EXTERNAL INSULATIONS
Contract NAS9-10583

Interim Study Report
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Colspan, Inc. T. M. Flynn

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External Insulation Systems

for

Cryogenic Storage Systems

Contract NAS 9-10583

INTERIM STUDY REPORT
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Prepared for: NASA/Manned Spacecraft Cente.
Propulsion and Power Division
Technical Monitor: ROBERT K. ALLGEIER
Houston, Texas

Prepared by: THOMAS M. FLYNN
JERRY B. KIRGIS
JOHN R. WILSON

COLSPAN

P.O. BOX 3467
BOULDER, COLORADO 80303

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ABSTRACT

Cryogenic storage systems for the extended space missions of the future will require more fluid capacity than current systems, and thus new design and development techniques will need to be evaluated.

This report describes the results of the third phase of a program to investigate high performance external insulation systems for use on flight weight cryogenic gas storage systems. "External insulation" here means anything added to a cryogenic storage system for the purpose of thermally protecting it from its environment. This definition exludes the vacuum annulus of a dewar. The fluids stored are hydrogen and oxygen.

The result of the first phase of the program was a Bibliography/Snyopses/Category Report of external insulation systems. In the second phase, each of the efforts referenced in the Bibliography was researched in depth to determine which of the concepts had the most promise for use and/or future development.

Five (5) concepts, considered to be the most promising based on thermal characteristics, applicability for the intended use, maintainability, reliability, and other factors considered pertinent were chosen for further evaluation during the third portion of the program.

In the third program phase, just completed, preliminary thermal analysis, support analysis, producibility, operability and other factors were considered for the five systems. Three systems, a shingle with substrate, fiberglass, and blanket, were chosen for detailed analysis in the fourth phase. Development work on mathematical models for that analysis is nearly completed, and summaries of the mathematical models and programming are presented.

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1.0 INTRODUCTION

As a consequence of the exhaustive survey of external insulation technology completed in the first phase of this study, it has been possible to examine completely the methods and materials used in the design and construction of external insulation systems. In light of this examination, work was begun to develop new methods for the design and performance evaluation of these systems. In the second phase of the study, the first of these methods was used to measure various systems against required or desired performance characteristics. The results of that work were twofold: a new evaluation technique suitable for application to many technologies was developed and demonstrated, and five promising external insulation systems were selected for further study.

The third program phase, whose completion is marked by this report, has seen the development of additional new evaluation techniques, and the accomplishment of significant further research concerning the properties and performance characteristics of the five selected systems. Hence this report represents a preliminary exposition of a comprehensive approach for evaluating external insulation systems. It is a precursor to the external insulation design reference manual which will result from the refinement of these techniques and the thorough parametric study to be performed in the final program phase.

2.0 THE FIVE SELECTED MATERIALS/CONCEPTS

Below are basic, simplified descriptions of the five external insulation systems selected for further evaluation and study during the Initial Study (Phase II) of this program. The descriptions, reproduced from the Initial Study Report, provide the basic framework of reference for analysis and evaluation performed in Section 3.0 of this report.

2.1 SHORT TERM INSULATIONS

The short term mission requires the usage of large quantities of cryogen in 6 hours or less; therefore, from both time and surface to volume ratio viewpoints, thermal performance requirements are necessary but low. Since virtually all the insulations considered can achieve this performance at moderate weight per unit area, mounting, environmental capability, reusability and weight become heavily weighted factors compared to repeatability and reliability. Superinsulations in general were omitted because of their extreme complexity and installation difficulties when used on very large tankage

2.1.1 Coated Shingles on a Substrate

A substrate of about one inch of fiberglass matting, foam or cork is applied directly to the tank wall. A purge bag surrounds the substrate and metal coated plastic film shingles are applied by taping or bonding the "upper" end to the purge bag. Nylon net or cord, or a second purge bag encloses the outer ends of the shingles.

The substrate provides adequate ground hold thermal performance at a minimum weight because the shingles limit radiative and convective heat inputs. The sublayer also eliminates potentially hazardous air cryopumping and fractionation in the insulation. The shingled super-insulation permits very rapid gas expulsion rates which enhances the launch environmental capability of gas filled superinsulation. The shingles are mounted in the vertical plane to provide maximum support in the direction of maximum "g" and other launch loads. Rapid pump out rates due to direct gas flow passages from the tank to its external surface ensure good thermal performance when the space environment is reached.

The substrate must be purged but its required volume is reduced greatly by the presence of the shingles. The purge bag is protected from mechanical damage by the easily replaceable shingles. Locally damaged areas are easily accessible and local thermal performance degradation does not propagate throughout the whole system.

Shingles may be prefabricated and stored, shipped and mounted in multi-layer subassemblies. Special shapes and cutouts may be precut and fitted to the tankage by adjusting their mounting location at installation time. They require a minimum of skill and precision for installation or re-installation. They may be shop or launch pad mounted.

2.1.2 Fiberglass

Fiberglass may be bonded directly to the tankage in the matting form or spiral wrapped in the fibrous form. The matted type requires a glass cloth external layer to provide mechanical strength. Generally, purging is required to eliminate air and water vapor absorption.

The material is applied in a great enough thickness to insure adequate ground hold performance. This material is relatively impermeable to gases so its performance is not degraded as greatly as most insulations, when purging is used. Varying amounts of epoxy filler may be added at the outer surface to tailor the toughness and mechanical strength for resisting damage and flight environments. This material is capable of withstanding relatively high temperatures so it will require less protection for launch and re-entry heating than any of the other alternatives considered. In space, its thermal performance is not as great as the radiation shield type insulations, but is adequate for short missions. This material is quite resistant to damage due to its toughness but it may be difficult to repair since it is an integrally bonded structure. The purge bag is more vulnerable and of larger volume than that used for shingles with substrate.

2.2 INTERMEDIATE TERM INSULATIONS

This mission requires a 6 hour to 20 day operating cycle and a high probability of being reused for several missions. These requirements represent a combination of the short and long term insulation characteristics. In particular, the insulation must survive launch while providing adequate thermal protection, it must achieve its ultimate space performance rapidly, and it must be designed for ease in maintenance and refurbishment. Several of the long term storage insulations can be used here but the most attractive system utilizes shingles, which are unsuitable for long term storage. It should be noted that the shingles described for short term storage are equally useful when used without the substrate. Because that system was selected earlier, it will not be selected as an intermediate term insulation.

2.2.1 Coated Reflective Shingles with Embossed or Tufted Spacers

This insulation is made up of multiple reflective layers of shingles with special spacers to minimize gas trapping. The spacers may be an embossed (bumpy) reflector (Dimplar), embossed fiberglass (Marshield), or tufts of Dacron thread bonded to the reflector (Superflock). It is enclosed in a purge bag.

This insulation shares the advantages of the shingled insulation discussed under short term missions. Differences between these insulations include an extremely rapid pump down to minimize launch damage due to depressurization and to achieve maximum performance in space in a minimum time. Its space performance for a given weight is not degraded by the low performance sublayer but its ground performance is decreased by the presence of purge gas in the open space between shields. Also, the purge bag must be mounted on an external surface, where it is susceptible to handling damage. Shingle mounting and minimization of spacer material makes it very easy to maintain and refurbish. The materials involved are tough and not easily damaged, so good useful life can be achieved without excessive precautions.

2.3 LONG TERM STORAGE

This mission requires maximum thermal performance in space while ground hold and launch performance become relatively insignificant. Since performance is to be maximized, the repeatability in achieving a known performance is very important to the success of a given mission. Large variations in performance from one tank to the next would not be tolerable. Also, the system must withstand the environment with no or at least predictable degradation to assure the desired mission lifetime.

2.3.1 Blankets of Coated Reflectors with Net Spacers

This insulation is made up of metal coated plastic films separated by nylon net spacers. Blankets or panels of these materials are laid up and sewn together into a quilted configuration. Edges of a given blanket are interleaved with adjoining ones when the system is installed. Various mechanical fasteners, such as buttons or clips, are used to support the system. A vacuum or purge bag encloses the system.

The space environment performance of this insulation is very high when it it evacuated internally. Its weight is very low. System pump down time is not as short as for shingled insulation due to the tortuous gas flow paths but it does not suffer from lateral conductive heat leak directly to the tank. The seams between blankets permit much easier pump down than a continuous wrapping of insulation. Nylon net is not only a very rugged and flexible spacer, but it does not outgas significantly and is quite permeable to gas flow.

Ground hold performance and maintainability are limited by the requirement of purging or evacuation to limit air cryopumping and its attendant thermal and hazard penalties. Maintenance requirements are not great because blankets are easily prefabricated and fitted and may be replaced a section at a time.

Since the blankets can be prefabricated, repeatability can be controlled quite closely. Also, penetrations can be pre-designed and fitted as required in the mounting operation. Finally, this configuration is ideal for performing meaningful laboratory tests which closely represent the mounted insulation.

Metallic foils are extremely susceptable to mechanical damage when used in this system. As well, their increased lateral conductivity results in much poorer repeatability of joint and penetration designs.

2.3.2 Continuous-Wrapped Coated Reflectors with Net Spacers

This system utilizes the same insulating materials as the previously described system, except in seamless form. This requires a vacuum bag.

By eliminating the seams, the thermal performance is theoretically higher and the minimization of mounting fixtures reduces its weight. This scheme is difficult to fabricate compared to blankets because of the continuous wrapping required. Pump down is greatly inhibited by the lack of gas flow paths from inner layers to the surface. This means that a flexible outer vacuum bag is required so that the insulation can be pumped mechanically on the ground. Vacuum shrouds are extremely susceptable to damage and difficult to repair. In addition, any damaged insulating material is hard to replace.

...rformance repeatability is hard to achieve with this insulation. ... each penetration must be accommodated individually during ...llation and the system usually cannot be prefabricated by shop p...edures. Continuously-wrapped insulations are difficult to support as ...rmly as blankets and thus may shift and/or be damaged during gro...d hold and boost.

The primary reason for including this insulation scheme is to accommodate small (~ 5 ft^3) tankage which must be included in the long term storage category. This form of insulation is necessary, since small curvature radii are not easily covered with blanket systems.. Second, small tanks require a highly efficient protection system due to their large surface to volume ratio. Third, careful hand installation becomes feasible for these smaller tanks, and vacuum bags for these volumes are not difficult to maintain. Generally one seam is permitted at the equator of the small tank under this "continuous alternative".

3.0 INTERIM STUDY PROGRAM

3.1 REQUIREMENTS

A noted earlier, this report is intended to be an intermediate step in the development of definitive results from the evaluation of a few selected external insulation systems, according to criteria set forth in the Initial Study Report and Statement of Work of Contract NAS9-10583. Those evaluation criteria are reproduced in Table I through VIII. The first step in the evaluation procedure was completed in the Initial Study Program phase by making ratings of the various external insulation systems according to these criteria. In the phase of the study just completed, the selected systems have been subjected to preliminary thermal and structural analysis, with particular attention paid to system performance under varying environmental conditions, producibility, and areas of possible performance improvement. The results are presented in tables, drawings and discussion which elucidate further the properties and development possibilities of the selected systems. Using the results of this study, a comprehensive approach for external insulation systems evaluation has been conceived, and is outlined in Appendix A.

Three systems, selected on the basis of the above mentioned criteria and on the results of this preliminary analysis, will be subjected to a complete parametric analysis using this approach. The process and basis used for the selection of these three systems is described in Section 4.0.

3.3 TANKAGE DESIGN FOR PRELIMINARY STUDY

Five tank sizes (32,000, 12,000, 2,000, 100, and 5 ft^3) have been selected from those listed in the work statement for preliminary insulation evaluation and analysis. The sizes were selected to be representative of the range and extremes of the desired mission requirements. Both spherical tanks and cylindrical tanks with spherical

TABLE I

PARAMETRIC STUDY GUIDELINES

1. Cryogenic storage of hydrogen and oxygen only.
2. No external cooling available (e.g., refrigeration.)
3. Vapor cooling by contained cryogen permissable.
4. Throttling devices not permissable (e.g., Joule-Thomson throttling.)
5. Hemispherical heads on cylindrical tanks.
6. Sufficient parameters should be chosen so that the results of the study can be utilized as a design reference manual and as a useful tool for the determination of required future development areas.
7. Sample calculations, where necessary for technical comprehension or beneficial for extending the study limits, shall be included with the report on the results of the parametric study.

TABLE II

PARAMETRIC STUDY AREAS OF CONSIDERATION

Short Term - 0 to 6 hours including ground hold and boost.

Cryogen	Pressure, psia	Volume Range, ft^3
O_2	40	4000 to 12,000
H_2	40	4000 to 37,000

Long Term - 7 days to 6 months including ground hold, boost, and space storage

Cryogen	Pressure, psia	Volume Range, ft^3
O_2	40	5 to 5000
H_2	40	5 to 5000

Environments:

Ground hold	-	$T = 70^\circ F$
		$P = 14.7$ psia
Boost	-	$T = 70^\circ F$
		$P = 14.7$ psia to 0.5 psia in 100 seconds
Space Storage	-	$T = 70^\circ F$
		$P = 10^{-7}$ torr

TABLE III

REQUIRED PARAMETERS FOR PARAMETRIC STUDY

1. The parametric study shall include; but not be limited to, an optimization for insulation thickness, insulation weight, tank L/D ratio, and heat leak for each insulation concept for each of the following volumes:

   a. Oxygen and Hydrogen -- Long Term Storage

      Volume, ft^3 -- 5, 20, 50, 100, 200, 500, 1000, 2000, 3000, 4000, and 5000.

   b. Oxygen -- Short Term Storage

      Volume, ft^3 -- 4000, 5000, 6000, 8000, 10,000, and 12,000.

   c. Hydrogen -- Short Term Storage

      Volume, ft^3 -- 4000, 5000, 6000, 8000, 12,000, 15,000, 21,000, 26,000 and 32,000.

2. The parametric study shall include a ranking of the three insulation concepts chosen for the final phase of the program. The three insulation concepts shall be compared on a parametric basis by a method that will substantiate the relative ranking of the insulation concepts.

3. Any other parameters considered pertinent and/or necessary for the evaluation of the three insulation concepts shall be included in the parametric study.

TABLE IV

CONCEPT SELECTION CRITERIA

1. Operability
2. Reliability
3. Maintainability
4. Maintenance requirements
5. Ground-hold requirements
6. Useful life
7. Reusability
8. Susceptibility to ground-hold, boost, and spaceflight environments
9. Adaptability to mounting within a spacecraft
10. Required development
11. Shelf life
12. Weight
13. Cost
14. Ground support requirements

CONCEPT SELECTION CRITERIA

Table VI, which follows, contains the final choice of concept selection criteria. They were chosen from the previous tables, from new information learned in the course of the study, and in cooperation with the technical contract monitor.

TABLE V

CONCEPT SELECTION CRITERIA

1. Thermal performance
2. Susceptibility to ground-hold, boost, and spaceflight environments
3. Useful life
4. Required development
5. Weight
6. Reusability and refurbishment possibilities
7. Ground-hold requirements
8. Repeatability of installed insulation
9. Reliability
10. Maintainability
11. Operability
12. Adaptability to mounting in a spacecraft
13. Lab vs. installed consistency
14. Cost

TABLE VI

PRIORITY RANKING

SHORT TERM 0 - 6 HOURS

		Weight Factor
*	1. Susceptibility to ground-hold, boost and spaceflight environment	15
*	2. Reuseability	15
*	3. Thermal Performance	15
*	4. Adaptability to mounting in a spacecraft	15
	5. Weight	10
	6. Useful life	9
	7. Ground-hold requirements	8
	8. Maintainability	7
	9. Required development	6
	10. Reliability	5
	11. Repeatability of installed performance	4
	12. Operability	3
	13. Lab vs. installed performance	2
	14. Cost	1

*These properties are "must" category

TABLE VII

PRIORITY RANKING

INTERMEDIATE (ORBITER TYPE MISSION) 6 HOURS TO 20 DAYS

		Weight Factor
*1.	Thermal performance	15
*2.	Susceptibility to ground-hold, boost, and spaceflight environments	15
*3.	Reuseability	15
*4.	Maintainability	15
*5.	Useful life	15
6.	Weight	10
7.	Repeatibility of installed performance	9
8.	Ground-hold requirements	8
9.	Reliability	7
10.	Operability	6
11.	Adaptability to mounting in a spacecraft	5
12.	Required development	4
13.	Laboratory vs. installed performance	3
14.	Cost	2

*These properties are "must" category

TABLE VIII

PRIORITY RANKING

LONG TERM 20 DAY -- 6 MONTHS

		Weight Factor
*1.	Thermal performance	15
*2.	Useful life	15
*3.	Repeatability of installed performance	15
*4.	Susceptibility to ground-hold, boost, and spaceflight environments	15
5.	Ground-hold requirements	10
6.	Operability	9
7.	Weight	8
8.	Adaptability to mounting in a spacecraft	7
9.	Reliability	6
10.	Maintainability	5
11.	Required development	4
12.	Reuseability	3
13.	Lab vs. installed performance	2
14.	Cost	1

*These properties are "must" category

head designs have been considered for the three intermediate sizes, while only the cylindrical design is considered for the largest tank and a spherical design is selected for the 5 cubic foot tank. Spherical heads rather than the more economical flattened (torispherical, etc.) shapes have been used in this preliminary study as they were specified as a ground rule in the Contract. Cylindrical diameters of 5, 10, 20 and 33 feet have been used wherever tank length does not exceed several hundred feet. In total, eleven tanks are considered for both hydrogen and oxygen.

