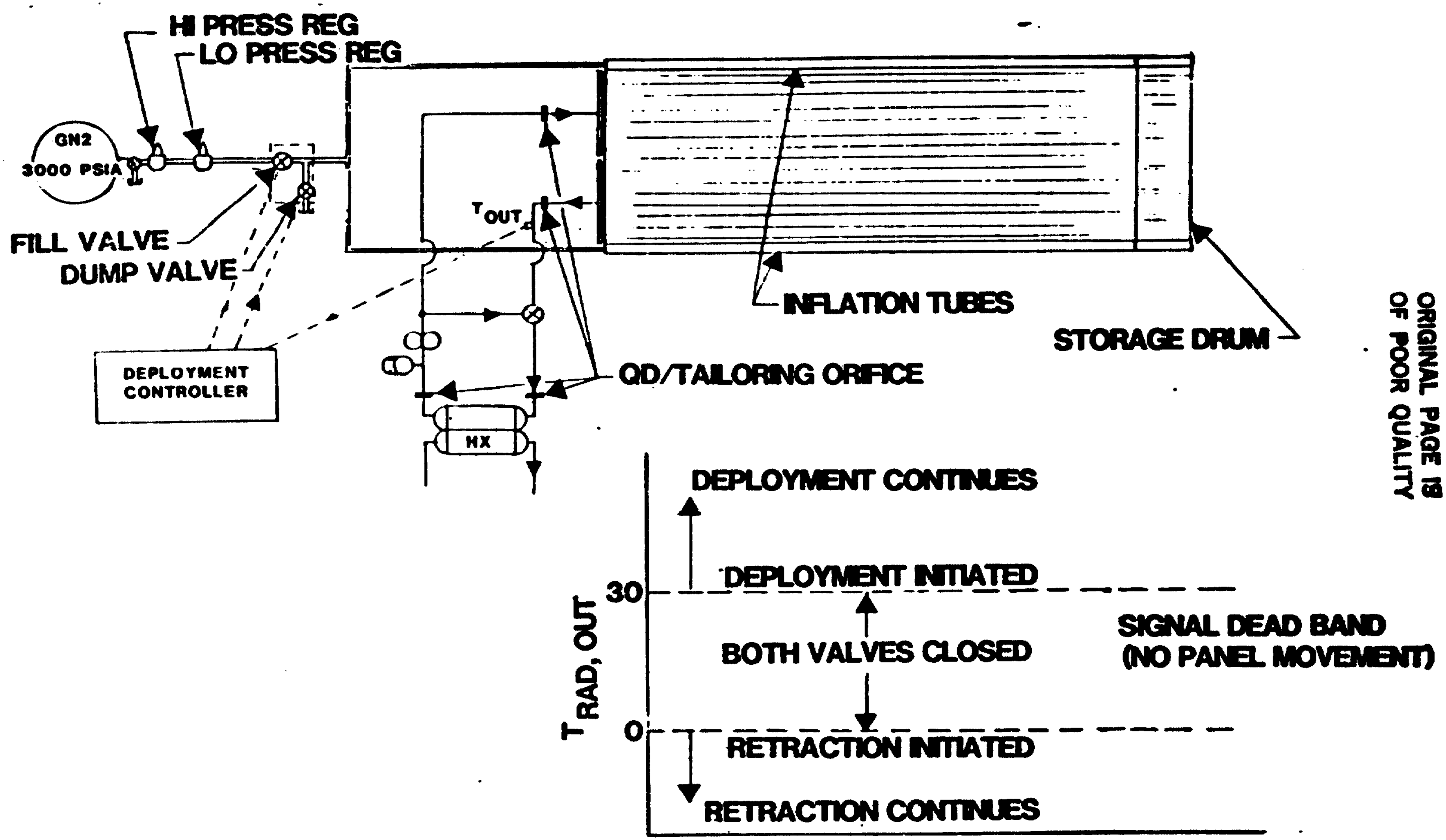

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FIGURE 13 SOFT TUBE RADIATOR DEPLOYMENT/RETRACTION CONTROL

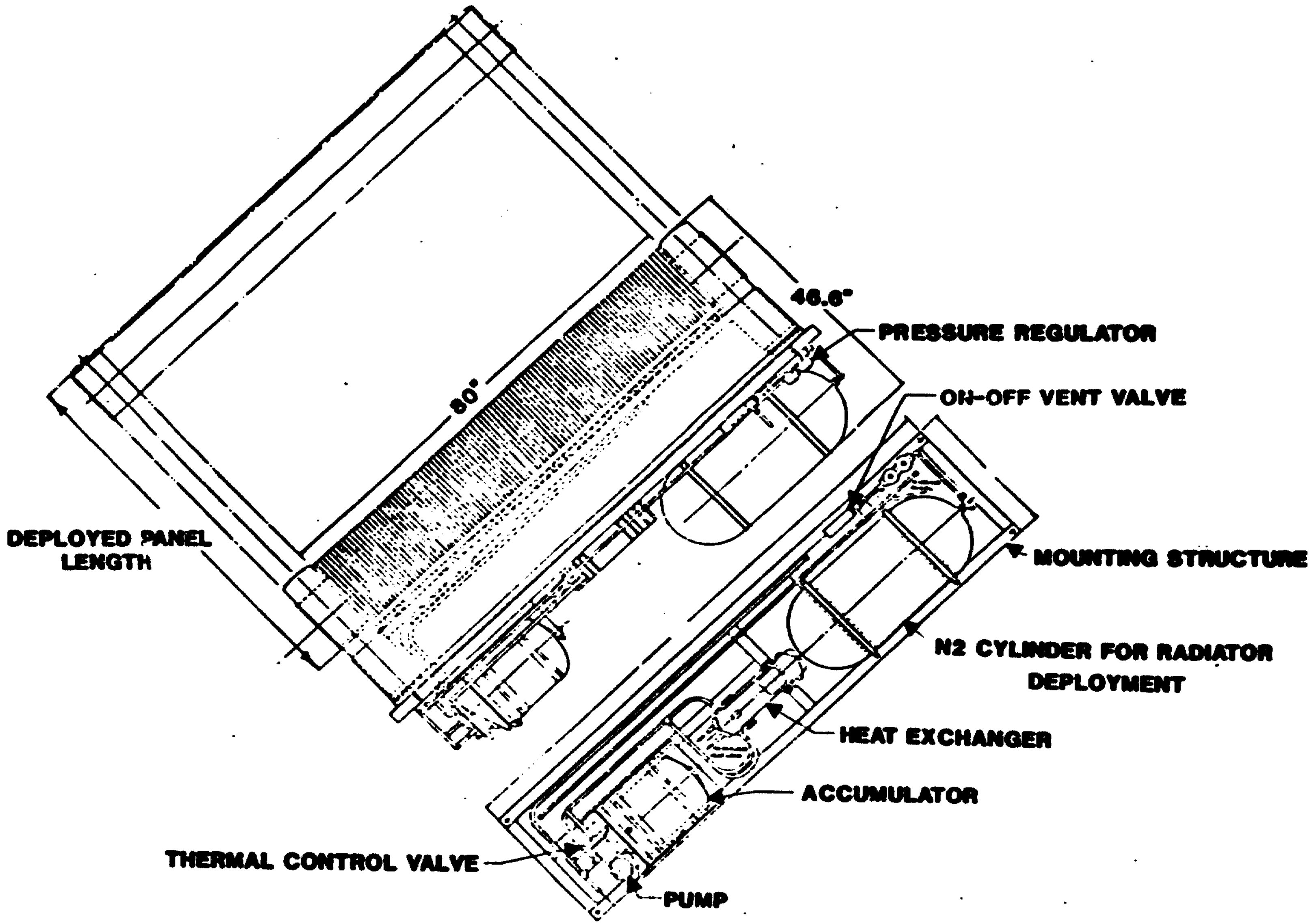

FIGURE 14 FLEXIBLE RADIATOR PNEUMATIC DEPLOYMENT PACKAGE

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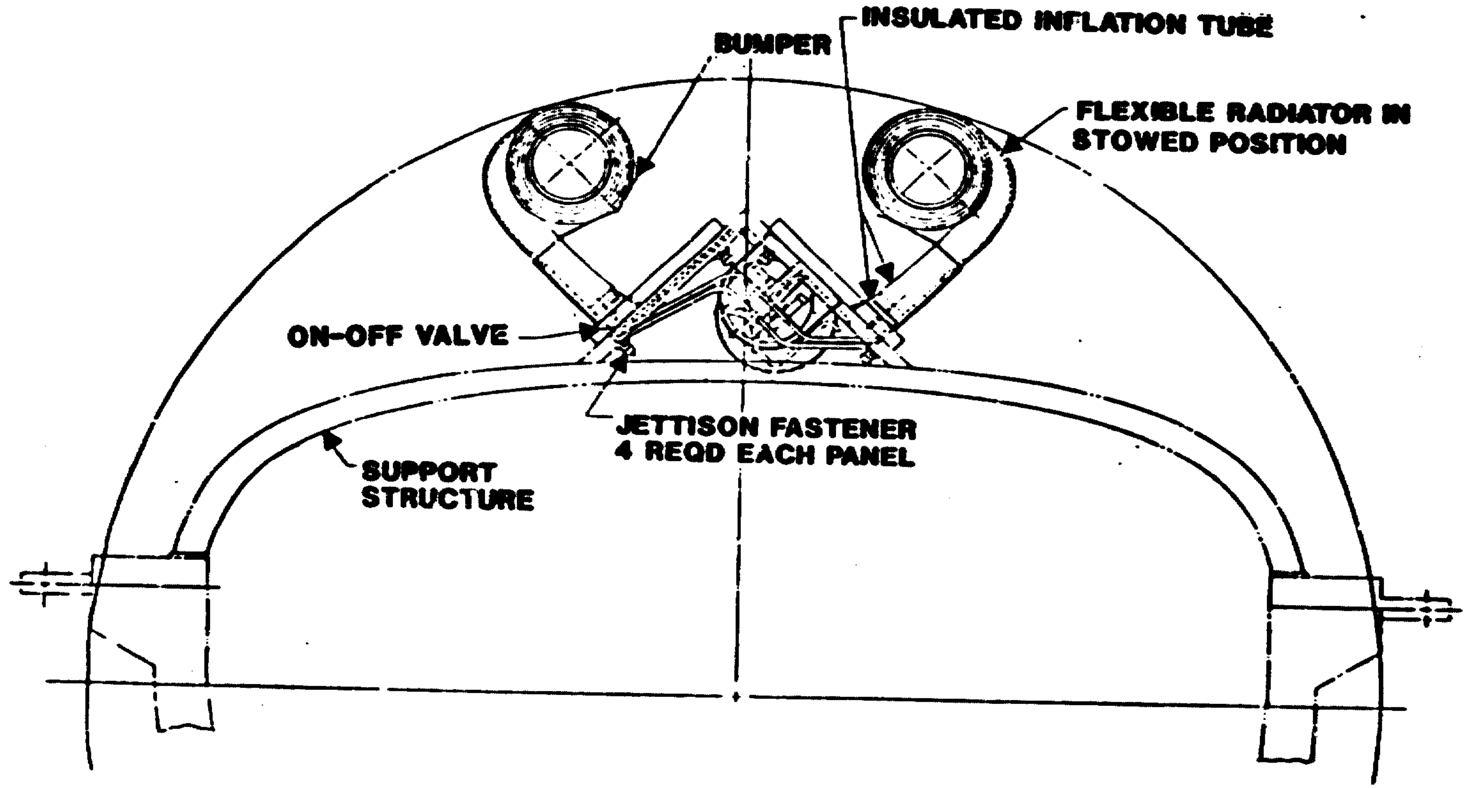

FIGURE 15
FLEXIBLE RADIATOR PNEUMATIC DEPLOYMENT IN STOWED POSITION

TABLE III
4 kW FLEXIBLE RADIATOR MODULE
PNEUMATIC DEPLOYMENT

Panel (80" wide by 27' long)		33.5
Panel Clamp		4.0
Panel Manifold and Fittings		6.0
Drum and Plumbing		15.6
Inflation Tube & Spring Support, Clamps, and Hardware		54.5
Accumulator Package		20.5
Heat Exchanger		16.4
Coolant Plumbing, Clamps and Hardware		5.4
N_2 Cylinder		88.5
Cylinder Mtg. Clamps		2.8
N_2 On-Off-Vent Valve (2)		3.0
N_2 Plumbing, Clamps and Hardware		2.5
N_2 Regulator		1.0
N_2 Elect. Control Box		2.0
Mounting Frame		32.5
Jettison Fasteners		2.0
	DRY WEIGHT	290.2
Coolanol 20		27.0
N_2 Gas		23.4
	WET WEIGHT	340.6
Production Growth (8%)		27.2
	PRODUCTION WEIGHT	368

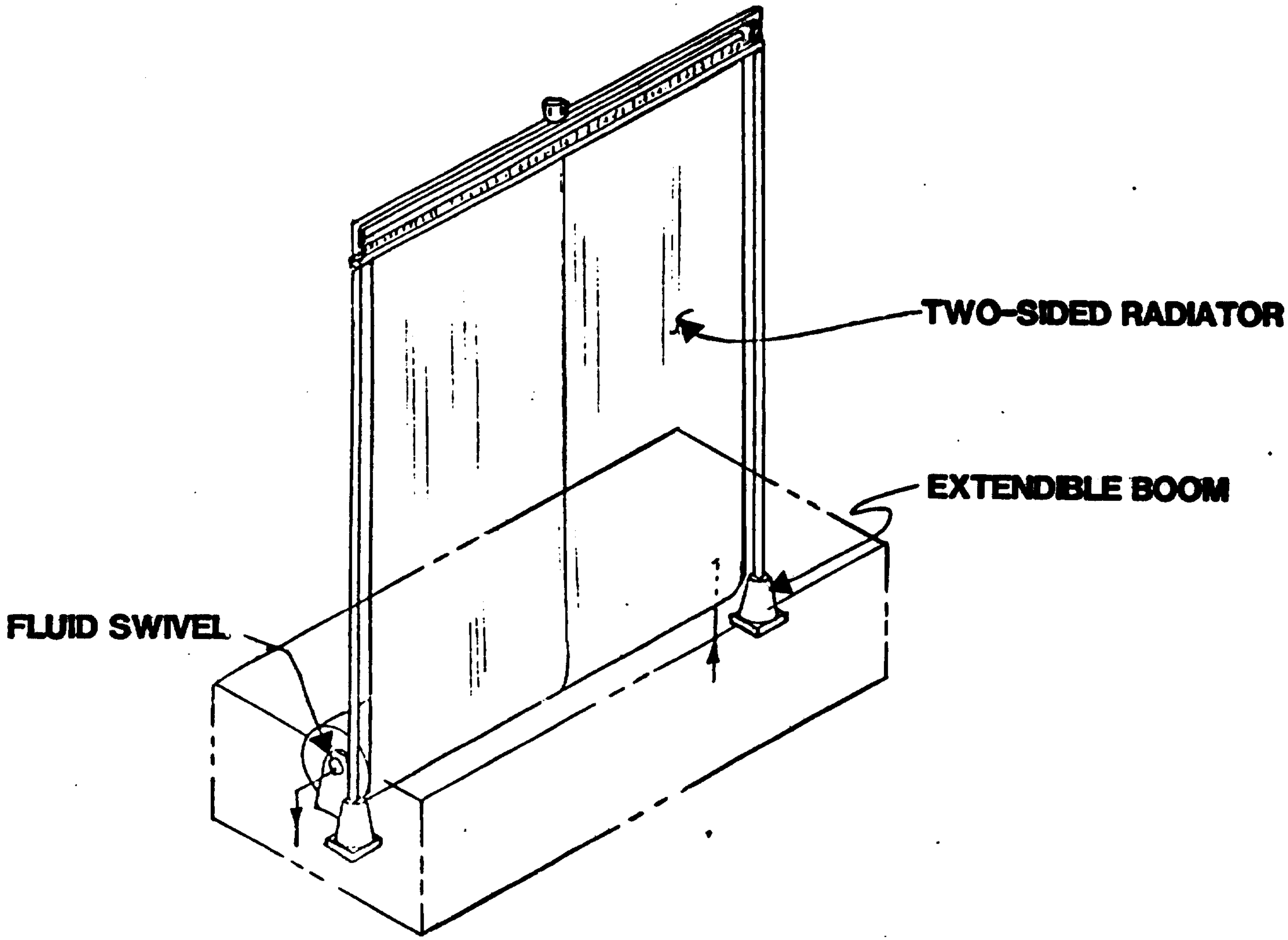

FIGURE 16 FLEXIBLE RADIATOR, DUAL BOOM DEPLOY, SPOOL AT BASE

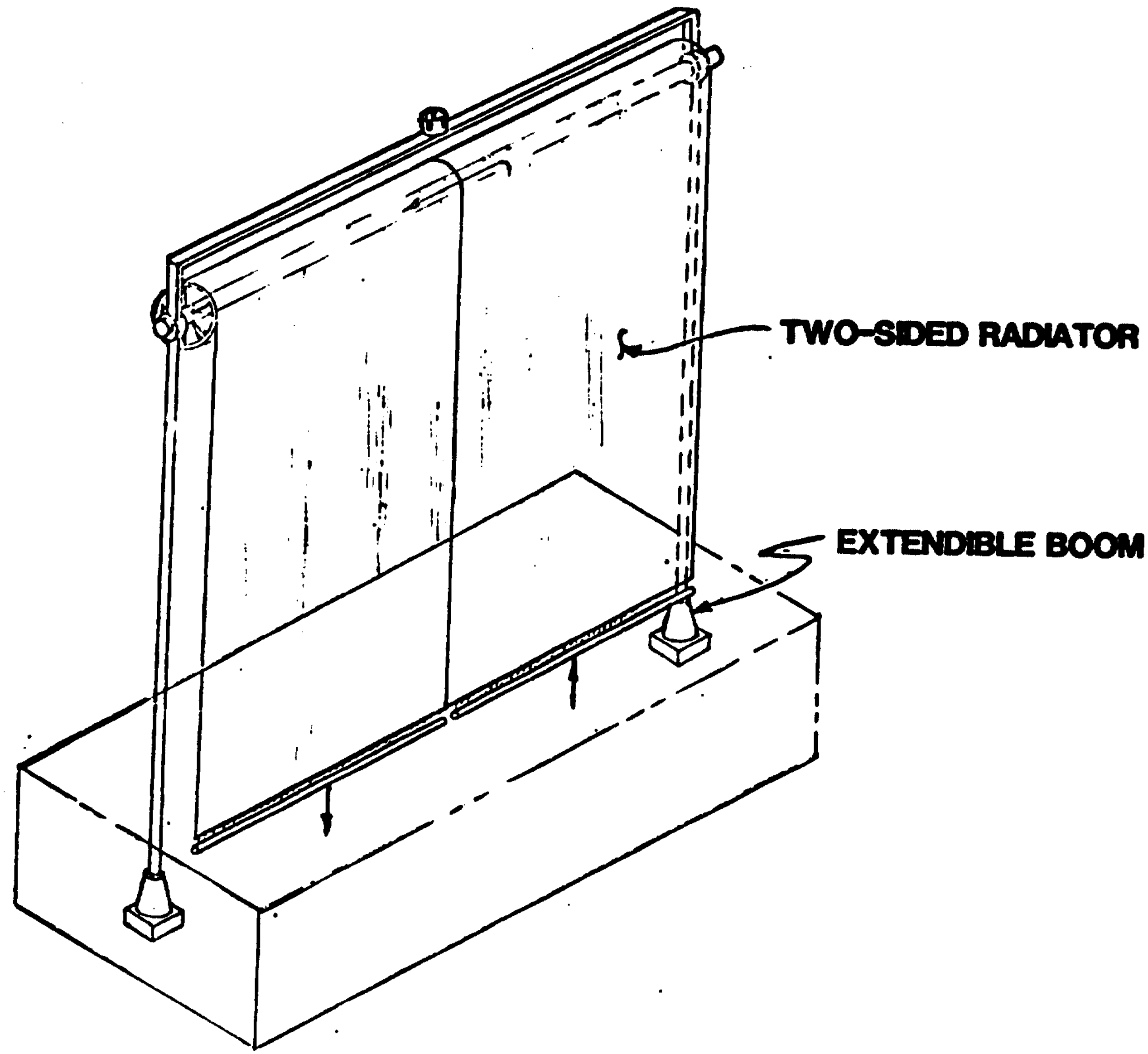

FIGURE 17 FLEXIBLE RADIATOR, DUAL BOOM DEPLOY, SPOOL OUTBOARD

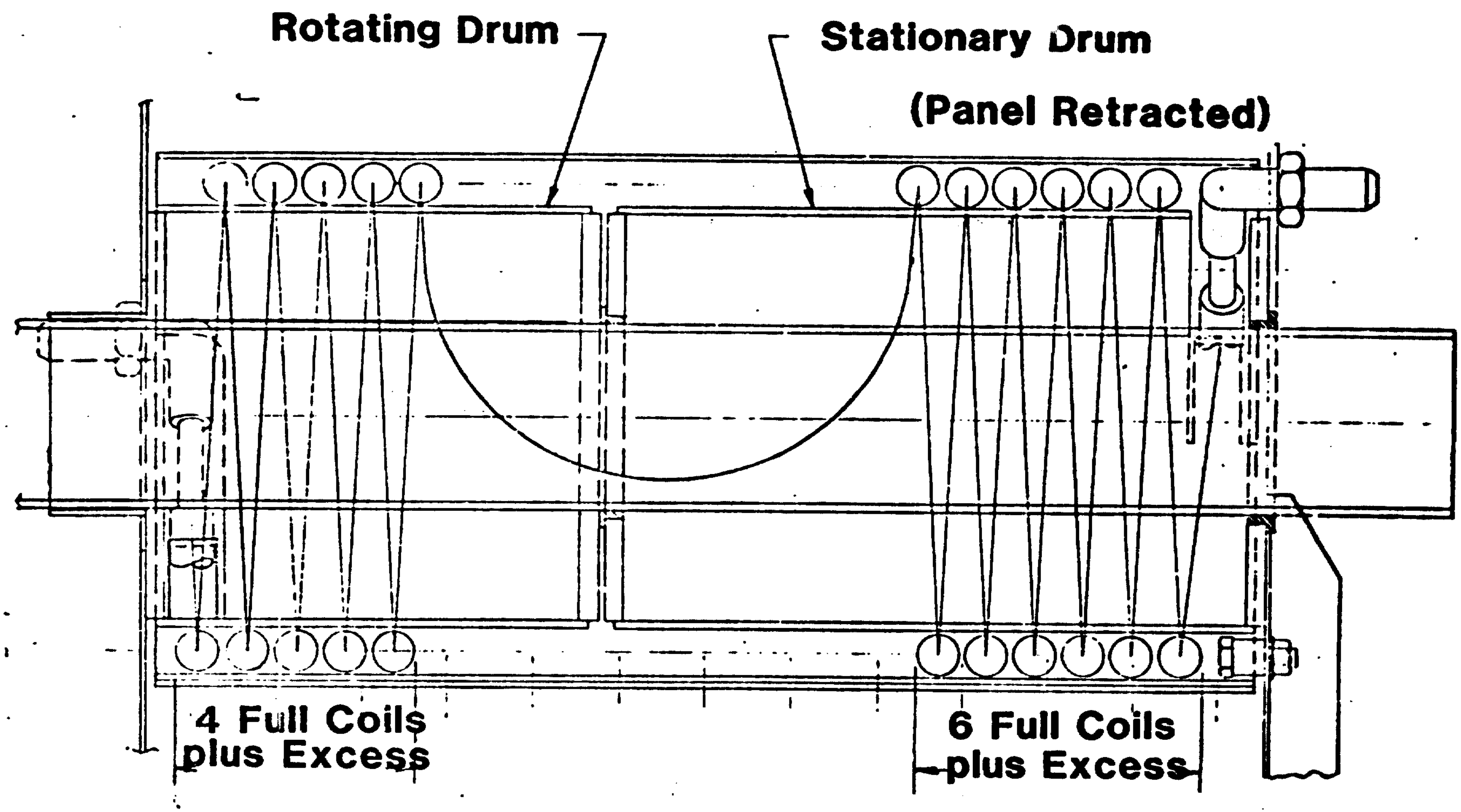

Figure 18 Coiled Flex Hose transports the fluid across the rotating joint

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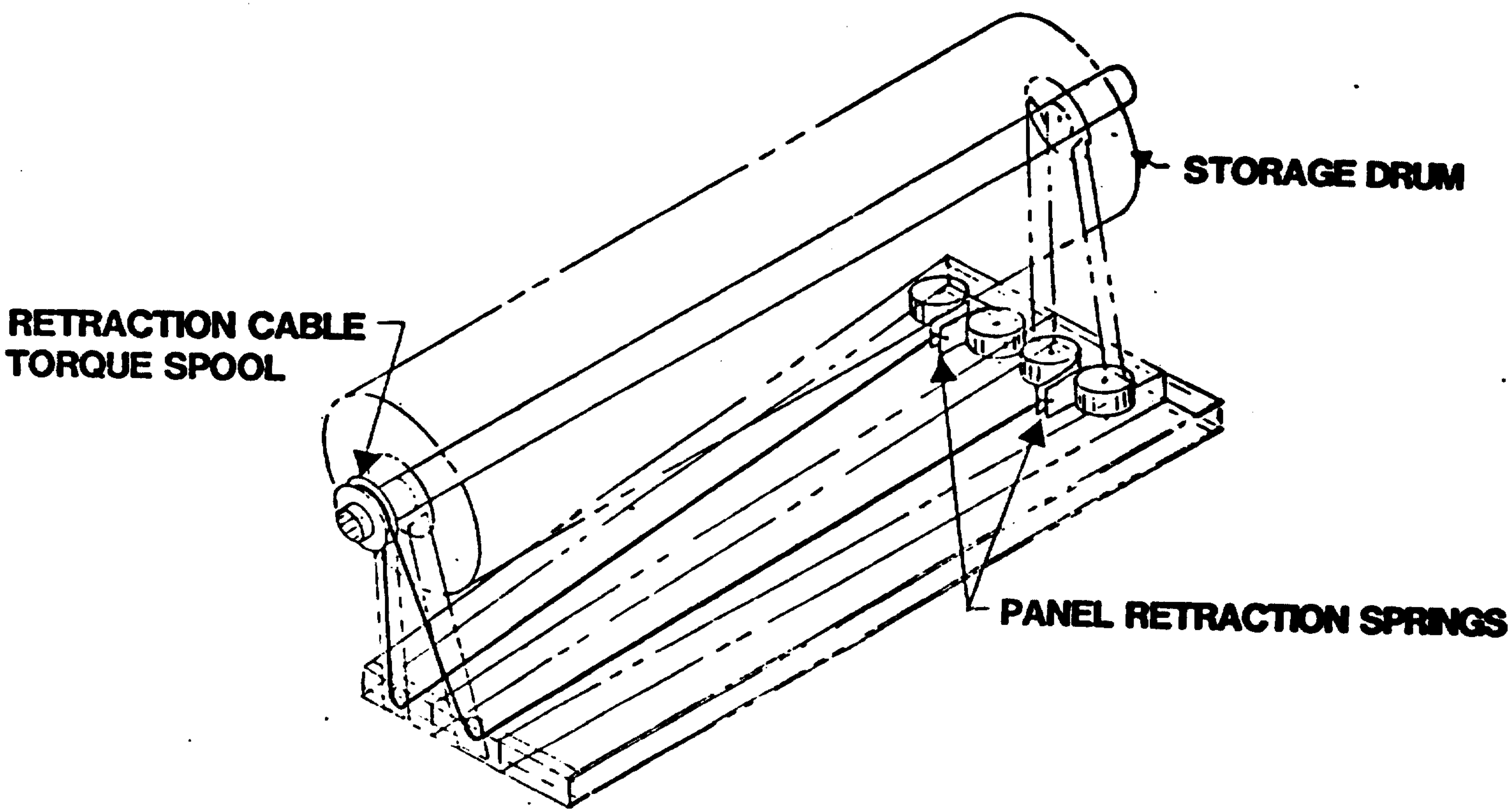

FIGURE 19 RETRACTION SPRINGS apply a panel retracting torque to the storage drum

the base of the radiator with fluid swivels for fluid transfer across the rotating joints (see Figure 16). Using this method, two extendible booms (one on each side) push on the end of the panel to deploy it, pushing against the retraction springs in the drum (see Figure 19). As the radiator panel is deployed, retraction springs (Figure 19) are extended by a 1/16 inch stainless steel cable which winds up on a cable spool attached to the storage drum axle. Panel retraction torque is a constant torque applied by a set of springs through the cable to the storage drum axle. This torque remains constant throughout panel deployment and retraction. Since the storage drum always has a restoring torque applied, panel retraction is initiated by retracting the deployable boom. This retraction mechanism was used on a hard-tube flexible radiator.

One advantage the extendible boom deployment method has over the pneumatic deployment method is the ability to actively control the panel area without the use of expendables. Since the booms are electric motor driven, electric power is used for active area control. Figure 20 illustrates system interfaces required for this. The boom deployment rate is controlled electronically based upon the sensed radiator outlet temperature.

Figure 21 shows a 4 kW boom deployed flexible radiator subsystem module (3.4 kW to a 0°F sink temperature; 5.1 kW to a -40°F sink temperature). It also shows the fluid circulation components required for a subsystem module. Figure 22 shows two 4 kW modules stowed in the Space Shuttle Orbiter cargo bay. Weight estimates for the boom deployed 4 kW system are shown in Table IV. The total system weight is approximately 228 pounds compared to 368 pounds for the pneumatic deployment method.