Each tank has been sized roughly to provide design loads for establishing a support system. Arbitrarily, 347 stainless steel with an ultimate strength of 128,000 psi has been used in the tank structural calculations. A design factor of 1.5 on UTS has been used. Tank wall thicknesses were calculated for 60 psi internal pressure and an ullage volume of 10 percent. Tank wall weights were increased by 20 percent to account for stiffeners and an additional 50 percent was added to the oxygen tanks to account for the inertial load carrying capability, (this may include local doublers, stiffeners and loading rings, etc.). Table I summarizes the tank design information.

This load information was used to size the tank supports. The support design has been based on the study reported in NASA-37[1] summarized in the Bibliography/Synposes/Category report. Based on this report, filament wound fiberglass struts have been selected. Six

[1] All references are reported in the form used in the Bibliography/Synposes/Category report. See page 98 for a comprehensive list of these references.

struts have been used for spherical tanks and cylindrical tanks with cylinder lengths less than 2.5 feet. Longer cylindrical tanks use twelve supports as indicated schematically in Figure 1. The plane of each pair of supports is inclined outward 10 degrees from the vertical to provide support for lateral loads. The detail construction of these supports is given in NASA-37 and is shown in Figure 2. The supports have been designed for a combined acceleration and vibration load of 8.5 G downward (tension and 3.5 G upward (compression) using the following equations:[2]

$$P + \frac{g/g_o\,(W_o/n)}{\cos 10 \cos 45}$$

$$F_t = \frac{4P}{(do^2 - di^2)}$$

$$P_{cr} = \frac{{}^3E(do^4 - di^4)}{64\,L^2}$$

W = static load
n = number of supports
g = acceleration
do = O.D. of support
di = I.D. of support
L = length of support
F_t = tensile stress (UTS = 140,000 psi)
E = elastic modulus 5.4×10^6 psi
P_{cr} = critical buckling stress

[2] A design safety factor for UTS of 1.5 is used.

These equations have been solved simultaneously for the support diameters using lengths of 1.5 and 3 feet. The results are shown in Table I where the design giving a minimum area to length ratio has been selected for each tank.

Fill and vent lines have been sized to cool down and fill the 32,000 and 12,000 ft^3 tanks in 1/2 hour with a maximum pressure head of 40 psi in 20 feet. The vent pipe has a pressure drop less than 5 psi in 3 feet. The smaller tank lines were sized to fill in 1/4 hour. All wall thicknesses are the minimum available in the required size. Usage lines have been sized according to an assumed mission profile as follows. Short term missions were assumed to use all the cryogens in 1/2 hour while the mid-term (6 hour to 7 days) tankage was emptied in 2 hours total. The long term mission was assumed to provide a continuous flow for 3 months. All use lines were sized for pressure drop less than one atmosphere in a 20 foot line. The various pipes are summarized in Table IX. In addition to the plumbing shown in the table, each tank over 5,000 ft^3 is assumed to include two 1/2" thin wall instrumentation conduits. All smaller tanks have one conduit each.

TABLE IX

TANK DESIGN SUMMARY

Nominal Volume	32,000 ft^3		12,000 ft^3		
Configuration	20 ft cyl	33 ft cyl	Spherical	10 ft cyl	20 ft cyl
Head Thickness, in	0.0495	0.0817	0.073	0.0248	0.0495
Cylinder Thickness, in	0.105	0.173		0.0526	0.105
Structural Weight, H_2/O_2 (lbs)	11090/16650	16280/24500	9800/14700	7585/11350	5470/8200
Surface Area, ft^2	7407	5440	2700	5844	3092
Spherical Radius, ft			14.7		
Cylinder Length, ft	98	19.9		[illegible]76	29
Loaded St H_2, lbs.	152,590	157,780	62,800	[illegible]0,585	58,470
Loaded Wt O_2, lbs.	2,276,650	2,284,500	864,700	[illegible]1,350	858,200
Support OD, in, H_2/O_2	3.81/7.5	3.75/7.5	3.3/7	[illegible]1/6.5	4.1/6.5
Support ID, in, H_2/O_2	3.5/5	3/5	3/5	[illegible]0/5.5	4.0/5.5
Support Length, in, H_2/O_2	36/36	36/36	36/36	[illegible]/36	36/36
Number of Supports	12	12	6	[illegible]	12
1 Fill Pipe, in, H_2/O_2	4p/6p	4p/6p	3p/4p	[illegible]/4p	3p/4p
1 Vent Pipe, in, H_2/O_2	5p/8p	5p/8p	4p/5p	[illegible]/5p	4p/5p
1,2 Use line, in	7 ps	7 ps	4ps. 2pm	[illegible]s, 2pm	4ps, 2pm

1. p = pipe size, T = tube size
2. s = short term, M = Mid-term, L = long term

TABLE IX

TANK DESIGN SUMMARY

Nominal Volume	2,000 ft^3			100 ft^3		5 ft^3
Configuration	Spherical	5 ft cyl	10 ft cyl	Spherical	5 ft cyl	Spherical
Head Thickness, in	0.0403	0.0124	0.0248	0.0148	0.0124	0.00547
Cylinder Thickness, in		0.0263	0.0526		0.0263	
Structural Weight, H_2/O_2 (lbs)	1640/2450	2358/3540	1268/1900	81/122	98/148	4.1/6.2
Surface Area, ft^2	825	1858	994	110.2	117.3	15.2
Spherical Radius, ft	8.11			2.98		1.1
Cylinder Length, ft		113	21.5		2.47	
Loaded St H_2, lbs.	10,460	11,178	10,088	522	539	26
Loaded St O_2, lbs.	143,950	145,040	143,400	7202	7228	360
Support OD, in, H_2/O_2	2.6/4.5	2.04/5.2	1.6/4.5	2.01/2.05	2.01/2.05	0.76/1.26
Support ID, in, H_2/O_2	2.5/4.0	2.00/5.0	1.5/4.0	2.00/2.00	2.00/2.00	0.75/1.25
Support Length, in, H_2/O_2	36/36	18/36	18/36	36/18	36/18	36/36
Number of Supports	6	12	12	6	6	6
1 Fill Pipe, in, H_2/O_2	2T/3P	2T/3P	2T/3P	1T/1.5T	1T/1.5T	1/4T/1/2T
1 Vent Pipe, in, H_2/O_2	2P/4P	2P/4P	2P/4P	1.25T/2T	1.25T/2T	3/8T/5/8T
1,2 Use line, in	1TM, 1/4TL	1TM, 1/4TL	1TM, 1/4TL	1/4TL	1/4TL	1/4TL

1. p = pipe size, T = tube size

2. s = short term, M = Mid-term, L = long term

TABLE [illegible]

APPROXIMATE INSULATION WEIGHT

Tanks/Insulation	Weight lbs.
32,000 ft^3	
33 ft. cyl.	4080
20 ft cyl	5660
12,000 ft^3	
20 ft cyl	2360
10 ft cyl	4480
spherical	2060
2,000 ft^3	
10 ft cyl	760
5 ft cyl	1420
spherical	630
100 ft^3	
5 ft cyl	89.4
spherical	84.0
5 ft^3	
spherical	11.6

TABLE XI

GROUND-PURGED THERMAL PERFORMANCE, BTU/hour

Tanks/ Insulations	Fiberglass		Fiberglass-Shingles		Dimplar Shingles		Net Spaced Blankets		Continuous	
	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2
32,000 ft^3										
33 ft cyl	162,000	121,000	92,200	68,800	180,000	147,500	359,000	295,000	359,000	295,000
20 ft cyl	220,000	164,000	125,500	93,500	244,000	200,000	488,000	400,000	488,000	400,000
12,000 ft^3										
20 ft cyl	91,000	68,500	52,200	38,900	101,500	83,500	204,000	167,000	204,000	167,000
10 ft cyl	173,000	129,500	99,000	73,700	192,500	158,000	385,000	317,000	385,000	317,000
spherical	80,000	60,000	45,800	34,000	89,000	73,000	178,000	146,000	178,000	146,000
2000 ft^3										
10 ft cyl	29,500	22,000	16,850	12,500	32,800	26,900	65,500	54,000	65,500	54,000
5 ft cyl	54,900	41,100	31,400	23,400	61,200	50,000	122,000	100,500	122,000	100,500
spherical	24,400	18,300	14,000	10,400	27,200	22,300	54,200	44,700	54,200	44,700
100 ft^3										
5 ft cyl	3,460	2,640	1,980	1,470	3,870	3,170	7,700	6,320	7,700	6,320
spherical	3,250	2,440	1,860	1,390	3,640	2,980	7,250	5,980	7,250	5,980
5 ft^3										
spherical	449	337	257	192	500	411	1,000	823	1,000	823

TABLE XII

SPACE EVACUATED THERMAL PERFORMANCE, BTU/hr

Tanks/	Fiberglass		Fiberglass-Shingles		Dimplar Shingles		Net Spaced Blankets		Continuous	
	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2
32,000 ft^3										
33 ft cyl	10,750	8020	1042	887	1999	1592	223	276	-----	-----
20 ft cyl	14,600	10,900	1633	1329	3219	2502	254	302	-----	-----
12,000 ft^3										
* 20 ft cyl s/m	6090	4546	597/ 591	477/ 472	1104/ 1098	851/ 847	124/ 118	124/ 119	-----	-----
* 10 ft cyl s/m	11,500	8620	1191/ 1184	937/ 932	2317/ 2311	1781/ 1771	210/ 204	210/ 206	-----	-----
* spherical s/m	5310	3970	240/ 234	230/ 225	375/ 371	330/ 325	126/ 122	144/ 139	-----	-----
2,000 ft^3										
* 10 ft cyl m/l	1960	1460	220/ 218	184/ 183	418/ 417	333/ 332	47/ 46	56/ 54	-----	-----
5 ft cyl	3650	2730	381	316	724	570	74	85	-----	-----
spherical	1625	1210	208	187	406	324	46	67	45.7	66.3
100 ft^3										
5 ft cyl	233	177	38	32	61	52	15	16	15.1	16.75
spherical	219	165	22	22	26	26	-----	-----	14.65	16.35
5 ft^3										
spherical	31	24	7.0	9.2	7.1	8.9	-----	-----	5.67	7.51

s = short term storage, m = mid-range storage, l = long term storage

TABLE XIII

APPROXIMATE EVACUATION TIME

(100 second launch period)
(to 10^{-3} mm Hg, to optimize performance)

Fiberglass	10 min
Fiberglass & shingles	20 min
Dimplar shingles	10 min
Net blankets	750 min
Continuous	1120 min

3.3 COMPARISON OF THE MATERIALS/CONCEPT

3.3.1 Thermal Analysis

Each of the insulation systems described in Section 2 has been evaluated to determine its thermal performance characteristics. An insulation design has been fitted to each of the tank systems described in Section 3.2. A preliminary thermal analysis has been accomplished for each system to provide a basis for evaluating the relative merits of each insulation and the effects of tank design. This section briefly describes this study.

Insulation System Design

A design has been established for each insulation system which results in identical insulation weight penalties. Table 10 lists the installed insulation weight for each of the tanks under investigation. The listed weights are representative of 3 inches of one side aluminized Mylar shingles mounted on 1-1/2 inches of fiberglass sublayer. All the other systems were designed to weigh the same so that their thermal performance can be compared directly.

Shingle systems have been designed to minimize the number of joints which cause thermal degradation. Each shingle is 4 feet long and wide enough to surround the tank in one piece. These dimensions were selected to permit the use of readily available 4 foot wide rolls of aluminized Mylar.

Each shingle in the substrate system is made up of 70 layers of crinkled reflector without spacers. These layers are bonded together and to the substrate purge bag at their upper ends using a continuous bond line adhesive. Shingles are tiered 3 deep at all points, providing 210 layers of insulation standing about 3 inches high. The one seam required for each shingle is made into a 6 inch lap joint. The seam locations for various shingle layers are indexed about the tank to eliminate any direct radiation windows between the tank and its surroundings. The shingles are used over the entire tank except the two polar regions where circular disc caps are utilized. A light weight open mesh of dacron netting encompasses the shingles to provide control of shingle location without appreciably compressing the material.

The fiberglass substrate and the fiberglass only insulations are made of 3 lb/ft^3 fiberglass "felt" bonded directly to the tank wall. Enough epoxy resin is impregnated into the felts to assure structural integrity. An open weave fabric bonded directly to the fiberglass provides a relatively porous (easy to evacuate) purge bag. This region is purged with helium during cold tank ground hold to eliminate air condensation in the insulation. 1-1/2 inches of fiberglass is used in the sublayer insulation while 3 inches is used for the fiberglass alone insulation.

Dimplar, embossed both sides aluminized Mylar, has been selected for the mid-range mission analysis. The embossed patterns in this material provide integral spacers between reflective layers to facilitate evacuation. 210 layers of this material standing 6 inches high in a shingled configuration provides the required insulation weight penalty. The shingle design is identical to that discussed previously except an open weave cloth purge bag encloses the entire system for ground hold protection.

Mylar aluminized on both sides, and with nylon net spacers in a blanket configuration has been selected for consideration for the long term missions. Four foot square blankets of 150 layers each of reflectors and shield provide the appropriate insulation comparison weight in a 3 inch thickness. The blankets are preassembled on a jig holding four nylon studs which penetrate the la yup. Nylon retainer washers over the studs are used, every 30 layers to provide support and some dimensional control. The studs are subsequently bonded directly to the tank wall. Blanket seams are made by interleaving groups of ten to twenty reflectors in adjacent blankets to make a "saw tooth" pattern. The large number of reflectors in each "leaf" is used to facilitate installation and to improve pump-out characteristics as compared to individual shield interleaving. Each shield is perforated (1.88% of area)[3] to facilitate evacuation.

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[3] This number is derived from empirical measurements found in National Bureau of Standards.

Due to the size and pre-formed characteristics of these blankets, they are impractical for the very small tanks (5 ft^3) and have not been considered for that application. The entire blanket assembly is enclosed in a purge blanket to meet ground hold requirements.

In very small tanks, the surface to volume ratio becomes large and the contours become severe. A continuous wrapped insulation becomes practical and necessary for these designs. The continuous wrapped systems of nylon net spaced, both sides aluminized Mylar considered here include designs where the insulation has been pre-formed into two parts, which are applied layer by layer with one interconnecting joint at the tank equator. Generally, this insulation requires hand forming and hand installation. 150 layers of this material are used to provide the proper insulation comparison weight. Shield perforations are provided to facilitate space evacuation.

This system has been considered for tankage with diameters less than 10 feet and lengths up to 30 feet. Insulating larger tanks in this fashion would prove to be extremely difficult. This insulation system must also have provision for purge during ground hold.

Each of the insulation designs, except the all fiberglass system, have utilized special insulation at each penetration described in the tank design table. A fiberglass annulus with a cross section as shown in Figure 10 has been placed around and in contact with each penetration. The basic insulation is butted against this intermediary in an attempt to eliminate any direct radiation through the insulation interface joint. Ideally a number of thin fiberglass washers should be used to build up the annulus so it can be interleaved with primary insulation. This intermediary is designed to minimize the insulation thermal degradation associated with the thermal shorting of the warm layers of the multilayer insulation to a relatively high conductivity penetration.

Analysis Technique

Mathematical, computerized models for full thermal analysis are under development for studying external cryogenic insulation systems. These tools are not yet operational (see Appendix A for a description); therefore, preliminary thermal performance estimates have been synthesized from the data and analysis found in the literature and reported in the Bibliography/Synopses/Category Report. All insulations have been treated as consistently as possible so that relative figures are accurate even if the absolute magnitudes are only approximate. Each insulation analysis has been split into several factors where applicable: basic idealized system, degradation due to joints, degradation due to mounting, degradation due to evacuation perforations, and penetration degradation.

Basic shingle performance has been estimated by adding the normal and lateral heat flows directly. Since one end of the shingle is attached directly to the tank, heat may flow by conduction and radiation parallel to the reflective layers to the tank. This mode proves to be dominant in these designs. For the shingles on a substrate, the shingle and substrate conductivities are considered to be in series and are treated as a composite solid. The all fiberglass and the net spaced insulation designs were treated as one dimensional heat transfer media for evaluating bulk insulation properties. In all cases, heat flow was treated as a linear function of temperature using experimentally determined, effective thermal conductivities. All such values were selected from the literature, and represent mean or nominal values to minimize biasing.

Effective conductivities for the various materials for both normal and parallel heat flow have been selected from NBS-100, NBS-11, TCM-11, DDC-19 and NASA-3 (parallel) where extensive experimental data has been reported. Joint degradation values have been based on experimental studies reported in NASA-30 and NBS-26. DDC-22 has been used to estimate support thermal degradation. Perforation effects on thermal conductivity have been estimated from results presented in NBS-81. Each of these reports give experimental degradation and/or thermal conductivity data directly. The continuous insulation has been further degraded by a factor of 50% to represent the performance degradation resulting from installation technique, as reported in the literature.

Penetration effects have not been studied extensively enough to provide direct evaluation of their thermal degradation. Theoretical investigations of penetrations have been reported in NBS-112 and NBS-119. In both cases, numerical, simplified heat transfer models have been solved for a range of parameters. Although none of the results presented are directly applicable, they are expected to be representative of the magnitude of degradation to be expected. A combination of these results have been used to evaluate the losses associated with the penetrations required in our designs. In particular NBS-112 was used to evaluate conductivity effects in the basic insulation while NBS-119 was used to establish the effects of penetration size, intermediary insulation properties and insulation thickness. Unfortunately, in the work reported in NBS-119, the conductivity of the penetration was not studied; in all cases the penetration was assumed to be at the tank temperature. In addition to the basic insulation degradation estimates derived from the above reports, a linear conductive heat leak was computed for each penetration under the assumption that it acts in parallel with the insulation degradation factor.