4.3 Extendible Mast Deployment/Retraction

An alternate mechanically driven deployment system would utilize a mast triangular truss structure. Masts are much more rigid than the previously-discussed booms and are, likewise, space proven. The Solar Electric Propulsion (SEP) deployable solar array will soon demonstrate the feasibility for using a mast on a large 12.5 kW wing, as a Shuttle pallet mounted flight experiment.

Because of its stiffness, only a single mast would be required for flexible radiator deployment/retraction. It would be centrally mounted on one side of the panel, and interface the outboard end of the radiator through a yoke. To support this concept a specification was prepared and submitted to potential suppliers for informational proposals. An example* continuous longeron boom 9 inches in diameter and 29 feet long would provide sufficient strength and stiffness. The boom would deploy from an 11-inch diameter x 25-inch long canister weighing 14.6 lbs.

5.0 FLUID SYSTEM CONSIDERATIONS

The selection of the working fluid involves a number of system considerations which include materials compatibility, flow stability and low load performance. The fluid selection is discussed below.

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*Courtesy AEC-ABLE Engineering Company

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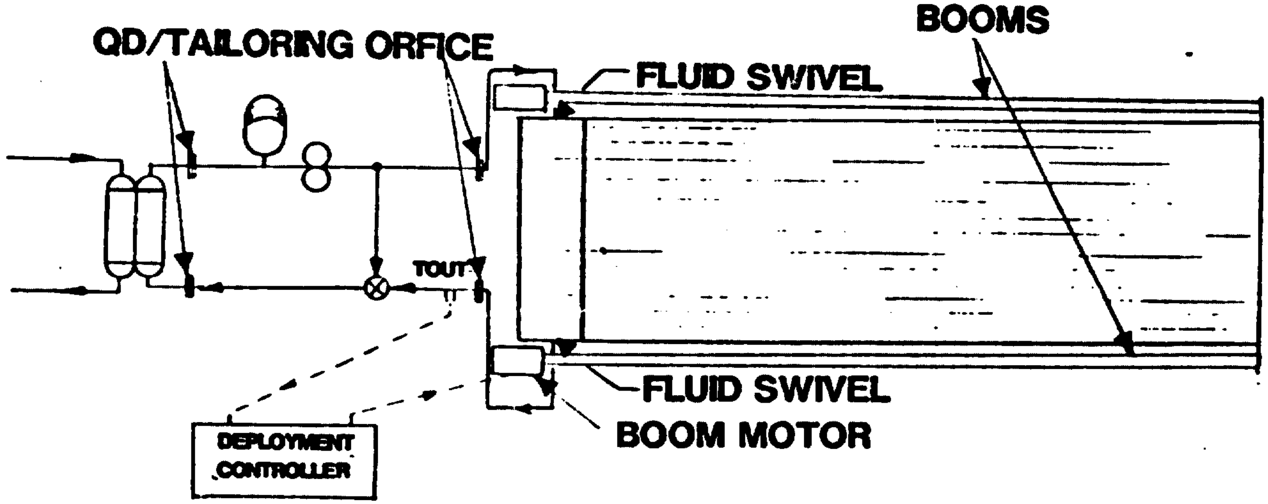

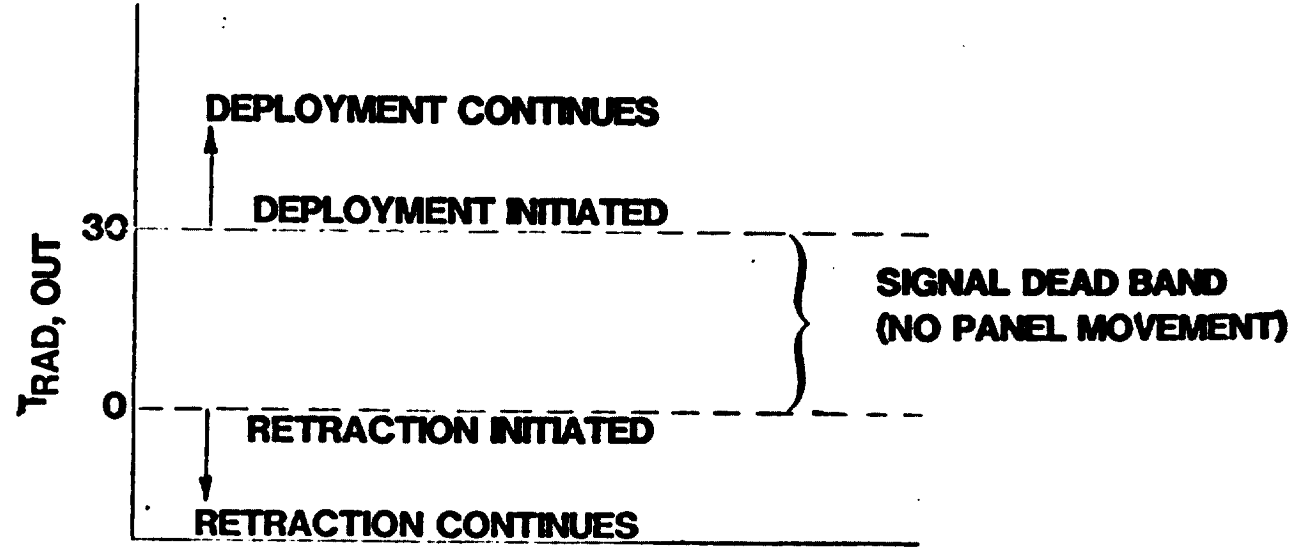

FIGURE 20 SOFT TUBE RADIATOR DEPLOYMENT/RETRACTION CONTROL

BOOM DEPLOYMENT - DRUM NOT DEPLOYED

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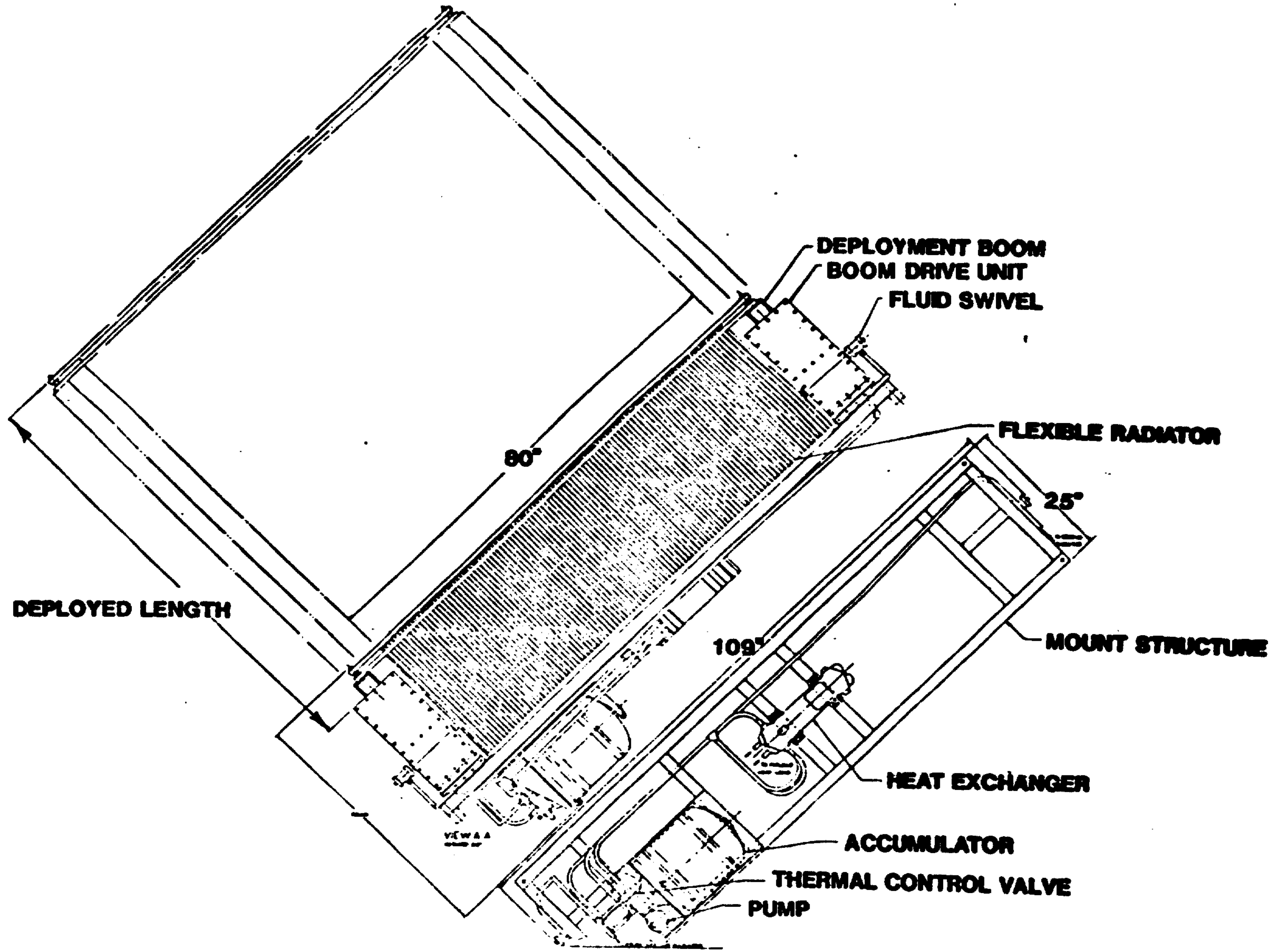

FIGURE 21 FLEXIBLE RADIATOR - BOOM DEPLOYMENT PACKAGE

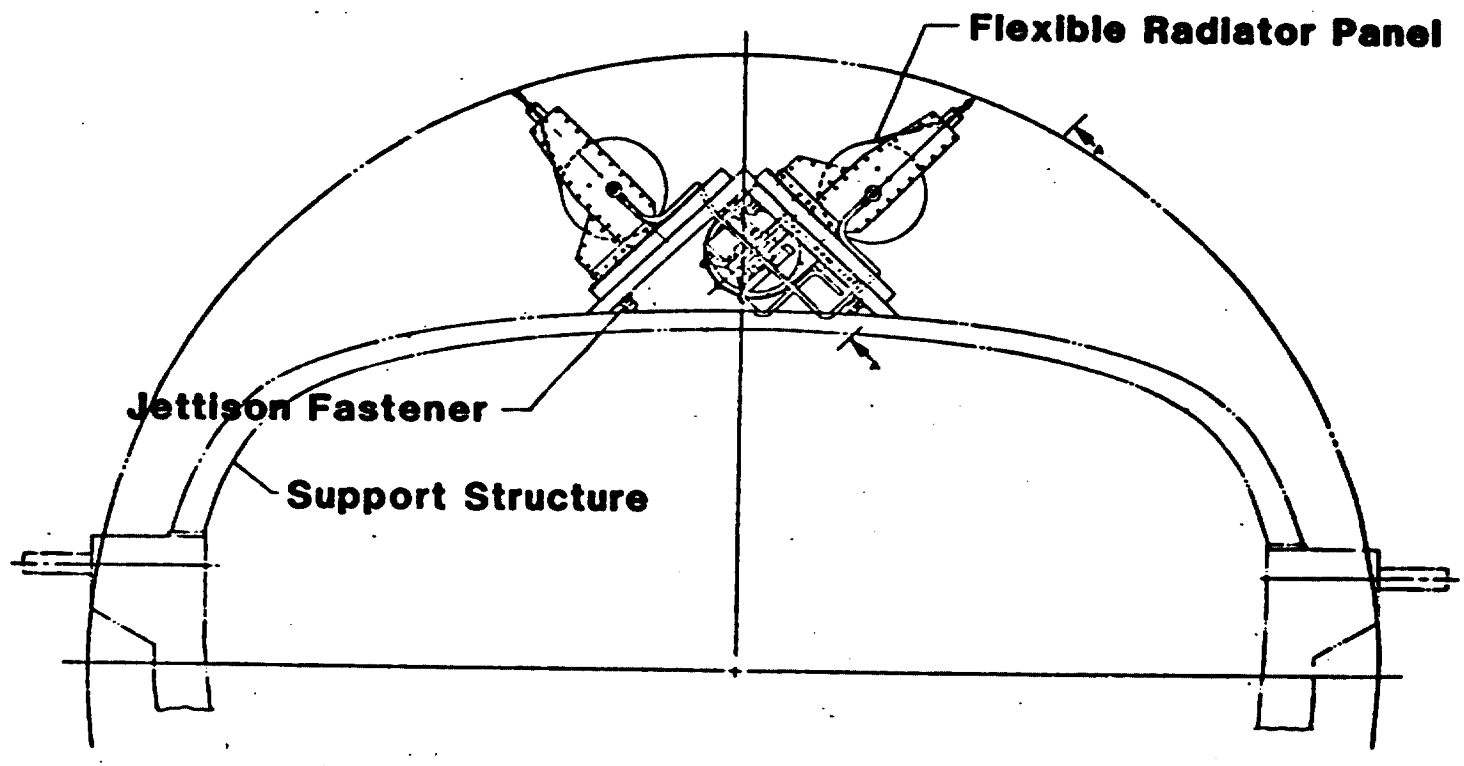

Figure 22 Flexible Radiator Boom Deployment In Stowed Position

TABLE IV
4 kW FLEXIBLE PANEL RADIATOR
BOOM DEPLOYMENT

Panel (80" wide by 27' long)		33.5
Boom Drive Unit		26.0
Manifold and Fittings		6.0
Clamp		4.0
Swivel		2.5
Drum with Plumbing and Shaft to Swivel		31.0
Accumulator Package		20.5
Heat Exchanger		16.4
Coolant Plumbing, Clamps and Hardware		5.4
Mounting Frame		36.4
Jettison Fasteners		2.0
	DRY WEIGHT	183.7
Coolanol 20		27.0
	WET WEIGHT	210.7
Production Growth (8%)		16.9
	PRODUCTION WEIGHT	228

5.1 WORKING FLUID SELECTIONS

Early fluid studies for the soft tube flexible radiator revealed that some of the commonly used Freon type fluids were not acceptable for the Teflon tube because of excessive permeability. Literature data for Freon 22 and 12 indicate high leakage rates due to permeability of the tubing. Tests were made for Freon 11 and 21 by Vought (Ref. 1) which showed the permeability at 80°F for Freon 21 to be 1.42×10^{-8} lb/day-in-psi and for Freon 11 to be 0.36×10^{-8} lb/day-in-psi. These rates result in a leakage, for a 30 day mission for one panel at 100 psi, of 17 lb of Freon 21 and 4 lb of Freon 11. At temperatures above 100°F, the Freon 11 leakage is higher than Freon 21 (see Figure 23). Permeability tests were also conducted for the 3M Company FC fluid (FC 77 and 88). It was found that these fluids also permeate the Teflon tubing at unacceptable rates.

The leakage problem discussed above resulted in a fluid trade study to evaluate alternate candidate fluids. Table V shows a comparison of the fluids considered in the study, along with a relative weight and area comparison. Glycol/water was determined to be the best all around fluid with Coolanol 15 a second choice. (Coolanol 20 was not included in the comparison.) All the other candidates considered have a problem with permeating the Teflon tube. Glycol/water is the lowest weight and area for the two fluids but requires a higher minimum outlet temperature. Figure 24 shows the allowable outlet temperatures as a function of inlet temperatures for stable fluid flow. At 100°F inlet temperature, Glycol/water can operate down to -20°F and Coolanol 15 can operate down to -70°F. Manufacture of Coolanol 15 has been discontinued since the fluid evaluation was performed. A similar fluid, Coolanol 20, is a candidate for its replacement, but it requires that the outlet temperature not go below -38°F for 100°F inlet as shown in Figure 25.

5.2 HEAT LOAD CONTROL

Because the heat rejection would be excessively high at the minimum outlet temperatures allowed for the acceptable fluids, a heat load control method other than a simple bypass of the radiator is required. One attractive method for heat load control on the Flexible radiator is by varying the area by continuously deploying or retracting to provide the amount of heat rejection needed for the heat load. A control system rate analysis for the area control was performed for the prototype flexible radiator to determine the approximate rate deployment and retraction required. The prototype system should move at a rate which requires approximately 7 or 8 minutes for full deployment or retraction. By using this method of heat load control, a very high maximum-to-minimum heat load can be achieved. By proper thermal design, the radiator can be surrounded with insulation in the retracted condition, reducing the minimum load heat rejection to a negligible amount. This would permit storage on-orbit during quiescient periods with little or no heat load.

The deployment method has a significant impact on the ability to control the panel area. Two deployment methods are described in Section 4.0. The pneumatic method, which has been built and tested on the prototype unit, requires the use of expendable nitrogen gas for each retraction/deployment cycle. The deployable boom method requires no expendable gas but requires power. See Section 4.0 for more detail on the deployment methods.

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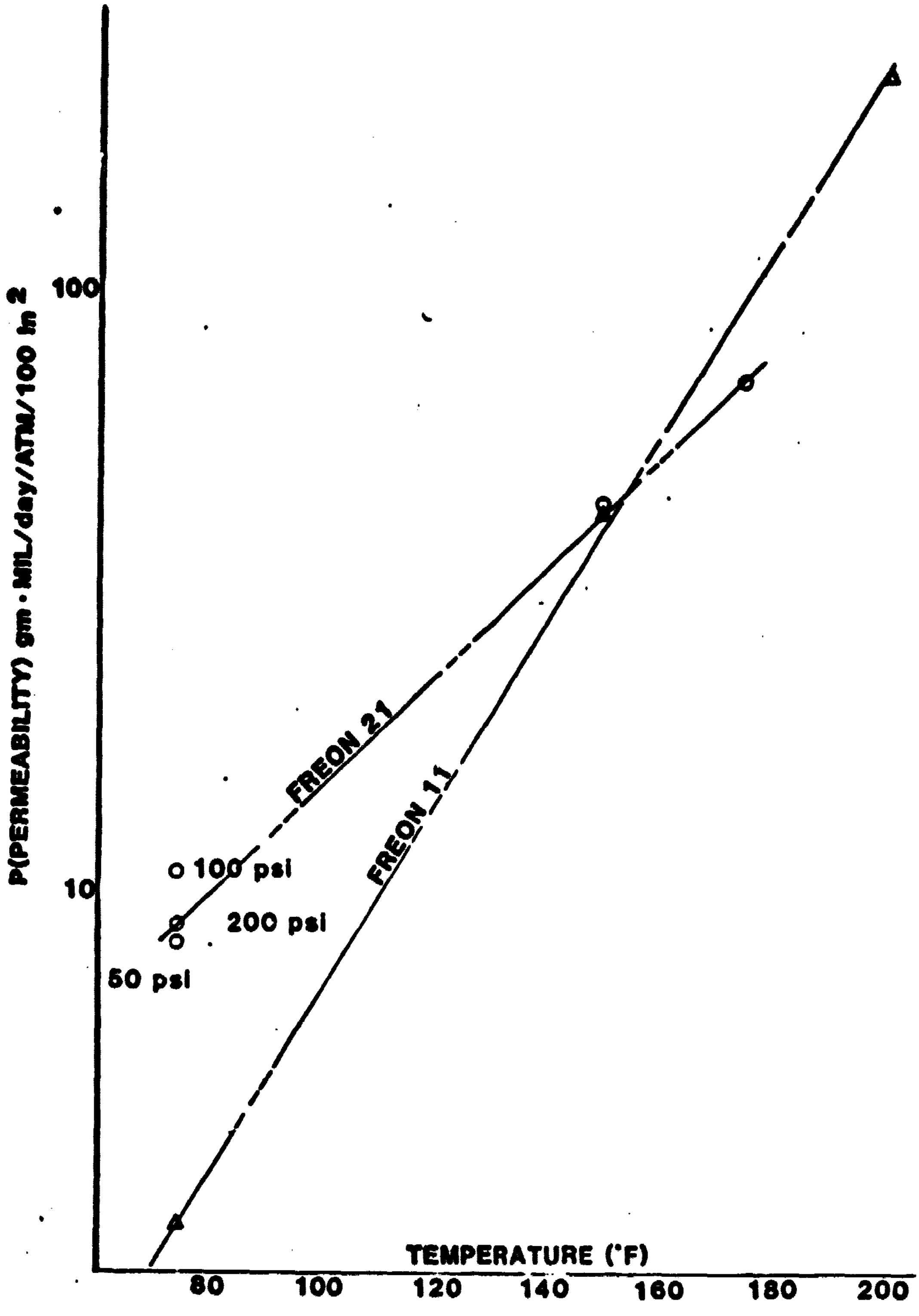