In all cases, the performance in space has assumed evacuation to a pressure less than 10^{-3} torr, where residual gaseous conduction becomes insignificant. Ground hold estimates have been based upon one dimensional heat transfer data for helium filled basic insulation. The transition from the ground hold condition (high heat flux) to the evacuated condition in space can be very important in determining and insulation applicability for short and intermediate duration missions. An evacuation analysis program is currently under development (see Appendix A) but it is not yet available. The literature search has not revealed any comprehensive studies of this pump-out problem. A number of individual laboratory sized experimental investigations have been reported but they do not lend themselves to scaling or basic analysis because of geometrical effects. NBS-41 has reported a simplified diffusion equation analysis which is applicable to shingle systems; this forms the basis for the rough pump-out estimates presented here. The solution predicts pump-out times for shingles and indicates that the time factor appears in the following form:

$$P \propto e^{-Dt/L^2}$$

P = pressure in insulation
D = diffusion coefficient
L= length of path to the vacuum
t = time

This relationship was used to scale the insulation pump-out times reported in the reference to represent the fiberglass, net blanket and continuous insulation evacuation times. Estimates of diffusion coefficients and pump path lengths including the effects of perforations were selected from a composite of data and estimates presented in DDC-7, DDC-24 and NBS-61. These values will be subject to considerable refinement when the computer model described in the appendix is completed.

Results of Thermal Analysis

The thermal performance of each of the five insulations mounted on each of the eleven tanks containing alternatively hydrogen or oxygen are presented in Tables 11 and 12. Table 11 pertains to the ground hold condition and Table 12 presents the evacuated performance in space estimates. During launch and the early portions of space flight, the insulation is subject to low external pressure which eventually evacuates the material. Since gaseous conduction results in very high heat fluxes compared to the evacuated condition, this pump-out is critical for adequate thermal performance in the short missions. Table 13 presents estimates of this pump-out time for the various insulations. The numbers presented there are probably rather optimistic since a detailed outgassing and diffusion analysis has not been performed.

The pump-out estimates confirm the idea that blanket and continuous type insulations will not achieve their inherent high performance in short or intermediate missions as quickly as the shingles. On the other hand, these pump-out times are essentially insignificant in 6 month missions.

An examination of the ground hold estimates show that shingles on a substrate provide the best performance in all cases. This is because the helium purge gas is confined to a narrow region near the tank, in a semipermeable material. The purge gas contibutes about 50% of the heat leak in the fiberglass while it contributes about 90% to the multilayer heat transfer. The shingles of this insulation are immersed in air, which does not degrade the insulation as badly as helium.

The estimates of performance in space show the obvious advantages of blankets and continuous wrapped systems. One caution must be given; that is the penetration and non-repeatable installation factors become a large portion of the heat leak in these insulation. In particular, the continuous wrapped insulation has historically been extremely sensitive and unrepeatable with respect to installation procedures. Secondly, the Dimplar shingle insulation shows excessive heat leak due to lateral conduction in two layers of aluminum per reflector. This material (as well as "Superflock") should probably be considered in a blanket design, where its lateral conductivity is not so detrimental and its pump out characteristics can be fully exploited. A third factor of importance in evaluating the shingles (of either type) is the potential performance increase achievable by interrupting the lateral conduction path along the aluminum coating. This can be achieved by incorporating very small spaces of non-aluminized material at discrete intervals to break up the "pure metal" conduction path. Since lateral conduction contributes about 80% of the heat flow in this insulation a considerable improvement may be made.

3.3.2 Supports and Cryogen Cooling

Little consideration has been given to advanced support design during the course of this study. The reason is the excellence and technical thoroughness of the NASA funded work presented in NASA-34. That report presents a state of the art evaluation of tank support systems and sophisticated support thermal decoupling schemes. Design information is given for many systems, and has been used in the tankage design for this study.

A good survey of cryogen vent cooling techniques may be found in DDC-19. Figure 3 illustrates the basic approaches taken for using vent cryogen to reduce insulation heat leak. It is clear from the examinati of these approaches that they can be adapted to virtually any external insulation system. Insulation performance improvements resulting from cryogen cooling have not been examined in detail for this preliminary study, but will be in the next phase.

3.3.3 Systems Fabrication

It is fabrication that produces the well-established discrepancies between sophisticated thermal performance design calculations and the observed rate of cryogen loss in real tanks. To properly evaluate an external insulation system's likely performance when installed, one must have a good appreciation of the materials and practices which are used to realize the insulated storage vessel. The techniques used vary with the type of insulation system, but we are presently concerned with the five systems types selected in the earlier phase of this study. Those systems have many portions of similarity in their conception. For example, the fiberglass system has problems also associated with the purged substrate of the short-term shingle system. The shingle systems share a common material with the blanket and continuously wrapped systems. Consequently, most understanding is gained by considering the fabrication problem conceptually, pointing out as necessary the techniques and problems as they apply to the individual systems. If this is done in an orderly fashion, semi-quantitative conclusions can be drawn concerning the degradation of performance, geometry constraints, and relative cost of the systems under consideration.

The Physical Form of Cryogen Tanks

Although cryogen tanks are sometimes fabricated in unusual shapes, such as biconvex (pillow) forms for special circumstances, by far most vessels are derived from a geometrical form possessing axial rotational symmetry. Shapes in this category are cylinders, spheres, oblate spheroids, toroids, etc. A suitable insulation wrapping or mounting scheme can usually be found for such shapes, and at least for larger volumes, regularized to the extent that some mechanical apparatus can be used during the installation.

There are some circumstances when the use of mechanical installation apparatus is a distinct advantage. These range from reasons of reproducibility from tank to tank, to obtaining maximum thermal performance for a given system by closely controlling insulation positioning during installation. There are other circumstances, pertaining primarily to continuously wrapped multilayer systems installed on large tankage, where the installation could not be made properly without a jig or fixture oriented to the tank geometry. Fiberglass systems are not sensitive to positioning tolerances, and do not require positioning equipment for installation.

Other insulation system constraints arising from tankage geometry are due to the fact that a tankage system must possess penetrations. Penetration is a general term used to denote any apparatus which must pierce the insulation. For most systems, such devices fall in the following categories:

1. tubes or piping; used for tank instrumentation, or cryogen venting, fill, or withdrawal
2. tank support structures; rings and/or struts, etc
3. tank access structures; manholes
4. insulation mounting structures; studs, cable attachments, etc.

By inspection, one can verify that many of these penetrations have a similar geometrical structure comprised of a cylindrical structure set with the cylinder axis colinear with the normal to the tank surface at the point of attachment. This observation indicates that an analytical solution for the heat flow in such a geometry would be of wide utility. Since research indicates that such a solution has not been published in the open literature, the development of this solution was given priority in this study as a major contribution to design and evaluation methods. This model is described later in this report and, although the development is not complete at the present time, significant progress in demonstrating the correct approach for obtaining the solution and in solving the computational problems associated with the model has been made. The Appendices present a current summary of the status of this work.

The materials used in the construction of cryogenic tanks are the metals typically associated with high performance aerospace structures, such as sophisticated alloys of steel, aluminum, titanium and so on. These materials present no insurmountable materials compatibility difficulties to external insulation system installation. The thermal properties of metals, however, give rise to the requirement for insulation systems, and also to a serious factor degrading the performance of external insulation systems. The problem of environmental gas cryopumping within to the insulation is a problem which has no reliable solution currently which does not compromise insulation system performance over some portion of its environmental operating regime. Although this problem normally is considered in connection with system ground hold, it may occur with serious consequences in space if the tank develops a leak at a closure or weld. Such leaks may also cause degradation of multilayer insulation systems performance by reduction of the insulation vacuum to a level greater than 10^{-4} torr, or by conduction if the leak cryopumps. An approach to insure prevention of closure leaks can have an effect on penetration geometry in the form of additional vent lines. Usually, these additional lines are routed to the tank at the point of installation, so that consideration of insulation installation for any penetration forms more complicated than those so far described will be neglected.

The Physical and Mechanical Characteristics of Typical Insulation Materials

Insulation materials as manufactured are flat rectangular sections. For some materials, currently in relatively greater volume of production, the length to width ratio of the section is great enough to be considered continuous. For particular types of systems, such as the shingle systems, or for materials being produced in low volume by hand labor (for example, "Superfloc") the materials may be manufactured only in smaller pieces. The basic material geometry leads to the major difficulty in insulation system fabrication, since the geometry of cryogen tanks differs fundamentally from that of the materials. Some attempts have been made to overcome this problem by mechanically preforming multi-layer materials to desired shapes (for example, to fit penetrations or tank heads) but, in general, such preforms have only limited usefulness due to insulation thickness build up during lay-up. Standard preforms would require continuous hand alteration during lay-up for this reason, and would save little installation labor. Hence, they appear to offer no advantages for hand lay-up unless required for some structural or attachment purpose.

Materials of concern here for fabrication evaluation of the five systems under study may be classified as:

1. Fiberglass batts
2. Coated plastic films

3. Adhesives

4. Supporting Materials; metals and plastics

Methods of Fabricating External Insulation Systems

The fabrication of an external insulation system commences with the fabrication of the system materials. Of the four categories of system materials mentioned above, only the fabrication of fiberglass and the radiation shields are of sufficient interest to merit description. Fiberglass is fabricated by extrusion or drawing from pools of molten glass. The rate and degree of control of the extrusion process, together with the method of gathering the fibers determines the form and density of the bulk finished matting. The finished product is typically pressed into batts.

Fiberglass can be produced from many glass types, most of which have similar thermal properties. If the material is designed for epoxy or other resin impregnation, (as many are) the surface of the fibers is often treated with a material to promote resin adhesion. The characteristics of materials used for this purpose are variable and may present a source of contamination resulting in performance degradation of other insulation system components. This point should be considered if the use of fiberglass as a substrate material is indicated.

The fabrication of radiation shield materials is now a routine manufacturing operation which, except for the metal foils. rests on the vigorous technology of the vacuum evaporation industry. (Foil fabrication is achieved through conventional metal rolling technology.) A typical type of coated multilayer film is NRC-2, a 0.25 mil Mylar film aluminized on one side, manufactured by National Research Corporation. Mylar is the designation for the duPont polyester, polyethylene terepthalate. This material, which serves as the spacer and aluminum substrate for NRC-2, is manufactured by conventional plastic film fabrication process, except that its unusual tensile strength (24,000 psi at 25°C) is produced by an additional mechanical molecular orientation process during manufacture. Unfortunately, this process also results in low film tear strength (33 g/mil at 25°C) at any unreinforced boundary. This property of Mylar does not appear to be widely known.

Rolls of the Mylar substrate are placed in a specially constructed evaporation chamber and are wound and rewound under vacuum and temperature conditions sufficient to remove excess moisture, plasticizer, and other contaminants from the film surface. At the conclusion of this process, high-rate evaporation sources are actuated and the material is rewound again with one surface exposed to the evaporation sources.

The evaporation sources for this process may be electron beam or resistance heated. Molten aluminum at evaporation temperatures is highly corrosive so that special composite materials are required for resistance heated evaporation boats. Typically, several thousand meters of material may be aluminized at one time at linear speeds of a few meters per second. The speed of transfer of material on the rolls determines the coating thickness, which for aluminum must be at least 500 Å to achieve opacity.

A simplified drawing of a typical metallizing apparatus is shown in Figure 4. Material produced by this process has a price to the user of approximately $10 per pound in smaller quantities. It is normally wrinkled in the as received condition, by die drawing before delivery.

This method of fabricating radiation shields gives rise to an easily handled, uniform product complete with spacer which has about half the weight of a comparable foil shield without spacer. Some typical weights, from NBS-66 are shown in Table XIV. The disadvantages of such material are those associated with evaporation processing in general, and with the use of aluminum as the radiation shielding element.

Vacuum evaporation processes are notorious for rigid cleanliness requirements, and require strict adherence to proven equipment operating procedures to obtain a reliably adhered coating. The adhesion of metallic coatings deposited by thermal deposition techniques has long been a source of problems to vacuum coaters, particularly if the coating is relatively thick. Sputtered films have much better adhesion characteristics, but sometimes lack the smoothness of thermally deposited variety. Sputtering has seen great progress recently, culminating in radio frequency apparatus capable of depositing non-metallic materials. It should be investigated seriously as a method for producing improved materials of the NRC type.

The choice of aluminum as the functional element of the shield is a compromise, but one that has performed better than the alternatives. Some of these other metals, and their emissivities are displayed and compared with aluminum in Figure 5, taken from NBS-125. The emissivity of fresh aluminum, prepared in a clean (oil free) vacuum system is quite low, but it rapidly rises as the material surface oxidizes on contact with air. Silver, which has an attractive emittance, usually reacts quickly to form a tarnished surface of high emissivity.

Unsuccessful attempts to prevent this by dielectric overcoating have been reported in the literature. The dielectric was not specified, but was reported to produce unacceptable emittances for the film. The emissivity of silver overcoated with silicon monoxide is shown in Figure5. Silicon monoxide is not durable, and additionally, is reactive to moist air. It is possible that a suitable protective material might be found among some of the modern polymers. Gold coatings have occasionally been used as an aluminum substitute, but they have typically been plagued with adhesion problems. However, the inertness of gold to emissivity degradation is an advantage. Aluminum, as well as degrading through oxidation, is a reactive metal, and at least one case of insulation failure from coating dissolution has been reported. Failure in this instance was attributed to moisture condensation in the insulation. Though far from perfect. aluminum continues to be the choice of materials for deposited shield construction, and may remain so. Better methods of coating application would probably help bring installed system performance closer to that theoretically, and devinitely should be pursued.

There are several new classes of coated plastic (and glass) materials which depart somewhat from the NRC-2 wrinkling approach for the control of conductive heat transfer through the radiation shield/spacer system. These have been given various trade names which are somewhat representative of the approach. The additional fabrication operations for some of these are novel and relatively obscure, and will be considered briefly. There is one class of materials which are embossed after coating (Dimplar, Marshield). This embossing usually is a pattern of raised bumps, on one or both sides of the film and is made by rolling the film through bumpy rollers (Marshield is embossed aluminized fiberglass). The advantages of this construction are several; including superior insulation recovery from vacuum bag compression prior to launch lack of recovery is frequently a major cause of degradation on a normal multilayer system. Additionally, insulation evacuation in space is quite rapid due to high permeability and is particularly important for purged configurations. Insulation conductivity can be closely and reproducibly controlled by embossed pattern shape and spacing. The only disadvantage seems to be a limitation on the thickness of insulation which can be put into a given space. Some of the above properties offset this last consideration to a great extent, since the insulation functions more efficiently on a per layer basis.

Another scheme relies on the application of nonconductive material to perform the same function as the embossed patterns. These are flocked materials, and rather esoteric in manufacture (Superflock, Superfloc). Superfloc is made by silkscreening and adhesive pattern of controlled shape and distribution on conventional coated film. Tufts of dacron or nylon thread are then distributed on the adhesive by vibrating the material in the manner of a drumhead. The vibration causes the thread clusters to move and adhere to unfilled glue spots, resulting in a uniformly dispersed separating element of controlled conductivity. The Superflock process is similar in conception, except that short nylon fibers are used in place of thread tufts. The material is applied by standard flocking process. However, before the adhesive cures, the flocked insulation material is passed through an electrostatic machine which orients the fiber axis perpendicular to the insulation sheet. The advantages of these insulation materials are the same as those of the embossed. All of these various processes yield materials which when installed produce high performance systems. For example, the Marshield system is reported to give nearly theoretical results when installed. These are innovative and well conceived schemes which should be pursued further in conception and development.

The fabrication of insulation system sub-assemblies is the next step above the materials fabrication level in the construction of the complete thermal protection system.

Systems fabricated at the subsystem level really only include shingle and blanket modules; those processes will be considered briefly.

Most large tanks for storage of cryogenic fluids are erected on the final site because of difficulty in shipping large assembled parts. Once a tank of this size (diameter equal to 15 feet or larger) is in place, it is extremely difficult to move it for insulation installation. This fact led to the development of high performance pre-fabricated blanket multi-layer insulations which could be installed on fixed tanks. The virtues of these insulation modules became apparent and they are now used also for smaller tankage where maintainability is a critical systems requirement. The methods of fabricating blanket modules depends somewhat on the insulation mounting scheme.

Insulation blankets which are supported by a few central mounting fixtures must have some method of distributing the support stress in the insulation mounting zone to other parts of the material in order to prevent insulation structural failure at the mounting points. One method for achievin this end is to fasten the insulation layers together, and also to a layer of strong, load bearing material. Since the fastening must be as thermally nonconductive as possible, so a quilting technique using fiber threads has bee successfully tried. In a typical process, the radiation shields and spacers are laid out on a slotted table and sewn between a pair of backings by hand, using needles and thread. Once fabricated, the blankets with- stand normal handling quite well. Other fabrication methods are employed for different mounting systems. For systems mounted on studs, the blanket is laid up on a table, and a mounting template is used to guide a device which cuts mounting holes completely through the layers. The most common hold cutting apparatus is probably an end sharpened stainless tube, chucked in a hand drill. While such cutters produce apparently satisfactory holes in many materials, such as foils and glass papers, there are better methods for Mylar which give higher system reliability. These techniques involve the use of a tubular cutter heated to 1000°F. At those temperatures, the film will melt and shrink back from the tool, producing by surface tension a reinforced "grommet" of film material around the hold. This technique can be applied after mechanically cutting the hole, but the labor of the operation is then essentially doubled. The heated tool process is definitely advantageous for systems which will encounter severe environmental conditions, due to the propensity of Mylar to tear as mentioned earlier. Layers must be separated to prevent welding during hole cutting. Fabricated blankets for stud mounting may be held together for handling by temporary fasteners which are removed or left in place after installation.