Figure 23 Permeability Test - FEP (Teflon) Tubing & Freon Fluid

TABLE V
COMPARISON OF RADIATOR DESIGN FOR CANDIDATE FLUIDS

FLUID	OPT DIA (INCH)	OPT WT (LB)	A/Amin	ADJUSTED WT (LB)	WEIGHT R-21 WT (LB)	A / A(R-21)
Oronite FC-100	.100	24.5	1.151	28.2	3.4	1.090
Ethylene Glycol Water (RS-89a)	.085	22.7	1.069	24.3	-0.5	1.012
Freon 21	.085	23.5	1.056	24.8	0	1.000
Freon 11	.090	26.0	1.062	27.6	2.8	1.0[illegible]6
Freon E-1	.075	24.0	1.075	25.8	1.0	1.018
Freon E-2	.080	24.4	1.204	29.4	4.6	1.140
FC-88	.075	24.0	1.075	25.8	1.0	1.018
FC-75	.075	26.0	1.128	29.3	4.5	1.068
FC-77	.075	26.6	1.220	31.7	6.9	1.155
Coolanol 15	.095	23.6	1.143	27.0	2.2	1.082

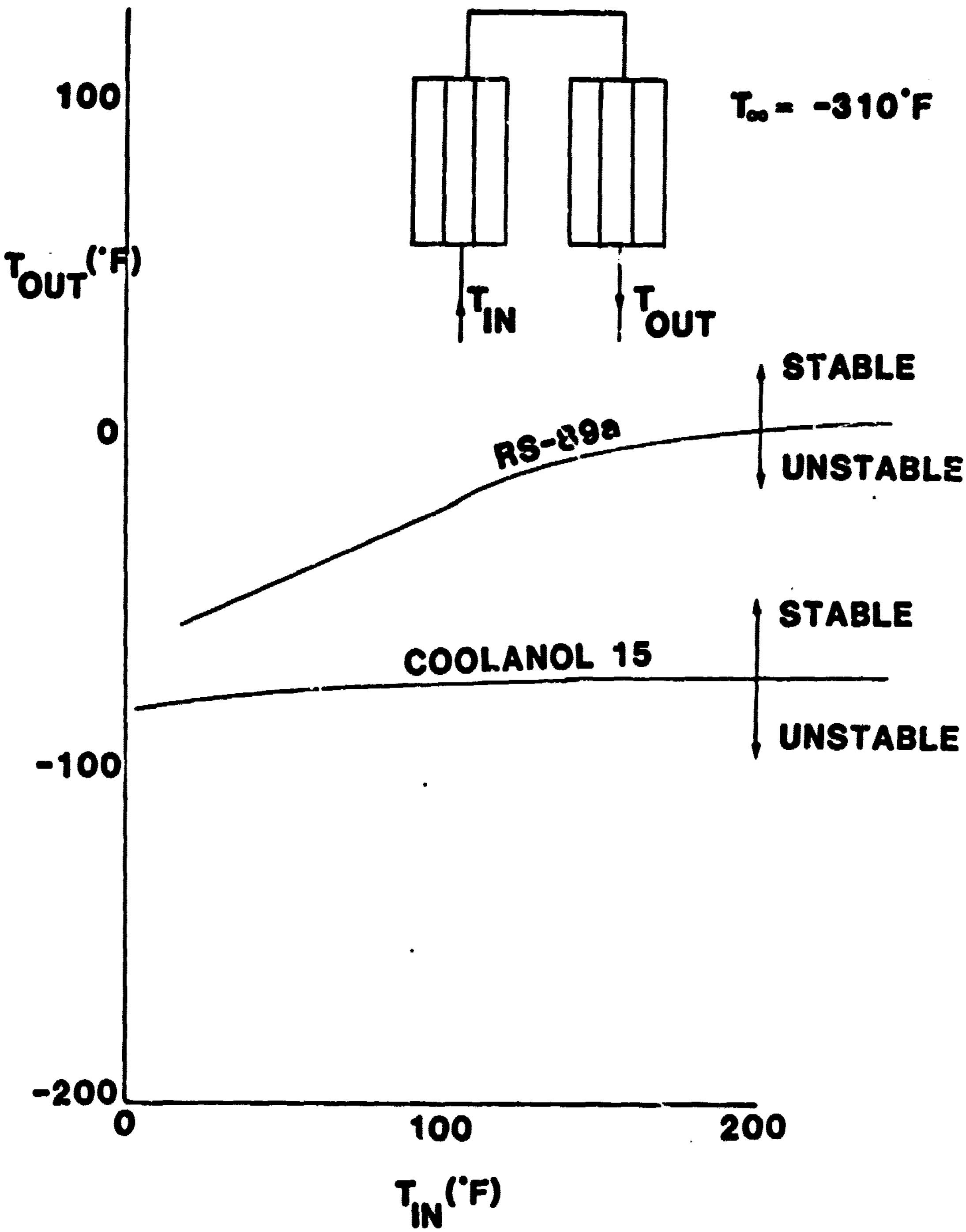

Figure 24 Approximate Stability Curves for Candidate Flexible Radiator Fluids

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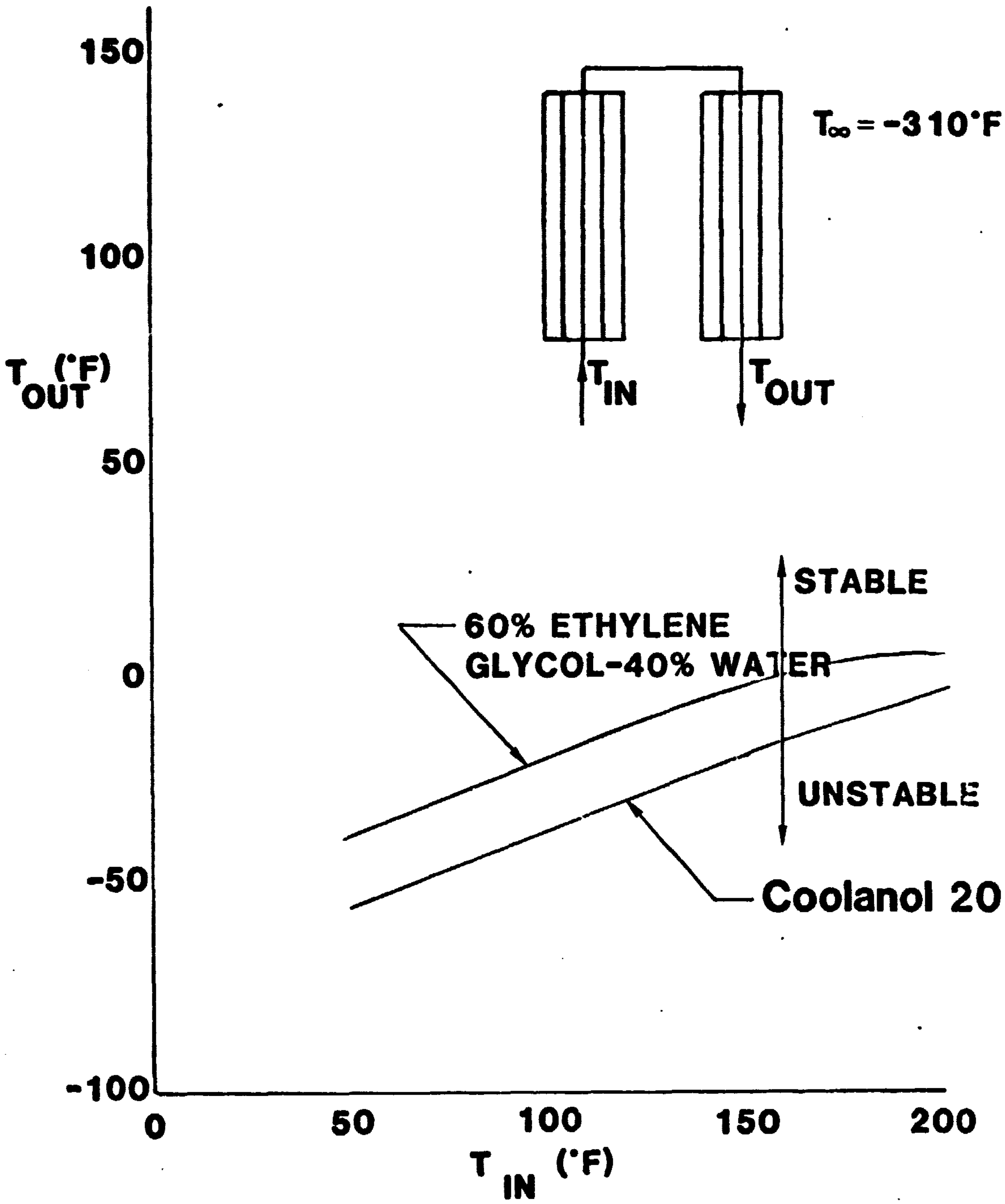


Figure 25 Approximate Stability Curve

5.3 FLUID CIRCULATION SYSTEM

The flexible radiator deployable panel may be converted into a flexible radiator heat rejection subsystem by the addition of a fluid circulation system. This fluid system provides the interface between the heat rejection panels and source of the heat load on the vehicle.