Shingle modules are fabricated in similar fashion to the blankets, except for different sizes and mounting configuration. The material is laid up on a table, cut to size in thicknesses of several layers using electric scissors, meanwhile separated with an expendable material such as kraft paper to prevent edge welding during cutting. Unless a purge or vacuum bag is to be added to the pack of shingles, the handling and installation from this point are similar to blanket systems.

The fabrication of continuous wrapped insulation systems is of course closely related to the insulation mounting system. For small tanks, the insulation is wrapped, cut, and fitted by hand. Usually cuts are held to a minimum except as necessary to clear penetrations, and surplus material is tucked out of the way. The insulation is secured with an adhesive tape as the work proceeds. As the insulation is handled extensively, it is necessary that proper precautions be taken to insure that the material is not handled without gloves. Although it is probably known widely by now that finger oils degrade insulation emissivities severely, there are older published reports showing insulation fabrication without gloves. For repeatability and highest performance, gloves must be worn.

For large continuously wrapped tanks, the system fabrication is normally done by rolling the tank about its axis in a special fixture while winding the radiation shield and spacer on the rotating tank from large spools. Usually the insulation support structure, a system of tension bands, is interwound with the insulation. For tanks insulated in this manner, the machinery must be stopped and a hole cut each time a penetration is encountered. This is laborious, time consuming, and leads to poor penetration thermal performance unless high standards of workmanship are maintained.

A variation of machine wrapping techniques has been derived from filament winding technology, and for certain shapes and types of tanks, this insulation installation technique provides good, reproducible results. Typically materials used for systems wrapped in this fashion are aluminized Mylar tapes and foam spacers.

The installation of blanket and shingle systems depends primarily on adhesive technology. The only adhesives which have shown consistently good performance are polyurethane adhesives with some exceptions among the epoxies. The one used most commonly is NARMCO 7139/7343. Polyurethane adhesives have some undesirable characteristics, among which are: (1) reaction with atmospheric moisture (2) wide wide variance in properties unless carefully manufactured (3) poor shelf life (4) creep at room temperature and little strength at higher temperatures (5) changes its properties rapidly with age, but they perform better than other compounds at cryogenic temperatures. Some typical insulation mounting systems are shown in Figures 6 and 7. In general, some insulation mounting structure must be attached to the tank. If it cannot be fastened mechanically be welding or by fastener technology, it must be mounted using adhesives. Studs for blanket or shingle mounting are typically adhered, and are usually made of a non-conductive material. In installation, the blankets or shingles are placed on the studs, and retainers snapped in place. Systems using fasteners such as button and string (Fig. 6) or Velcro tapes also use adhesive mounting. These mounts produce installation operations similar to the stud system. The modules are merely put in place and the fasteners joined.

Tension structures such as nets, which could be used as non-adhered mounting structures do not seem to have been investigated for external insulation supports. To avoid a weight penalty in the mounting, such structures would have to be sophisticated in design. For small tanks, however, they might allow the insulation to be removed easily for maintenance. For high reliability systems where adhesive failure could not tolerated, such a system might have additional advantages.

The installation of shingle systems, where not made using studs, is generally accomplished by direct adhesive bond of the shingle or shingle pack. Typically an adhesive tape of unspecified composition is used.

Now that the fabrication and installation methods have been outlined, we can examine the remaining component of external insulation systems: purge and vacuum bags. These bags are constructed of plastic/metal membranes, and are designed to segregate the insulation purge gas (usually helium) from the ambient atmosphere, or to prevent the ambient atmosphere from entering an evacuated insulation system. Both systems are technologica answers to the gas cryopumping problem mentioned earlier. Evacuation is the more efficient, because the thermal conductivity of the non-cryopumping purge gas is quite high. Evacuation, if it can be maintained, subjects the insulation system to mechanical compressive loads due to atmospheric pressure in most cases. There are some vacuum bag designs which do not, but these are the exception, not the rule.

The materials used in these containers are typically metal plastic laminates, such as Mylar/lead/Mylar (M/L/M) or Mylar/aluminum/aluminum/Mylar (M/A/A/M). Table 15 from NBS 58 shows a list of materials (with sources) which have been used for this application. Table 14 from NBS-73 shows the thermal properties of selected materials. Purge bags which are satisfactory in performance can be constructed from these film laminates. Ingenious zippers and other fasteners which open the bag rapidly and fully in space for evacuation have been developed. Vacuum bags, on the other hand, are not reliable at the present. They tend to develop leaks when wrinkles are formed by atmospheric loading, and at three cornor folds in the bag, etc. M/L/M and M/A/A/M seem to be optimum materials so far, but further development is needed.

After extensive searching, it is clear that a paucity of cost information exists concerning external insulation systems. As a result, the cost ranking done in the Initial Study phase was used for selecting the promising three systems. The Final Study will contain those cost results which are available.

4.0 SYSTEMS FOR FURTHER STUDY

Three of the five Materials/ Concepts have been selected for further study in the final phase of this program. This selection has been made on the basis of the Concept Selection Criteria shown in Tables 5-8. Space does not permit a listing to list the merits of the chosen systems, which are 1) Fiberglass 2) Shingles on a purged substrate and 3) Blankets. The reasons for these choices will be briefly summarized.

1) Fiberglass is rugged and provides low cost reusable thermal protection for short missions.

2) Shingles on a purged substrate give excellent thermal performance for short or intermediate term missions and can easily be maintained.

3) Blankets can give maintainable long term thermal performance, with reasonable repeatability.

Shingle systems without substrate were eliminated because they provide slightly poorer thermal performance. There are some missions for which they are appropriate, however.

Continuous systems were eliminated primarily for lack of penetration repeatability. They provide superior performance at maximum cost for some applications, and efforts to eliminate their disadvantages should be made.

TABLE XIV

PROPERTIES OF SHIELD MATERIALS

Material description	Thickness, in.	Weight, lb/ft^2	Nominal coating thickness, A	Coating emittance	Perforation, %
Aluminum foil	0.002	0.028	N.A.	0.025	None
Aluminum foil	0.0005	0.007	N.A.	0.025	None
Aluminum vacuum metallized on polyester film, one side only	0.00025	0.0018	275	0.047	None
Aluminum vacuum metallized on polyester film, two sides	0.00025	0.0018	375 50	0.035	None
Aluminum vacuum metallized on polyester film, two sides	0.00025	0.0018	375	0.025	None
Aluminum vacuum metallized on polyester film, two sides perforated	0.00025	0.0018	375	0.065	1.88
Silver vacuum metallized on polyester film, two sides	0.0005	0.0036	1000-2200	0.011-0.017*	None
Gold vacuum metallized on polyester film, two sides	0.00025	0.0018	1700-3400	0.017	None

*Higher emittance results from degradation of coating with time.

TABLE XV

LIST OF VACUUM CASING MATERIALS

	Description and Vendor
Film	Mylar -- E.I. duPont de Nemours & Company
Film	Tedlar PVF -- E.I. duPont de Nemours & Company
Film	Saran No. 7 -- Dow Chemical Company
Film	Scotchpack No. 10A3 -- Minnesota Mining & Mfg. Company
Film	Teflon FEP -- E.I. duPont de Nemours & Company
Film	Polyethylene, low density -- Visking Company
Film	Polyethylene, high density -- Visking Company
Film	Con-O-Lam 7NS30 -- Continental Can Company
Film	Tera-Film (polyester) -- Terafilm Corporation
Film	Polypropylene -- Avisum Corporation
Film	Acclar 22C -- Allied Chemical Company
Film	Acclar 33C -- Allied Chemical Company
Film	Polyurethane Estane No. 5740-x 070 -- B.F. Goodrich Co.
Mylar Laminates	1 mil bilaminate bonded with G-207 adhesive -- Goodyear Aircraft Corporation
Mylar Laminates	0.5 mil trilaminate bonded with G-207 adhesive -- Goodyear Aircraft Corporation
Metalized Mylar (one side)	1 mil aluminized Mylar

TABLE XV, con't

	Description and Vendor
Metalized Mylar (one side)	0.25 mil aluminized Mylar, 4-ply laminate bonded wit G-207 adhesive -- Goodyear Aircraft Corporation
Metalized Mylar (one side)	0.5 mil, 3-ply laminate, No. SS1000-4 -- Continental Can Company
MLM	1 mil Mylar, 0.8 mil lead, 1 mil Mylar -- Schjeldahl Company
AMA	0.35 mil aluminum, 1.5 mil Mylar, 0.35 mil aluminum -- Dobeckman Company
TAT	0.5 mil Tedlar, 0.25 mil aluminum, 0.5 mil Tedlar -- Schjeldahl Company
MAM	0.5 mil Mylar, 0.35 mil aluminum, 0.5 mil Mylar -- Dobeckman No. 34320
MAM	0.25 mil Mylar, 0.25 mil aluminum, 0.25 mil Mylar -- Alumiscal Corporation
MAM	0.5 mil Mylar, 1 mil aluminum, 0.5 mil Mylar -- Alumiscal Corporation
MAM	0.5 mil Mylar, 0.5 mil aluminum, 0.5 mil Mylar -- Dobeckman No. 32899
MAM Laminate	2-ply laminate of Dobeckman No. 32899 bonded with G-207 adhesive -- Goodyear Aircraft Corporation
MAAM	0.5 mil Mylar, 0.35 mil aluminum, 0.35 mil aluminum, 0.5 mil Mylar -- Dobeckman No. 34321
MAAM	0.5 mil Mylar, 0.35 mil aluminum, 1.5 mil Mylar, 0.35 mil aluminum, 0.5 mil Mylar
MAAM	0.5 mil Mylar, 0.35 mil aluminum, 0.5 mil Mylar, 0.35 mil aluminum, 0.5 mil Mylar -- Dobeckman No. 3432?

TABLE XVI

Casing material*	Material thickness, in	Helium permeability (at STP), $cm^3/(sec)(ft^2)(atm)$	Thermal conductivity times thickness Btu/(hr) (°F)
Mylar laminate (M/M)	0.002	>20 000. $\times 10^{-8}$	0.000146×10^{-3}
Aluminized Mylar laminate (Ma/aM/aM)	.0015	2 000.	.0804
Mylar lead Mylar laminate (M/L/M)	.0028	<.218	1.33
Mylar aluminium Mylar laminate (M/A/M)	.00135	<.218	3.76
M/A/A/M	.0017	<.218	7.5
M/A/M/A/M	.0032	<.218	7.5
Ma/aMa/aMa/aM	.0025	298.	.322
Ma/aMa/aMa/aM/Ma/aMa/aMa/aM	.005	136.	.644

*M, Mylar film; A, aluminum foil; L, lead foil; a, aluminized surface; (/) denotes adhesive bond line between layers.

PERMEABILITY AND LATERAL THERMAL CONDUCTIVITY PARAMETER FOR CANDIDATE VACUUM CASING MATERIALS

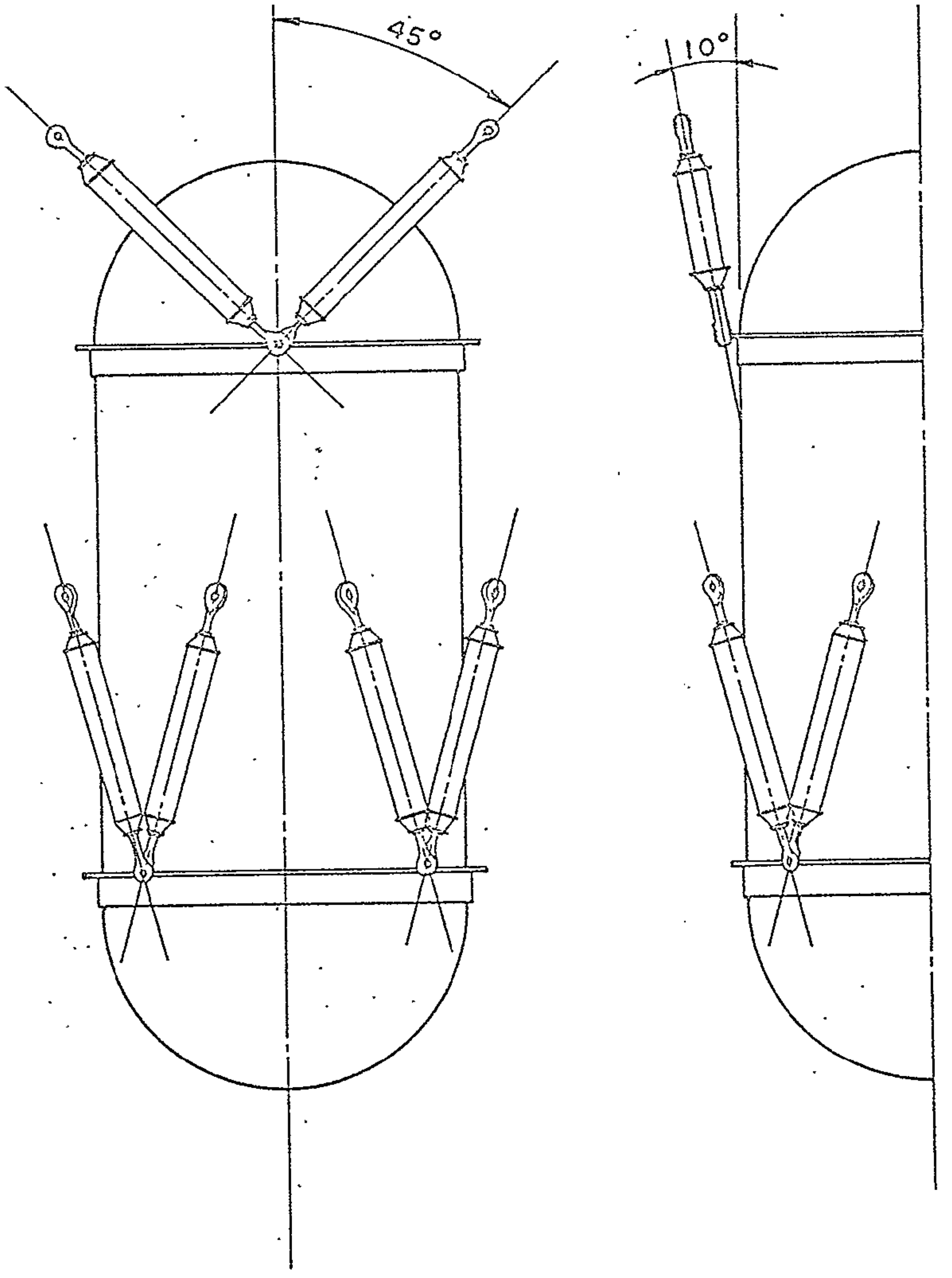


FIGURE 1
See Table 1 for Weights and Dimensions

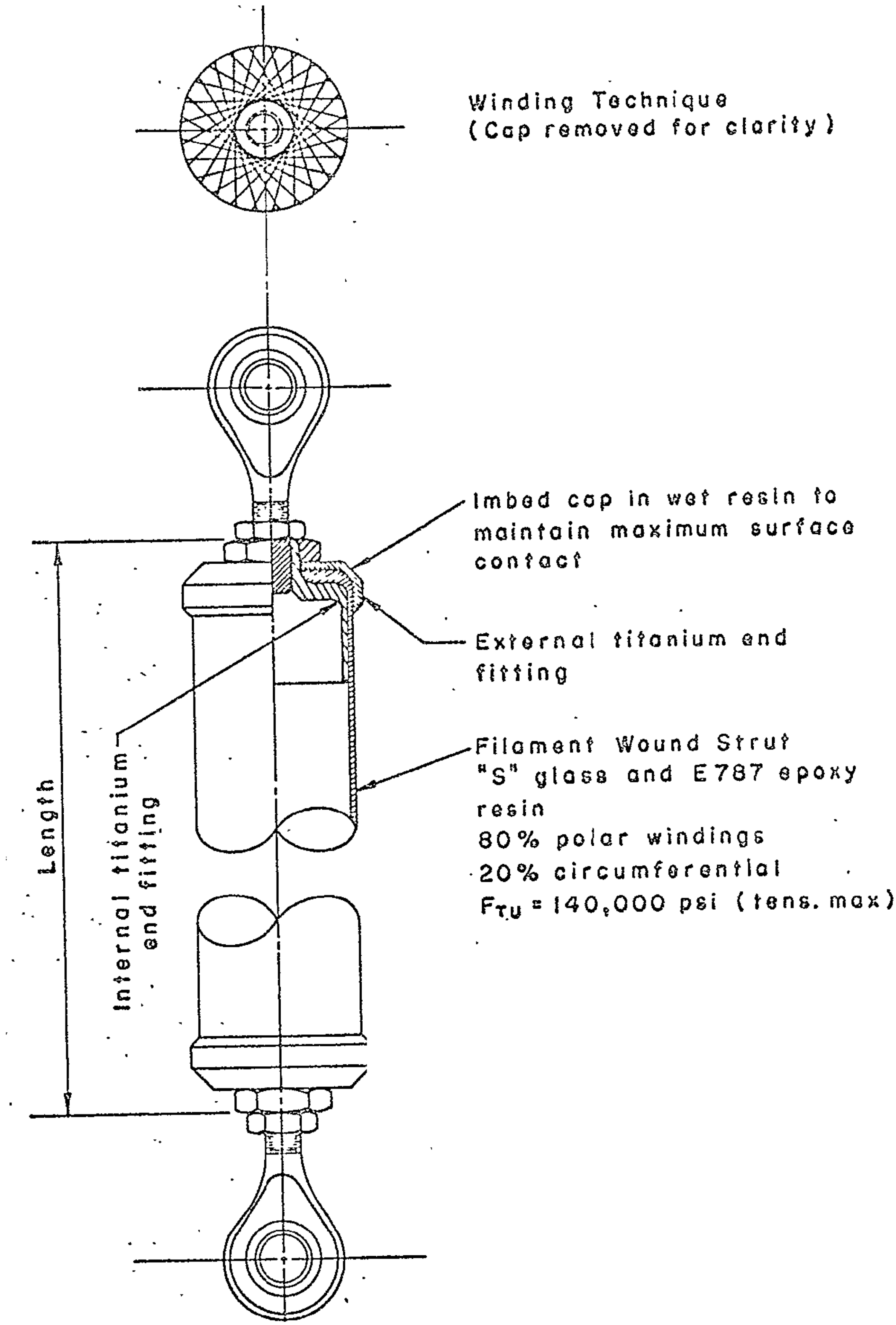

Winding Technique
(Cap removed for clarity)
Imbed cap in wet resin to
maintain maximum surface
contact
External titanium end
fitting
Filament Wound Strut
"S" glass and E787 epoxy
resin
80% polar windings
20% circumferential
F_{TU} = 140,000 psi (tens. max)
Length
Internal titanium
end fitting

FIGURE 2

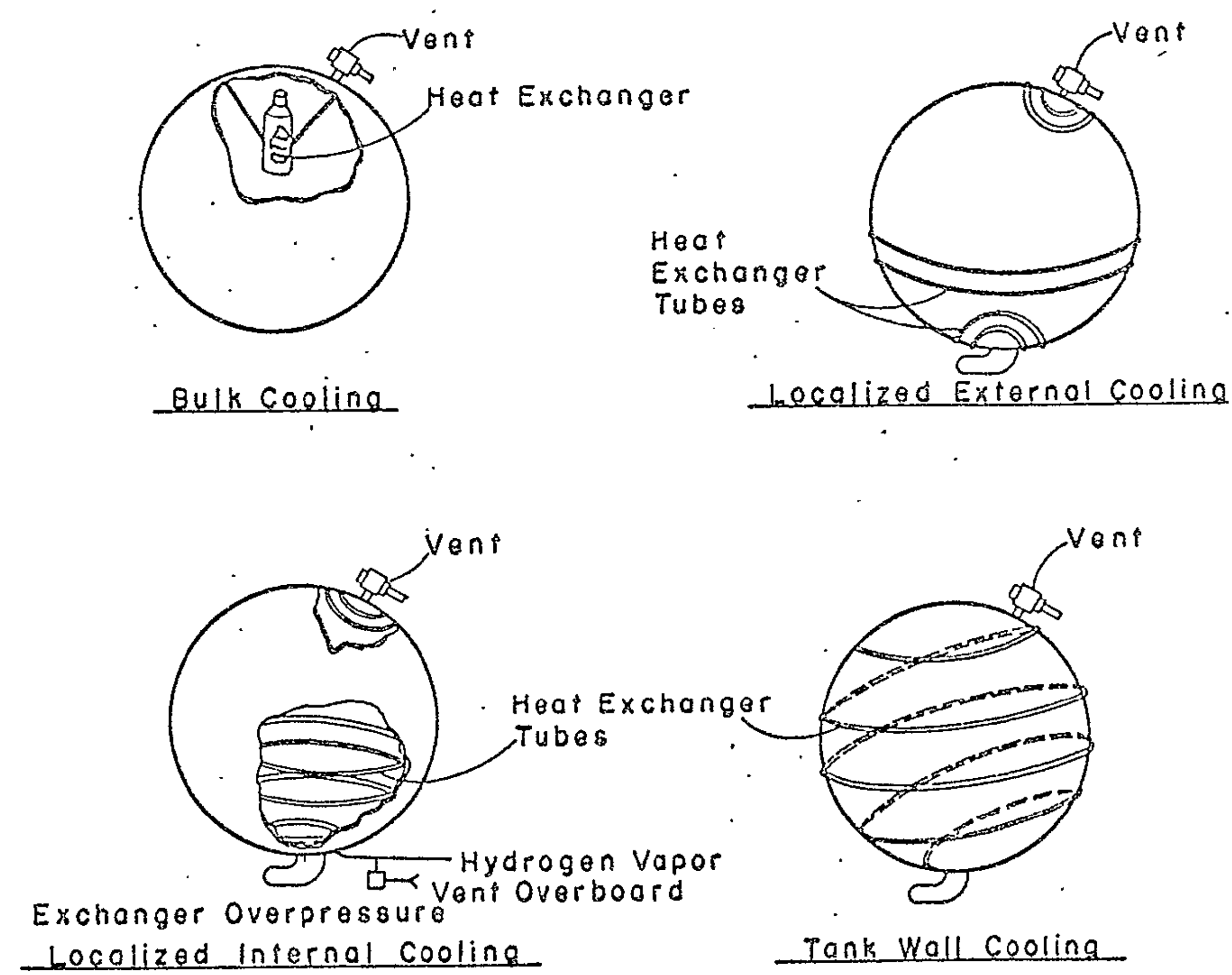

Vent
Heat Exchanger
Bulk Cooling
Vent
Heat
Exchanger
Tubes
Localized External Cooling
Vent
Heat Exchanger
Tubes
Hydrogen Vapor
Vent Overboard
Exchanger Overpressure
Localized Internal Cooling
Vent
Tank Wall Cooling

FIGURE 3

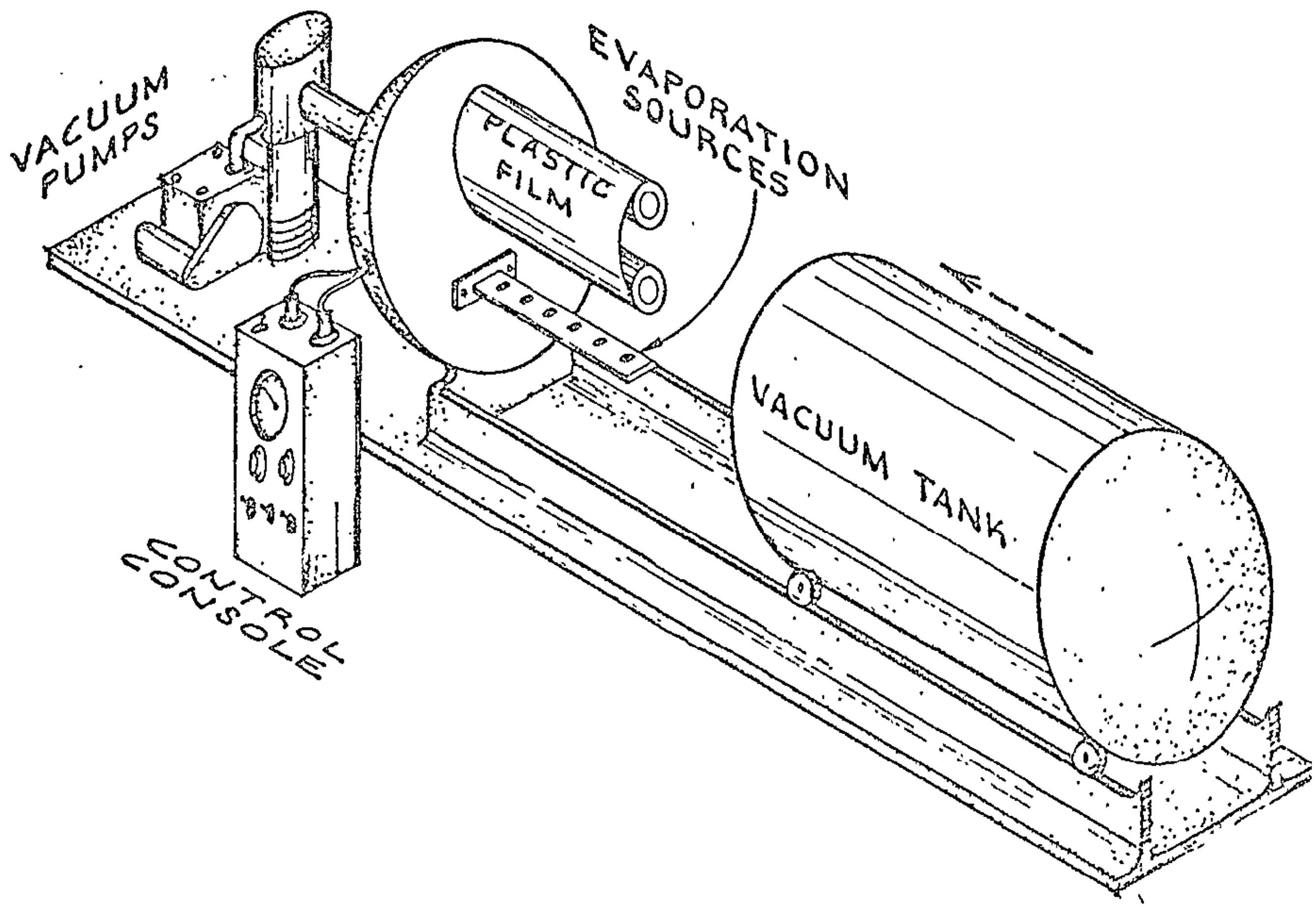
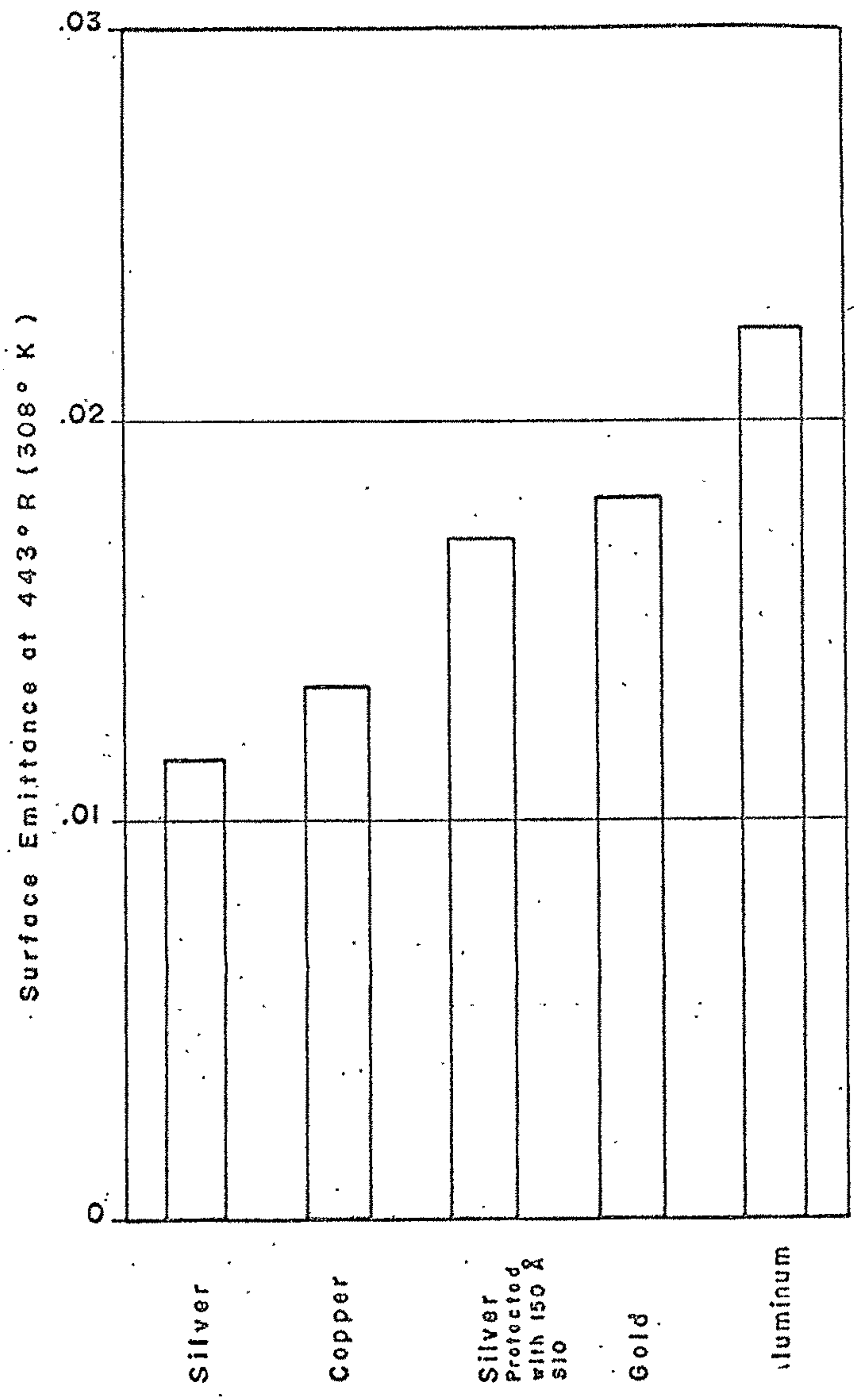