Figure 26 is a schematic of the fluid circulation system. It includes the fluid pump, fluid accumulator, interface fluid line connections at both the panel and heat load side, temperature control valve, an optional heat exchanger, and the interconnecting plumbing. The system shown is designed for three panels, each of which could reject 4.0 kW of heat for a total of 12 kW rejection. Pumps which were developed for the Orbiter can be used in this system with little modification. A derivative of Sundstrand pump Model 145656, shown in Figure 27, would be used for the Glycol/water system. This pump was developed to circulate water in the Orbiter environmental control system. A derivative of a similar pump, Model 145660, Figure 28, would be used for Coolanol 20. Table VI summarizes the fluid volume required for a 12 kW system (three 4 kW wings). The estimated volume change for the fluid over the maximum allowable temperature range is 500 to 550 in^3 for both Coolanol 20 and Glycol/water. Figure 29 shows a candidate temperature control valve. Figure 30 summarizes the fluid swivels that would be needed for the boom deployed system.

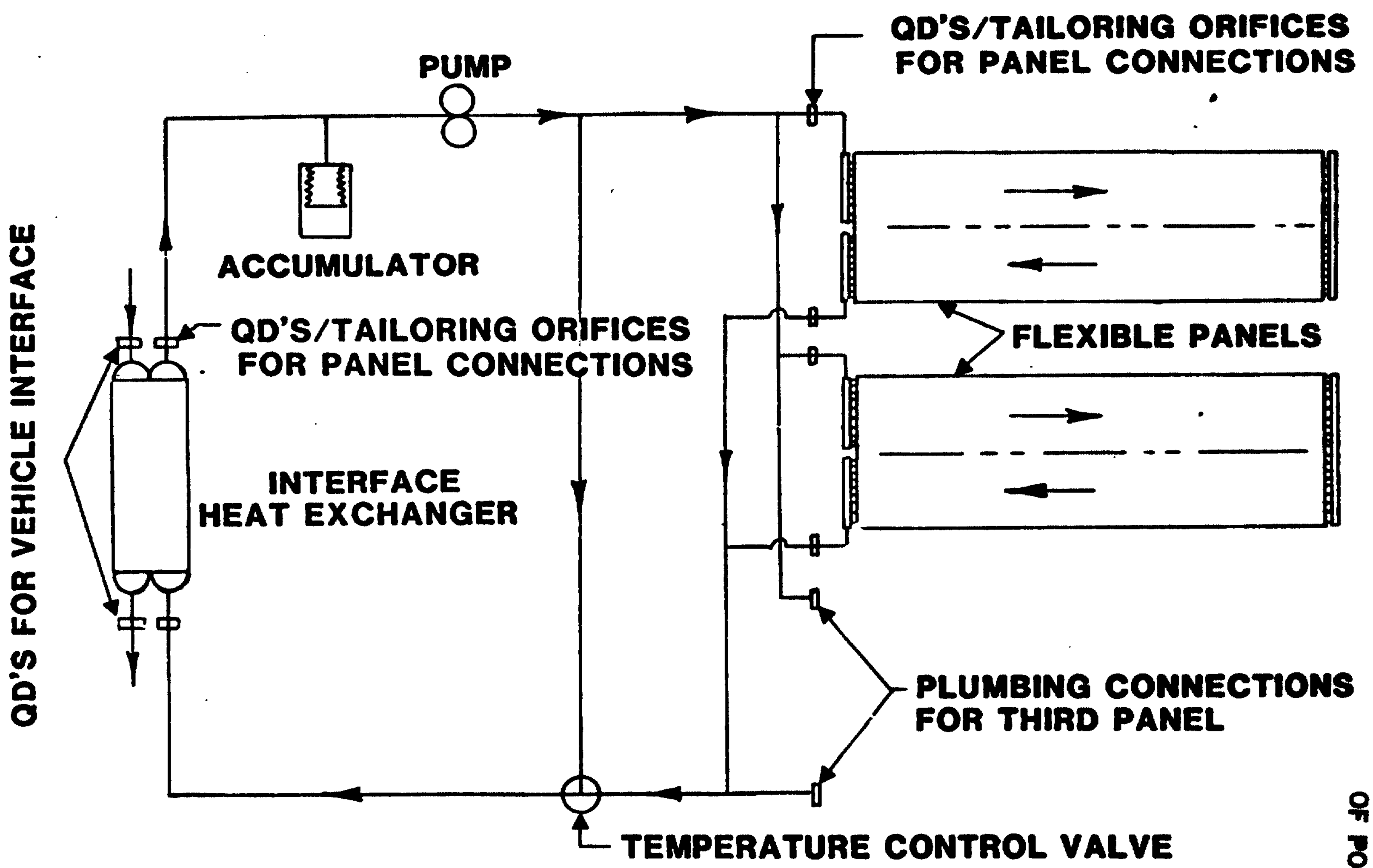
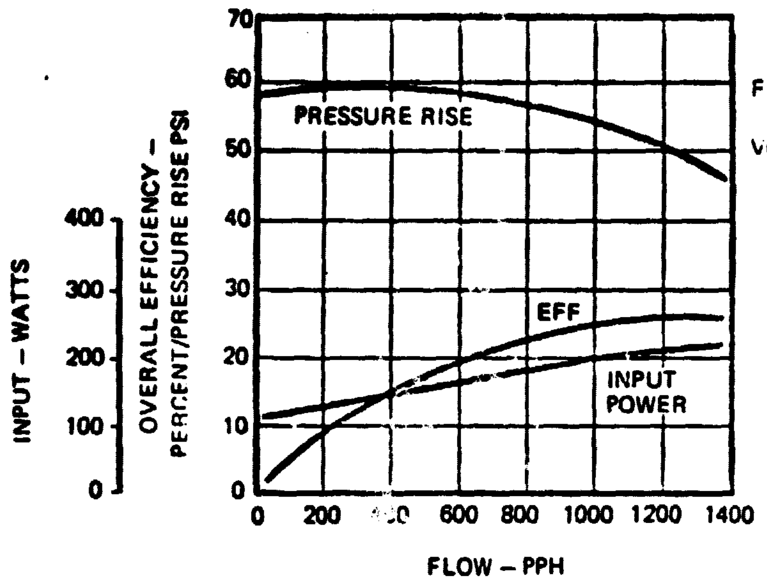


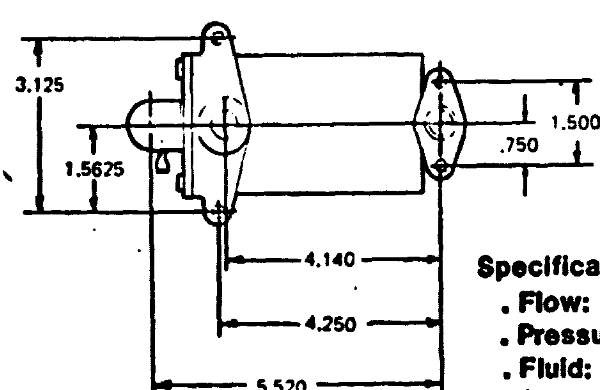
Figure 26 Flow System for Flexible Radiator

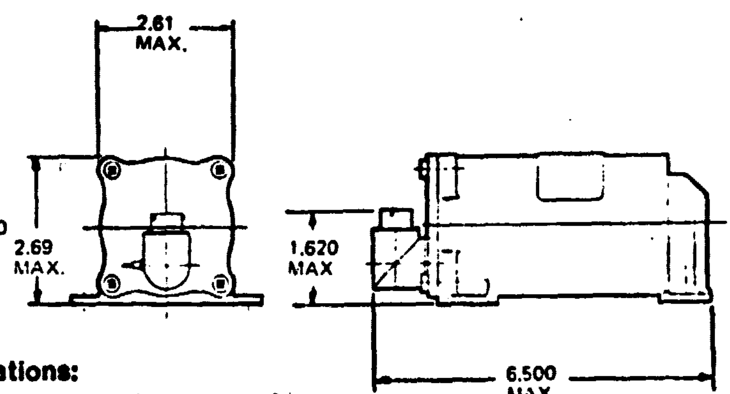
PERFORMANCE



FLUID: DEIONIZED WATER AT 70°F
VOLTAGE: 115/200 VOLTS/ 400 Hz, 3 PHASE

Model 145656

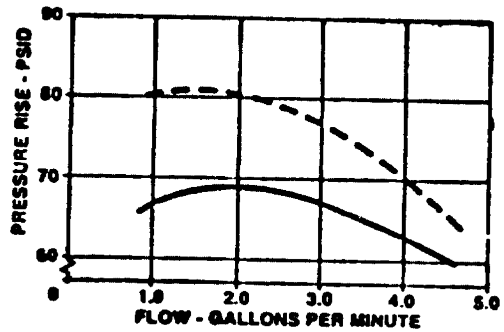




Specifications:

- Flow: 995 pph (1.91 gpm)
- Pressure Rise: 51-56 psi
- Fluid: De-Ionized Water
- Input Power: 115/200 Volts, 400 Hz, 43 Phase
- Current: 1.06 Amps per Phase
- Weight: 4.0 lbs