VACUUM PUMPS
EVAPORATION SOURCES
PLASTIC FILM
VACUUM TANK
CONTROL CONSOLE

FIGURE 4



METAL COATING

Thickness of 1000 Å

FIGURE 5

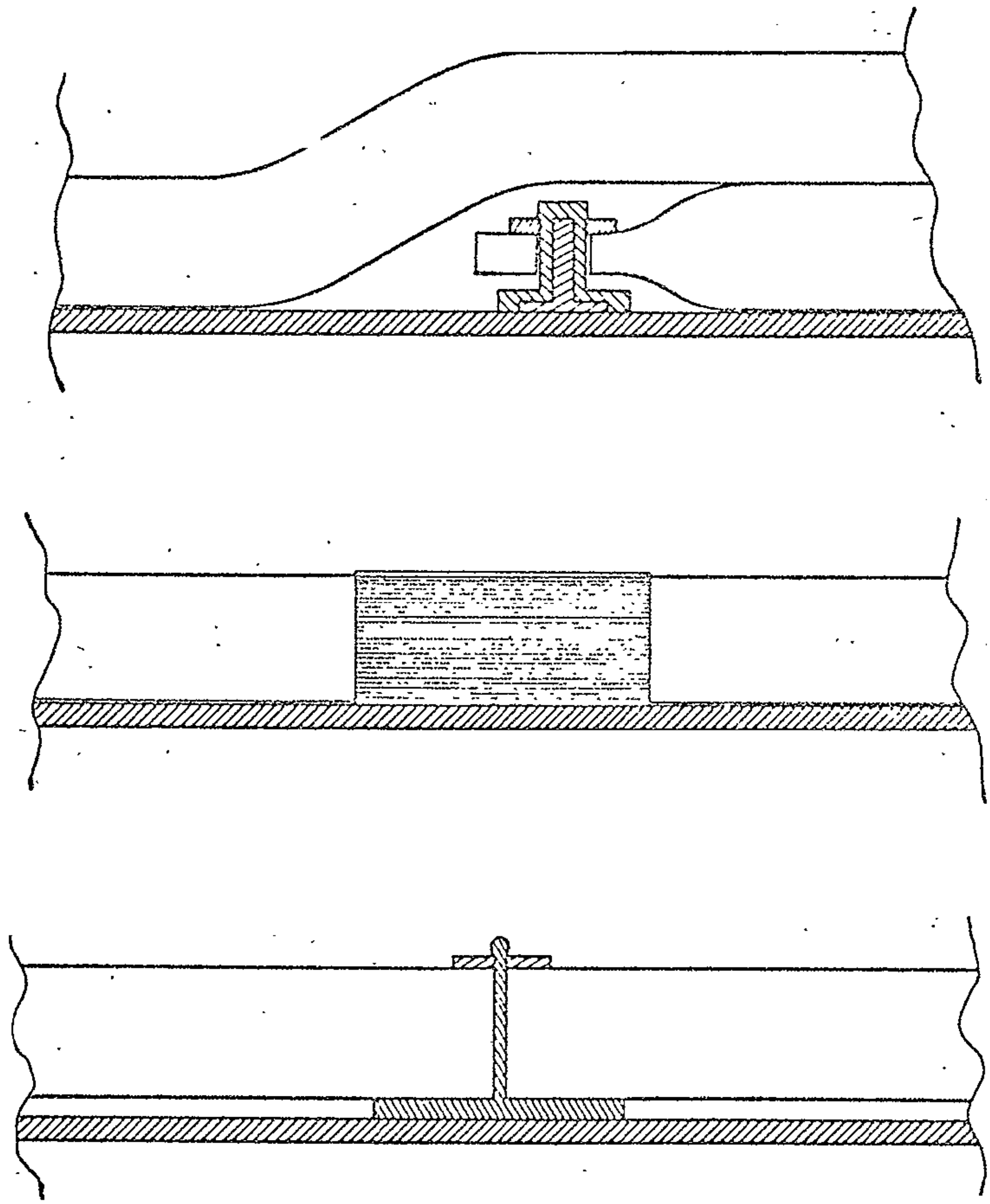


FIGURE 6

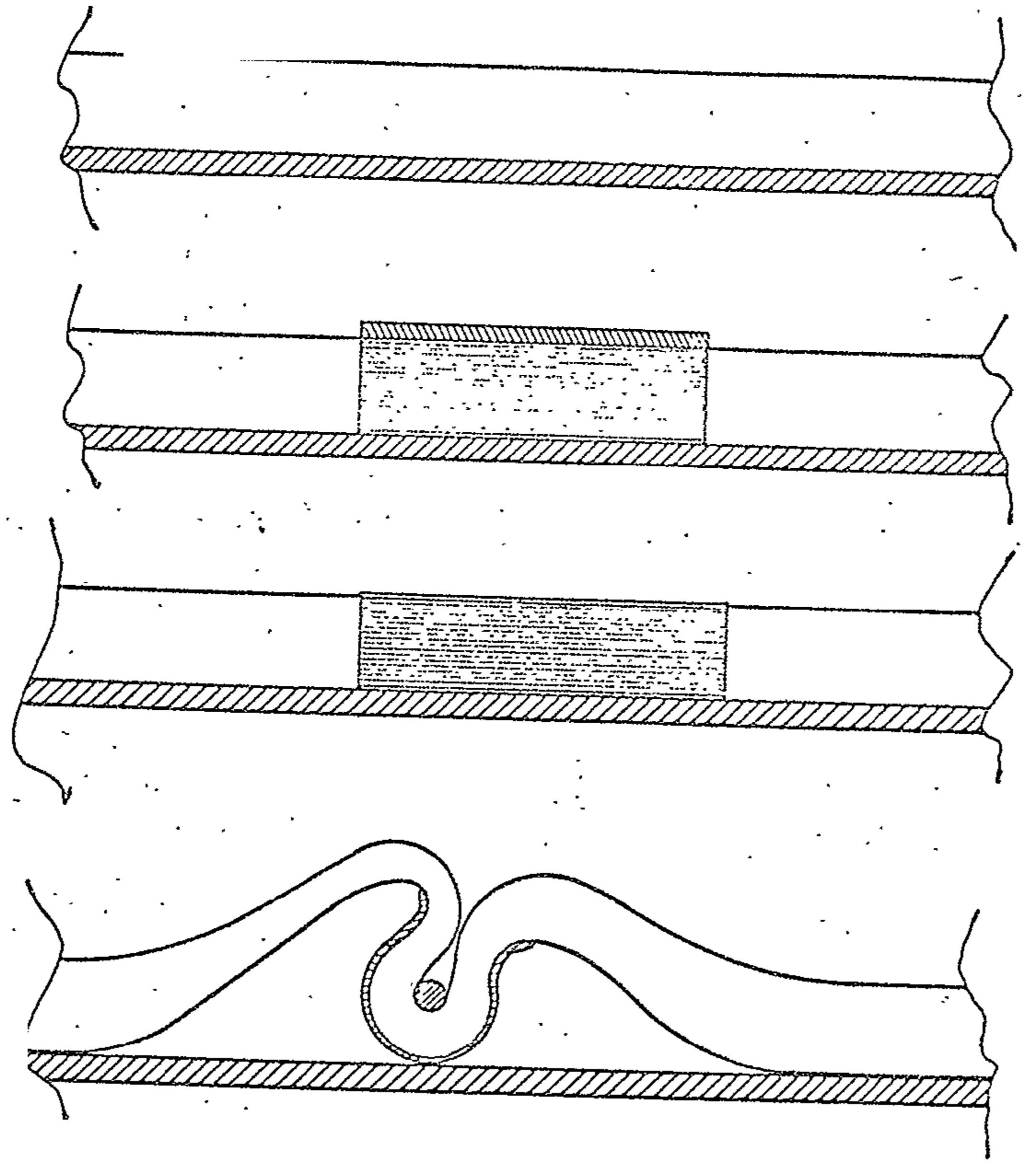
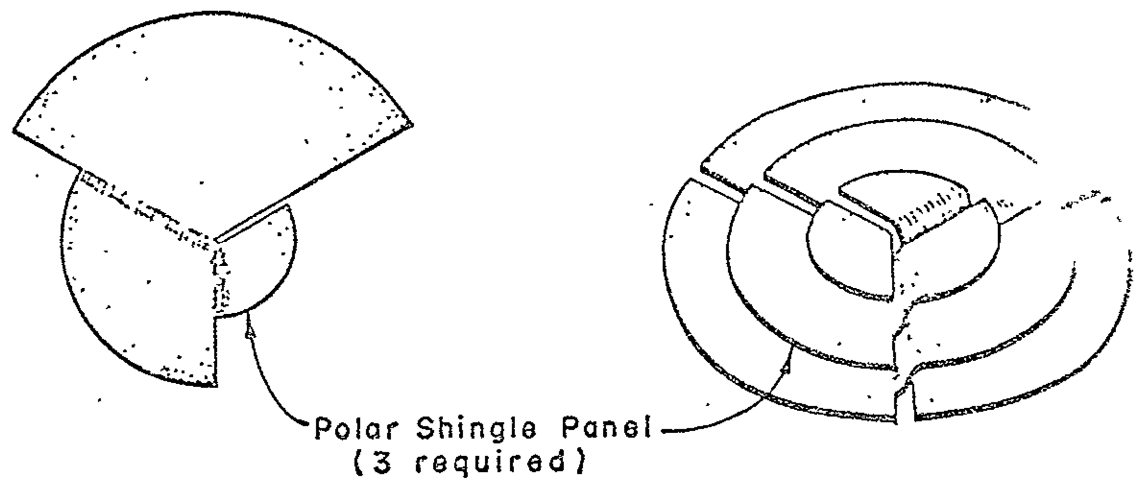
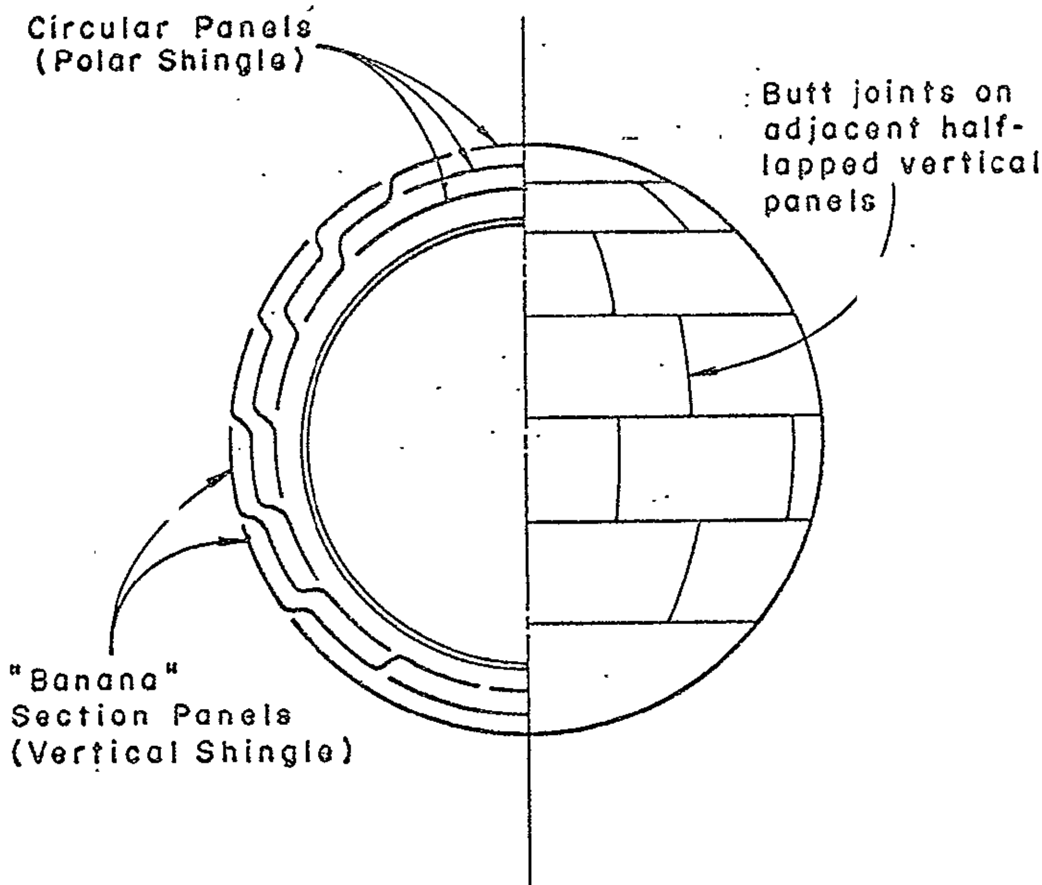


FIGURE 7

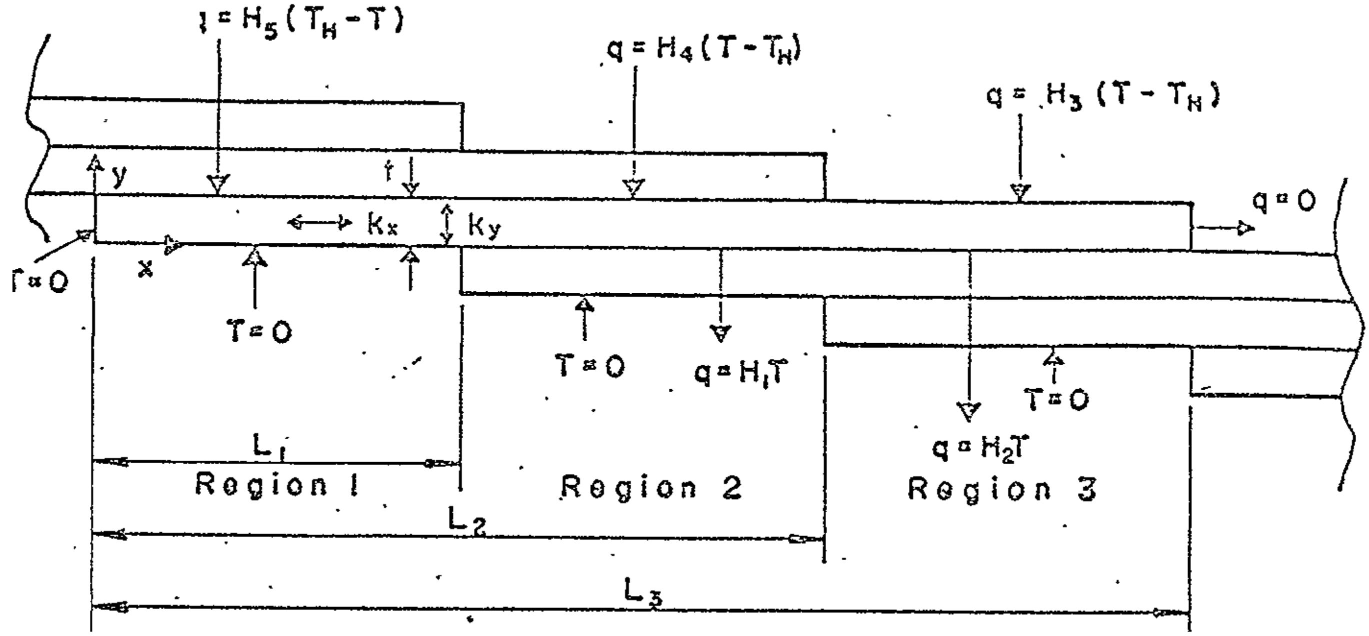


Polar Shingle



Double Shingled Insulation System for Spherical, Ellipsoidal or Cylindrical Tankage

FIGURE 8


q = $H_5(T_H - T)$
q = $H_4(T - T_H)$
q = $H_3(T - T_H)$
y
t
K_x
K_y
q = 0
T = 0
x
T = 0
T = 0
q = H_1T
T = 0
q = H_2T
L_1
Region 1
Region 2
Region 3
L_2
L_3

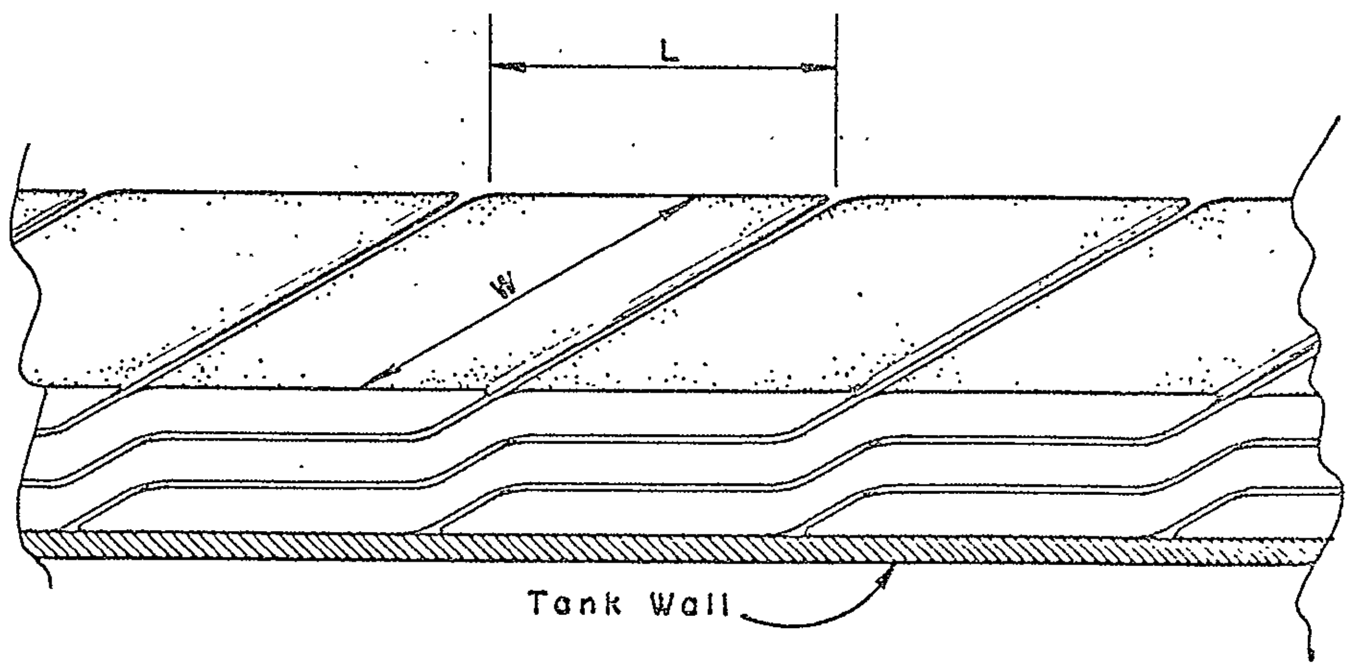
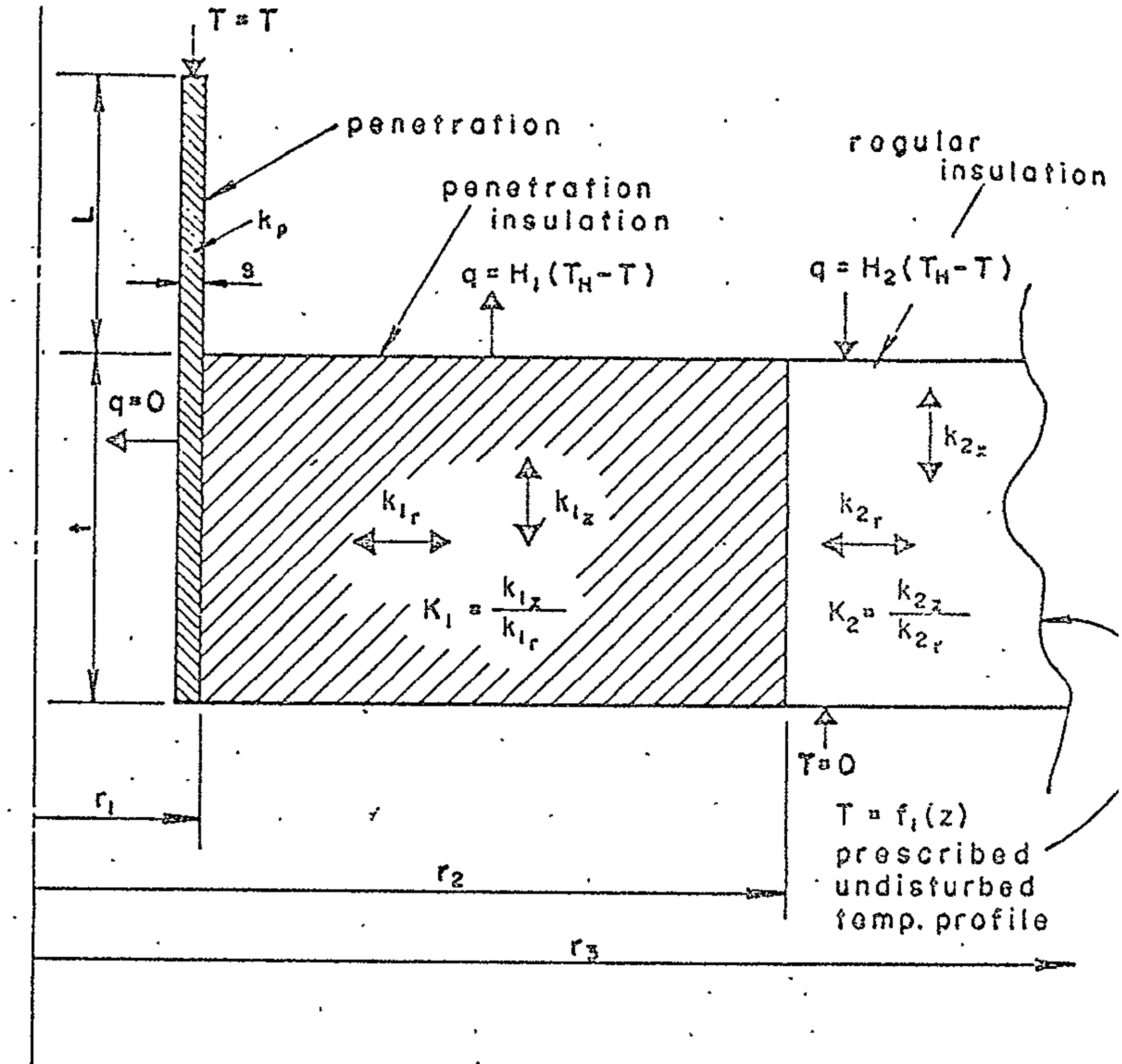
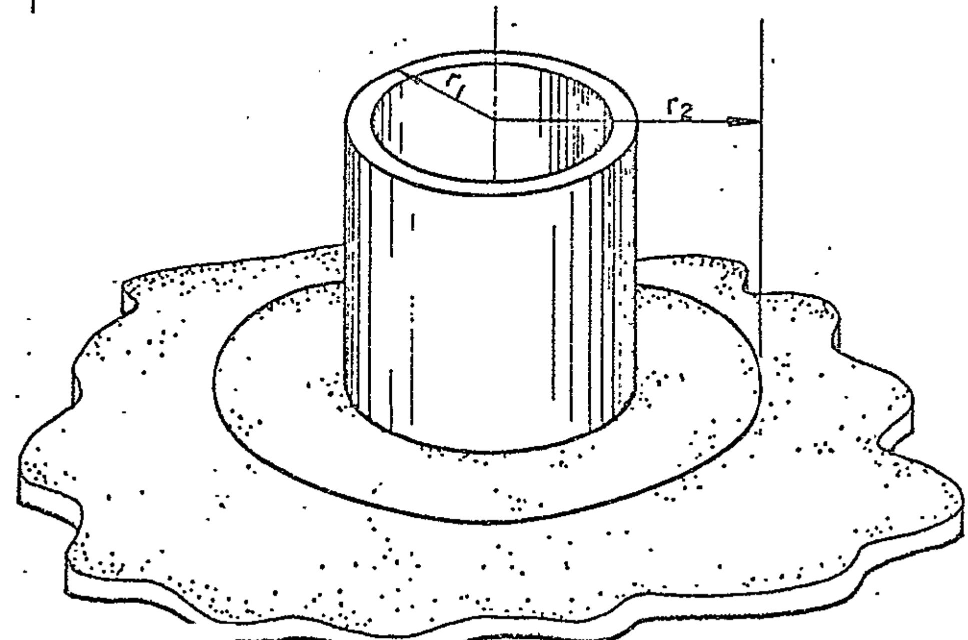

L
W
Tank Wall

FIGURE 9



T = T
penetration
regular insulation
penetration insulation
k_p
s
L
$q = H_1(T_H - T)$
$q = H_2(T_H - T)$
q = 0
t
k_{1_r}
k_{1_z}
$K_1 = \frac{k_{1_z}}{k_{1_r}}$
k_{2_z}
k_{2_r}
$K_2 = \frac{k_{2_z}}{k_{2_r}}$
T = 0
r_1
r_2
r_3
$T = f_1(z)$
prescribed
undisturbed
temp. profile



r_1
r_2

FIGURE 10

APPENDIX A

Mathematical Methods and Models

This appendix describes several of the mathematical models being developed for thermal analysis of the selected insulation systems. These models are in the development stage at this time and have not been used in this Interim Study. The complete programs will constitute subprograms in the overall executive insulation design program under development.

The executive program will provide the necessary logic; performing parametric mission analysis, tank design, weight summary, thermal performance and certain insulation design problems of reliability, maintainability, operability, etc. For a given set of input mission parameters, a preliminary design for the tank, and tank support and communicating lines will be computed. Basic insulation design parameters such as thickness, number of panels and/or joints, mountings and penetration designs will be determined. Basic thermal performance and weight data will be developed from the basic insulation sub programs for vacuum performance. The basic insulation will be analysed to determine the performance degradation resulting from penetrations, joints, and attachment methods. Ground hold tank performance will be determined by combining the basic insulation performance with a parallel gaseous condition heat transfer analysis. Insulation evacuation analysis will be performed to determine the period and magnitude of non evacuated performance degradation after launch.

The system thermal performance during the various phases of operation will be totalled for the mission duration.

This program is being written to facilitate sequential parametric studies with the out put designed to facilitate the investigation of the effect of any parameter on insulation performance. In addition, the insulation design parameters affecting the significant qualitative parameters of interest such as number of pieces, attachments, number of points and any other factors which appear important will be computed.

Thermal Performance of Multilayer Shingles

The literature survey has surfaced two basic experimental studies of multilayer shingles, (NBS-68, NBS-92). Both explored the effects of shingle length on the total heat transfer for foam spaced shingles. Although this published information is valuable for verifying the accuracy of analytic heat transfer models, no general theoretical or predictive methods have been reported in the literature.

Part of the intent of the Interim Study Program was to provide advanced methods of thermal analysis for external insulation systems. For a homogeneous isotropic material such as bulk fiberglass, there is little that one can do to improve an ordinary heat loss calculation. Continuous multilayer systems are also similar in that regard, if one takes their anisotropy into account. However, for shingled multi-layer systems, one can take shingle geometry into account, and move a step closer to a real system by breaking the system down in to an over-lapped subassembly level as shown in Figure 9.

Since shingles provide heat leak paths to the tank in both the normal and lateral directions, a two dimensional linear conduction analysis (and/or linearized radiation) based on the geometry shown in the figure has been developed. The analysis will permit a parametric study of various shingle designs and materials. The analysis has been programed for digital computer solution and is presently being checked.

The basic physical model as well as its associated mathematical notation are shown schematically in Figure 9. The mathematical model requires the solution of three coupled, second order, linear, partial differential equations and their associated boundary conditions as detailed below. The small two dimensionality in the x direction has been eliminated because it appears to be a second order effect.

$$\frac{\partial^2 T_1}{\partial X^2} + \frac{K_{y1}}{K_{x1}} \frac{\partial^2 T_1}{\partial y^2} = 0, \qquad 0 \le X \le L_1, \quad 0 \le y \le t$$

$$\frac{\partial^2 T_2}{\partial X^2} + \frac{K_{y2}}{K_{x2}} \frac{\partial^2 T_2}{\partial y^2} = 0, \qquad L_1 \le X \le L_2, \quad 0 \le y \le t$$

$$\frac{\partial^2 T_3}{\partial X^2} + \frac{K_{y3}}{K_{x3}} \frac{\partial^2 T_3}{\partial y^2} = 0, \qquad L_2 \le X \le L_3, \quad 0 \le y \le t$$

$$T_1 = 0, \quad 0 \le X \le L_1, \quad y = 0$$

$$-K_{y1} \frac{\partial T_1}{\partial y} = H_5 (T_1 - T_H), \quad 0 \le X \le L_1, \quad y = t$$

$$K_{y2} \frac{\partial T_2}{\partial y} = H_1 (T_2), \qquad L_1 \le X \le L_2, \quad y = 0$$

$$-K_{y2}\frac{\partial T_2}{\partial y} = H_4(T_2 - T_H), \quad L_1 \le X \le L_2, \quad y = t$$

$$K_{y3}\frac{\partial T_3}{\partial y} = H_2(T_3), \quad L_2 \le X \le L_3, \quad y = 0$$

$$K_{y3}\frac{\partial T_3}{\partial y} = H_3(T_3 - T_H), \quad L_2 \le X \le L_3, \quad y = t$$

$$T_1 = 0, \quad X = 0, \quad 0 \le y \le t$$

$$T_1 = T_2, \quad X = L_1, \quad 0 \le y \le t$$

$$K_{X1}\frac{\partial T_1}{\partial X} = K_{X2}\frac{\partial T_2}{\partial X}, \quad X = L_1, \quad 0 \le y \le t$$

$$T_2 = T_3, \quad X = L_2, \quad 0 \le y \le t$$

$$K_{X2}\frac{\partial T_2}{\partial X} = K_{X3}\frac{\partial T_3}{\partial X} \quad X = L_2, \quad 0 \le y \le t$$

$$\frac{\partial T_3}{\partial X} = 0, \quad X = L_3, \quad 0 \le y \le t$$

The solution to these equations is derived by separating the variables and solving three Sturn-Liouville problems in several steps. Each step is designed to provide three homogeneous boundary conditions which form the proper boundary conditions by forming a linear combination of the solutions. The cryogen temperature has been specified as zero and all other temperatures scaled to that value. Each of the linear heat transfer coefficients (H_1 through H_5) can represent a combination of conduction and linearized radiation. The form of the solution is shown below.

$$T_1 = \sum_{n=1}^{\infty} A_n \sin \lambda_{1n} X \sinh \frac{\lambda_{1n} y}{K_1} + \sum_{n=1}^{\infty} B_n \sinh \gamma_{1n} \sin \frac{\gamma_{1n} y}{K_1}$$

$$T_2 = \sum_{n=1}^{\infty} C_n \cos \lambda_{2n} X \left\{ \frac{H_1 K_2}{\lambda_{2n} K_{2y}} \sinh \frac{\lambda_{2n} y}{K_2} + \cosh \frac{\lambda_{2n} y}{K_2} \right\}$$

$$+ \sum_{n=1}^{\infty} D_n \cosh \gamma_{2n} (X - L_1) \left\{ \frac{H_1 K_2}{\gamma_{2n} K_{2y}} \sin \frac{\gamma_{2n} y}{K_2} + \cosh \frac{\gamma_{2n} y}{K_2} \right\}$$

$$+ \sum_{n=1}^{\infty} E_n \cosh \gamma_{2n} (L_2 - X) \left\{ \frac{H_1 K_2}{\gamma_{2n} K_{2y}} \sin \frac{\gamma_{2n} y}{K_2} + \cos \frac{\gamma_{2n} y}{K_2} \right\}$$

$$T_3 = \sum_{n=1}^{\infty} F_n \cos \lambda_{3n} (X - L_2) \left\{ \frac{H_2 K_3}{\lambda_{3n} K_{3y}} \sinh \frac{\lambda_{3n} y}{K_3} + \cosh \frac{\lambda_{3n} y}{K_3} \right\}$$

$$+ \sum_{n=1}^{\infty} G_n \left\{ - \frac{\sinh \gamma_{3n} (L_3 - L_2)}{\cosh \gamma_{3n} (L_3 - L_2)} \sinh \gamma_{3n} (X - L_2) + \cosh \gamma_{3n} (X - L_2) \right\}$$

$$\left\{ \frac{H_2 K_3}{\gamma_{3n} K_{3y}} \sin \frac{\gamma_{3n} y}{K_3} + \cos \frac{\gamma_{3n} y}{K_3} \right\}$$

$$\lambda_{1n} = \frac{(2n-1)\pi}{2L_1}, \quad \lambda_{2n} = \frac{n\pi}{L_2 - L_1}, \quad \lambda_{3n} = \frac{n\pi}{L_3 - L_2}$$

$$\gamma_{1n} = -\frac{H_5 K_1}{K_{1y}} \tan \frac{\gamma_{1n} t}{K_1}; \quad K_i \equiv \frac{K_{iy}}{K_{ix}}$$

$$-H_1 + \frac{\gamma_{2n} K_{y2}}{K_2} \tan \frac{\gamma_{2n} t}{K_2} = \frac{H_4 H_1 K_2}{K_{2y} \gamma_{2n}} \tan \frac{\gamma_{2n} t}{K_2} + H_4$$

$$-H_2 + \frac{\gamma_{3n} K_{3y}}{K_3} \tan \frac{\gamma_{3n} t}{K_3} = \frac{H_3 H_2 K_3}{K_{3y} \gamma_{3n}} \tan \frac{\gamma_{3n} t}{K_3} + H_3$$

Four of the remaining constants are determined from the compatability conditions at the region interfaces by equating like terms in the series. The final constants were determined by Fourier analysis of the outer surface boundary conditions. For example:

$$B_n = \frac{-K_{2x}}{\gamma_{1n} K_{1x} \cosh(\gamma_{1n} L_1) I_{5,n}} \sum_{m=1}^{\infty} E_m \gamma_{2m} \sinh[\gamma_{2m}(L_2 - L_1)] I_{8m,n}$$

$$I_{5m} = \frac{K_1}{\gamma_{1m}} \left[\frac{1}{2} \frac{\gamma_{1m} t}{K_1} - \frac{1}{4} \sin \frac{2\gamma_{1m} t}{K_1} \right]$$

$$I_{8n,m} = \frac{H_1 K_2}{\lambda_{2n} K_{2y}} \left\{ \frac{\sin\left(\frac{\gamma_{2n}}{K_2} - \frac{\gamma_{1m}}{K_1}\right)t}{2\left(\frac{\gamma_{2n}}{K_2} - \frac{\gamma_{1m}}{K_1}\right)} - \frac{\sin\left(\frac{\gamma_{2n}}{K_2} + \frac{\gamma_{1m}}{K_1}\right)t}{2\left(\frac{\gamma_{2n}}{K_2} + \frac{\gamma_{1m}}{K_1}\right)} \right\}$$

$$+ \left\{ \frac{\frac{\gamma_{1m}}{K_1}}{\left(\frac{\gamma_{1m}^2}{K_1^2} - \frac{\gamma_{2n}^2}{K_2^2}\right)} - \frac{\cos\left(\frac{\gamma_{1m}}{K_1} - \frac{\gamma_{2n}}{K_2}\right)t}{2\left(\frac{\gamma_{1m}}{K_1} - \frac{\gamma_{2n}}{K_2}\right)} - \frac{\cos\left(\frac{\gamma_{1m}}{K_1} + \frac{\gamma_{2n}}{K_2}\right)t}{2\left(\frac{\gamma_{1m}}{K_1} + \frac{\gamma_{2n}}{K_2}\right)} \right\}$$

These solutions exhibit uniform convergence for all values of the parameters and provide the expected smooth functional dependence on all variables and parameters. Total heat transfer to the tank is calculated by the following means:

$$Q = \int_0^t K_{1x} \frac{\partial T_1}{\partial X}\, dy + \int_0^{L_1} K_{1y} \frac{\partial T_1}{\partial y}\, dx$$

This solution provides the basis for studying the various parameters involved in superinsulation shingle insulation for performing parametric design studies.

The existence of large fast computers makes series solutions to such problems an attractive alternative to the typical numerical methods by which heat flow has been calculated in the past. Series solutions, properly derived, by their nature guarantee absolute and uniform convergence during computation. The rate of convergence is, of course, not guaranteed; fortunately, after initial errors were corrected. our solutions have proven to be well behaved during computation.

Thermal Performance of Multilayer Shingles on a Substrate

A model is being developed to extend the analysis described above to include the effect of a substrate on the performance of this basic insulation. The model and method of solution are identical to that described previously, except that the boundary conditions are modified. All the t = o boundary conditions include the substrate resistance in series with the resistance of the lower shingle layer. Formally, the only mathematical changes are replacement of the corresponding equations by the following:

$$K_{1y} \frac{\partial T_1}{\partial y} = H_c(T_1) \qquad 0 \le x \le L_1 \qquad y = 0$$

$$\frac{\partial T_1}{\partial x} = 0 , \qquad x = 0 , \qquad 0 \le y \le t$$

The temperatures and the releavent constants are quite similar to those indicated before and therefore are not reported here.

Insulation Degradation in the Region of a Penetration

The literature survey completed in Phase One of this study revealed two theoretical approaches to the penetration problem, (NBS-119, NBS-112). In both instances, a finite difference numerical model of the system was utilized. The latter group represented the system with a constant temperature penetration and a combination of linearized nodal radiation and conduction in the insulation. The reported investigation was limited to boundary temperatures greater than 300°K. In the former investigation, a finite difference model was developed to represent lateral conduction and normal radiation within a superinsulation.

The reported results did not include effects of penetration thermal properties and/or the effect of varying lateral insulation conductivity.

The results of these investigations have been useful in preparing the preliminary thermal performance characteristics presented in this report. The great variety of penetrations and insulation types under study here has limited the usefulness of the published results; therefore, an independent study of penetration modeling was initiated.

An analytical representation of the penetration problem has been selected for study. The analytical approach may provide a significant improvement in visualizing the interdependence of the many parameters involved, thus, providing a maximum of insight and information for a minimum of computational effort. A second reason for selecting the analytic model over a numerical model is the ease in scaling detailed computed results according to the grouping of "natural" parameters which appear explicitly, reducing the cost of parametric design studies. Third, numerical methods for solving finite difference equations are often conditionally unstable when bouldaries between unlike materials are present. This problem, which seems to be more serious in cylindrical coordinates than in rectangular systems, frequently produces "converged" solutions which are physically impossible. Generally the difficulty may be overcome on a case by case basis which can make the solution quite costly and time consuming. In what follows, a brief outline of an analytic solution to a penetration model is presented

Figure 10 depicts the physical model in cross section; the model assumes radial symmetry about the cylindrical penetration's axis. Region one represents an optional thermal stand off insulation which has constant conductivities which may be different in the radial and axial directions. Region two represents the primary tank insulation which may have different, constant conductivity values in the two directions. Radiation effects may be included approximately by including the appropriate linearized radiation expression in the conductivity value. Region 3 represents that portion of the penetration in contact with the insulation, while region 4 models the portion of the penetration outside the insulation. Conduction in the penetration is treated in one dimension. At all interfaces, perfect thermal contact has been assumed for the present, but it may be possible to include a finite contact resistance in the future.