PRESSURE RISE vs. FLOW

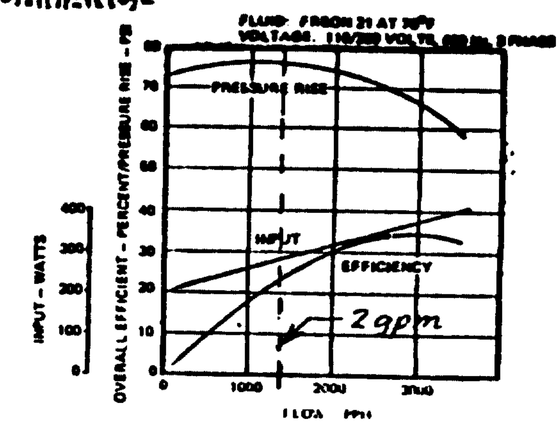


- - - - - SHUTTLE MOTOR/PUMP AT 400 HZ, 115 VAC WITH FREON 21 FLUID

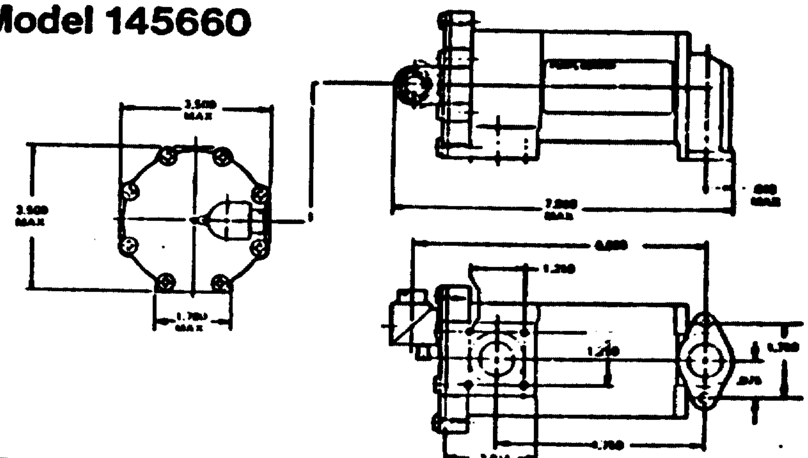
——— SIMILAR MOTOR/PUMP AT 450 HZ, 46.4 VAC WITH COOLANOL 20 FLUID

- ESTIMATED 1-3 GPM COOLANOL 20 REQUIRED FOR KIT RADIATOR CONFIGURATIONS
- ESTIMATED 35-50 PSI PRESSURE RISE REQD
- MODIFIED ORBITER FREON 21 PUMP MEETS THESE REQUIREMENTS - USE TAILORING ORIFICE TO ADJUST TO SPECIFIC KIT RADIATOR MISSION NEEDS
- SIMILAR ORBITER PUMP MODIFICATION FOR SIRE PROGRAM

PERFORMANCE



Model 145660



Sundstrand Aviation Mechanical

Figure 28 Representative Coolanol 20 Pump for Flexible Radiator

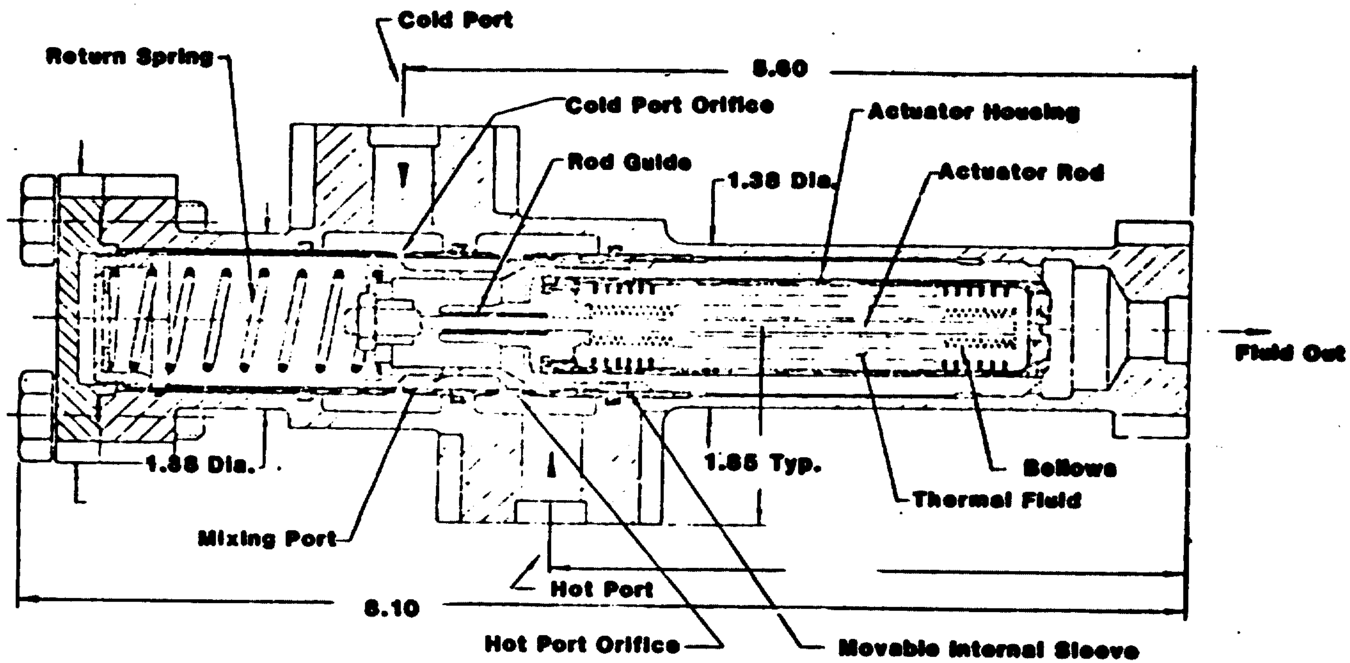
TABLE VI
COOLANOL 20 KIT ACCUMULATOR

COMPONENT DESCRIPTION	VOLUME, FT^3
Radiators (3 Wings, 1000 Ft^2)	0.550
Coldplates (20)	0.586
Payload Heat Exchanger (2 Loops)	0.071
Flex Hoses (Connecting C/P)	0.219
Hardlines	0.127
Interface Hose Assembly	0.253
Ullage	0.014
Miscellaneous	0.028
	1.848

Fluid Volume Temperature Range + 200°F to -50°F

Present Volume Change = 16.6%

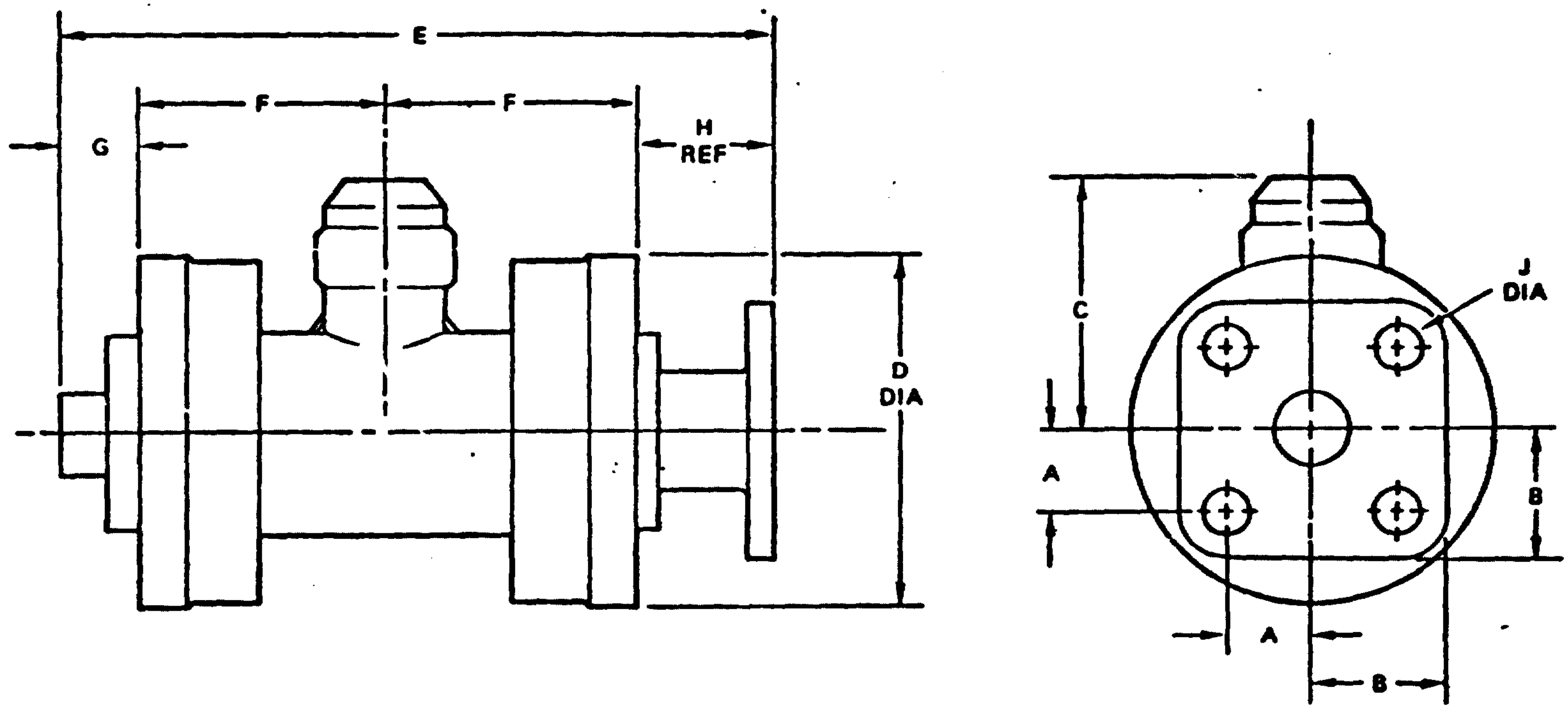
Accumulator Volume = .31 Ft^3



VALVE SCHEMATIC

- Prior use on Skylab
- Control mixed temperature to ± 2°F
- 2.5–5 psid Delta-P at 450 pph Coolanol
- Weight 3 lbs

Figure 29 Representative Thermal Control Valve (William Wahl Corp)



SWIVEL SIZE	WEIGHT *STEEL	WEIGHT AL	A	B	C	D DIA	E	F	G	H	J DIA
1/2	1.34	80	.44	.72	1.40	1.96	3.81	1.34	.38	.75	.25
5/8	1.42	.85	.48	.74	1.44	1.96	3.94	1.44	.40	.66	.25
3/4	2.04	1.22	.56	.80	1.78	2.22	4.35	1.61	.40	.73	.25
1.0	2.69	1.61	.62	.87	2.00	2.46	4.50	1.68	.40	.74	.25

SWIVEL SHOWN → 5/8

Figure 30 Vought Freon Swivel - Right Angle Design