At the outer insulation surface a linear heat transfer coefficient is used; this can model linearized radiation and/or convection. A prescribed undisturbed insulation temperature profile is used at the extreme right (far from the penetration) and zero temperature is prescribed at the lower surface, (cryogen temperature scaled to zero). The inside surface of the cylindrical penetration has no heat transfer and its outer extremity is maintained at the surrounding temperature, T_H.

The mathematical model requires the solution of four second order partial differential equations and their associated boundary conditions. The solutions take the form of infinite series of orthogonal functions. A brief description of the solution follows.

The differential equations and boundary conditions are:

$$\frac{k_{r1}}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_1}{\partial r}\right) + k_{z1}\frac{\partial^2 T_1}{\partial z^2} = 0, \quad r_1 \le r \le r_2, \quad 0 \le z \le t$$

$$\frac{k_{r2}}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_2}{\partial r}\right) + k_{z2}\frac{\partial^2 T_1}{\partial z^2} = 0, \quad r_2 \le r \le r_3, \quad 0 \le z \le t$$

$$-S K_p \frac{\partial^2 T_3}{\partial z^2} - k_{r1}\frac{\partial T_1}{\partial r}\bigg|_{r=r_1} = 0, \quad r = r_1, \quad 0 \le z \le t$$

$$-K_p \frac{\partial^2 T_4}{\partial z^2} = 0, \quad r = r_1, \quad t \le z \le t+L$$

$$T_1 = T_3 \;, \quad r = r_1 \;, \quad 0 \le z \le t$$

$$T_1 = T_2 \;, \quad r = r_2 \;, \quad 0 \le z \le t$$

$$K_{r1} \frac{\partial T_1}{\partial r} = K_{r2} \frac{\partial T_2}{\partial r} \;, \quad r = r_2 \;, \quad 0 \le z \le t.$$

$$T_2 = f_1(z) \;, \quad r = r_3 \;, \quad 0 \le z \le t$$

$$T_1 = T_2 = T_3 = 0 \;, \quad 0 \le r \le \infty \;, \quad z = 0$$

$$-K_{z1} \frac{\partial T_1}{\partial z} = H_1 (T - T_H) \;, \quad r_1 \le r \le r_2 \;, \quad z = t$$

$$\cdot K_{z2} \frac{\partial T_2}{\partial z} = H_2 (T - T_H) \;, \quad r_2 \le r \le r_3 \;, \quad z = t$$

$$T_3 = T_4 \;, \quad \frac{\partial T_3}{\partial z} = \frac{\partial T_4}{\partial z} \;; \quad r = r_1 \;, \quad z = t \;; \quad T_4 = T_H \;, \quad r = r_1 \;, \quad z = t + L$$

The mathematical solution to the problems associated with temperatures one and two are most easily solved by splitting the linear problems into three problems, each with three homogeneous boundary conditions. Each of these problems results in differential equations with separable variables. The separated equations are susceptable to Sturm-Liouville analysis producting eigenvalue and orthogonal eigenvector solutions. The solutions are of the following form:

$$T_1 = \sum_{n=1}^{\infty} A_{1n} \left[-I_0(\lambda_{1n} r) K_0(\lambda_{1n} r_2) + I_0(\lambda_{1n} r_2) K_0(\lambda_{1n} r) \right] \sin \frac{\lambda_{1n} z}{K_1}$$

$$+ \sum_{n=1}^{\infty} B_{1n} \left[-I_0(\lambda_{1n} r) K_0(\lambda_{1n} r_1) + I_0(\lambda_{1n} r_1) K_0(\lambda_{1n} r) \right] \sin \frac{\lambda_{1n} z}{K_1}$$

$$+ \sum_{n=1}^{\infty} C_{1N} \left[Y_0(\gamma_{1n} r_2) J_0(\gamma_{1n} r) - J_0(\gamma_{1n} r_2) Y_0(\gamma_{1n} r) \right] \sin \frac{\gamma_{1n} z}{K_1}$$

$$T_2 = \sum_{n=1}^{\infty} A_{2n} \left[-I_0(\lambda_{2n} r) K_0(\lambda_{2n} r_3) + I_0(\lambda_{2n} r_3) K_0(\lambda_{2n} r) \right] \sin \frac{\lambda_{2n} z}{K_2}$$

$$+ \sum_{n=1}^{\infty} B_{2n} \left[-I_0(\lambda_{2n} r) K_0(\lambda_{2n} r_2) + I_0(\lambda_{2n} r_2) K_0(\lambda_{2n} r) \right] \sin \frac{\lambda_{2n} z}{2}$$

$$+\sum_{n=1}^{\infty} C_{2n}\left[Y_0(\gamma_{2n} r_3) J_0(\gamma_{2n} r) - J_0(\gamma_{2n} r_3) Y_0(\gamma_{2n} r)\right] \sinh \frac{\gamma_{2n} z}{K_2}$$

where $K_i \equiv \dfrac{K_{iz}}{K_{ir}}$

and the eigenvalues λ and γ are determined from the boundary conditions and defined implicitly as follows:

$$\tan \frac{\lambda_{1n} t}{K_1} = -\frac{K_{1z} \lambda_{1n}}{K_1 H_1} \; ; \qquad \tan \frac{\lambda_{2n} t}{K_2} = -\frac{K_{2z} \lambda_{2n}}{K_2 H_2}$$

$$J_0(\gamma_{2n} r_2) Y_0(\gamma_{2n} r_3) - J_0(\gamma_{2n} r_3) Y_0(\gamma_{2n} r_2) = 0$$

$$J_0(\gamma_{1n} r_1) Y_0(\gamma_{1n} r_2) - J_0(\gamma_{1n} r_2) Y_0(\gamma_{1n} r_1) = 0$$

The constant B_{2n} is determined from the Fourier expansion of the prescribed temperature function $f_1(z)$ specified at $r = r_3$. The remaining constants are determined by matching the respective series at the material interface, the upper surface boundary condition, and from the matching boundary conditions at the penetration. The results are:

$$B_{2n} = \frac{2 \int_0 f_1(z) \sin \dfrac{\lambda_{2n} z}{K_2}}{t\left[I_0(\lambda_{2n} r_2) K_0(\lambda_{2n} r_3) - I_0(\lambda_{2n} r_3) K_0(\lambda_{2n} r_2)\right]}$$

Space does not permit the display of all coefficients.

The net heat flux to the tank in the region of interest is calculated from the temperature equations by performing the following operations

$$Q = \int_{r}^{r_2} 2\pi r K_{1z} \left.\frac{\partial T_1}{\partial z}\right|_{z=0} dr + \int_{r_2}^{r_3} 2\pi r K_{2z} \left.\frac{\partial T_2}{\partial z}\right|_{z=0} dr$$

$$+ 2\pi r_1 S K_p \left.\frac{\partial T_3}{\partial z}\right|_{z=0}$$

This solution has been programed and presently gives reasonable results with locally unphysical points . Sturm-Liouville theory indicates that the various series involved are absolutely convergent. Therefore, there should be no problem in attaining a stable solution to these formidable appearing equations. It is anticipated that all remainin_ errors can be rapidly rectified. A sample of the programming for this problem is illustrated in Appendix B.

Insulation Evacuation Analysis

An evacuation analysis is required for analysis of the early mission performance for purged multilayer insulations. A relatively simple gaseous diffusion analysis with the incorporation of sources to represent sublimation and outgassing has been reported in NBS-68. This basic series solution to the low pressure diffusion equation is being programed to provide a tool for evaluating the comparitive pump down and attendant thermal performance of the various methods of applying multilayer insulations

APPENDIX B

Below is reproduced a sample of the computer routines being developed for Phase IV of this study. The routine shown is the time-sharing version of the penetration analysis calculation explained in Appendix A. The routine is shown to illustrate the extensive use of subpı grams and general method of approach being taken to the analysis coding. An attempt was made to use this and other routines for preliminary analysis in the current program phase but the routine as shown apparently still contains minor errors, and the attempt was not successful.

```
      FUNCTION SINH(XX)
      YY=XX
      IF(XX-175.)20,20,10
10    XX=175.
20    CONTINUE
      SINH=(EXPF(XX)-EXPF(-XX))/2.0
      XX=YY
      RETURN
      END
      FUNCTION COSH(XX)
      YY=XX
      IF(XX-175.)20,20,10
10    XX=175.
20    CONTINUE
      COSH=(EXPF(XX)+EXPF(-XX))/2.0
      XX=YY
      RETURN
      END
      FUNCTION BJ(NU,X)
      IF(NU)100,10,100
10    IF(X-3.0)20,50,50
20    IF(X+3.0)5000,30,30
30    BJ=1.-2.2499997*(X/3.0)**2+1.2656208*(X/3.)**4
     1-.3163866*(X/3.)**6+.0444479*(X/3.)**8
     2-.0039444*(X/3.)**10+.0002100*(X/3.)**12
      GO TO 1000
50    CONTINUE
      F0=.79788456-.00000077*(3./X)-.0055274*(3./X)**2
     1-.00009512*(3./X)**3+.00137237*(3./X)**4
     2-.00072805*(3./X)**5+.00014476*(3./X)**6
      TH0=X-.78539816-.04166397*(3./X)
     1-.00003954*(3./X)**2+.00262573*(3./X)**3
     2-.00054125*(3./X)**4-.00029333*(3./X)**5
     3+.00013558*(3./X)**6
      BJ=(F0*COSF(TH0))/SQRT(X)
      GO TO 1000
100   IF(NU-1)5010,110,5010
110   IF(X-3.)120,150,150
120   IF(X+3.)5020,130,130
130   B=.5-.56249985*(X/3.)**2+.21093573*(X/3.)**4
     1-.03954289*(X/3.)**6+.00443319*(X/3.)**8
     2-.00031761*(X/3.)**10+.00001109*(X/3.)**12
      BJ=B*X
      GO TO 1000
150   CONTINUE
      F1=.79788456+.00000156*(3./X)+.01659667*(3./X)**2
     1+.00017105*(3./X)**3-.00249511*(3./X)**4
     2+.00113653*(3./X)**5-.00020033*(3./X)**6
      TH1=X-2.35619449+.12499612*(3./X)
     1+.00005650*(3./X)**2-.00637879*(3./X)**3
     2+.00074348*(3./X)**4+.00079824*(3./X)**5
     3-.00029166*(3./X)**6
      BJ=(F1*COSF(TH1))/SQRT(X)
1000  RETURN
```

```
5000  NOOP=7
      GO TO 6000
5010  NOOP=8
      GO TO 6000
5020  NOOP=9
6000  TYPE 666,(NOOP)
666   FORMAT($FAILED NOOP=$,I1)
      CALL EXIT
      END
      FUNCTION BY(NU,X)
      IF(NU)100,10,100
10    IF(X-3.0)20,50,50
20    IF(X+0.0)5000,30,30
30    BY=(2./3.1415926)*ELOGF(X/2.)*BJ(0,X)+.36746691
     1+.60559366*(X/3.)**2-.74350384*(X/3.)**4
     2+.25300117*(X/3.)**6-.04261214*(X/3.)**8
     3+.00427916*(X/3.)**10-.00024846*(X/3.)**12
      GO TO 1000
50    CONTINUE
      FO=.79788456-.00000077*(3./X)-.0055274*(3./X)**2
     1-.00009512*(3./X)**3+.00137237*(3./X)**4
     2-.00072805*(3./X)**5+.00014476*(3./X)**6
      THO=X-.78539816-.04166397*(3./X)
     1-.00003954*(3./X)**2+.00262573*(3./X)**3
     2-.00054125*(3./X)**4-.00029333*(3./X)**5
     3+.00013558*(3./X)**6
      BY=(FO*SINF(THO))/SQRT(X)
      GO TO 1000
100   IF(NU-1)5010,110,5010
110   IF(X-3.)120,150,150
120   IF(X+3.)5020,130,130
130   B=(2./3.1415926)*X*ELOGF(X/2.)*BJ(1,X)-.6[illegible]
     1+.2212091*(X/3.)**2+2.1682709*(X/3.)**4
     2-1.3164827*(X/3.)**6+.3123951*(X/3.)**8
     3-.0400976*(X/3.)**10+.0027873*(X/3.)**12
      BY=B/X
      GO TO 1000
150   CONTINUE
      F1=.79788456+.00000156*(3./X)+.01659667*(3./X)**2
     1+.00017105*(3./X)**3-.00249511*(3./X)**4
     2+.00113653*(3./X)**5-.00020033*(3./X)**6
      TH1=X-2.35619449+.12499612*(3./X)
     1+.00005650*(3./X)**2-.00637879*(3./X)**3
     2+.00074348*(3./X)**4+.00079824*(3./X)**5
     3-.00029166*(3./X)**6
      BY=(F1*SINF(TH1))/SQRT(X)
1000  RETURN
5000  NOOP=7
      GO TO 6000
5010  NOOP=8
      GO TO 6000
5020  NOOP=9
6000  TYPE 666,(NOOP)
666   FORMAT($FAILED NOOP=$,I1)
      CALL EXIT
      END
```

```
      FUNCTION BI(NU,X)
C     CALCULATES THE 0 AND 1 ORDER I BESSEL FUNCTION
C     /FOR3/ FILE......
      YY=X
      IF (NU)100,10,100
10    IF(X-3.75)20,50,50
20    IF(X+3.75)5000,30,30
30    BI=1.+3.5156229*X*X+3.0899424*X**4+1.2067492*X**6
     1+.2659732*X**8+.0360768*X**10+.0045813*X**12
      GO TO 1000
50    CONTINUE
      B=.39894228+.01328592/X+.00225319*X**(-2)-.00157565*X**(-3)
     1+.00916281*X**(-4)-.02057706*X**(-5)+.02635537*X**(-6)
     2-.01647633*X**(-7)+.00392377*X**(-8)
      IF(X-175.)691,691,591
591   CONTINUE
      X=175.
691   BI=B*EXPF(X)/SQRTF(X)
      GO TO 1000
100   IF(NU-1)5010,110,5010
110   IF(X-3.75)120,150,150
120   IF(X+3.75)5020,130,130
130   B=.5+.87890594*X*X+.51498869*X**4+.15084934*X**6
     1+.02658733*X**8+.00301532*X**10+.00032411*X**12
      BI=B*X
      GO TO 1000
150   CONTINUE
      B=.39894228-.03988024/X-.0036201*X**(-2)+.00163801*X**(-3)
     1-.01031555*X**(-4)+.02282967*X**(-5)-.02895312*X**(-6)
     2+.01787654*X**(-7)-.00420059*X**(-8)
      IF(X-175.)891,891,791
791   X=175.
891   CONTINUE
      BI=B*EXPF(X)/SQRTF(X)
1000  X=YY
      RETURN
5000  NOOP=1
      GO TO 6000
5010  NOOP=2
      GO TO 6000
5020  NOOP=3
6000  TYPE 666,(NOOP)
666   FORMAT($FAILED NOOP=$,I1)
      CALL EXIT
      END
      FUNCTION BK(NU,X)
C     CALCULATES THE 0 AND 1 ORDER K BESSEL FUNCTIONS
C     /FOR3/ FILE..........
      IF(NU)100,10,100
10    IF(X-2.0)20,50,50
20    IF(X)5000,5000,30
30    BK=(-ELOGF(X/2.0))*BI(0,X)-.57721566+.42278420*(X/2.)**2
     1+.23069756*(X/2.)**4+.03488590*(X/2.)**6+.00262698*(X/2.)**8
     2+.00010750*(X/2.)**10+.00000740*(X/2.)**12
      GO TO 1000
50    CONTINUE
      B=1.25331414-.07832358*(2./X)+.02189568*(2./X)**2
```

```
     1-.01062446*(2./X)**3+.00587872*(2./X)**4
     2-.00251540*(2./X)**5+.00053208*(2./X)**6
      IF(X-175.)6902,6902,6901
6901  BK=0.0
      GO TO 1000
6902  CONTINUE
      BK=B*EXPF(-X)/SQRTF(X)
      GO TO 1000
100   IF (N)-1)5010,110,5010
110   IF(X-2.0)120,150,150
120   IF(X)5020,5020,130
130   B=X*ELOGF(X/2.)*BI(1,X)+1+.15443144*(X/2.)**2
     1-.67278579*(X/2.)**4-.18156897*(X/2.)**6
     2-.01919402*(X/2.)**8-.00110404*(X/2.)**10
     3-.00004686*(X/2.)**12
      BK=B/X
      GO TO 1000
150   CONTINUE
      B=1.25331414+.23498619*(2./X)-.03655620*(2./X)**2
     1+.01504268*(2./X)**3-.00780353*(2./X)**4
     2+.00325614*(2./X)**5-.00068245*(2./X)**6
      IF(X-175)6904,6904,6903
6903  BK=0.0
      GO TO 1000
6904  CONTINUE
      BK=B*EXPF(-
1000  RETURN
5000  NOOP=4
      GO TO 6000
5010  NOOP=5
      GO TO 6000
5020  NOOP=6
6000  TYPE 666,(NOOP)
666   FORMAT($FAILED-BK NOOP=$I1)
      CALL EXIT
      END
      FUNCTION O(N)
      COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
     1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
      DIMENSION ALAM(2,0/50),GAM(2,0/50)
      O=((AK1/ALAM(1,N))**2*SINF(ALAM(1,N)*T/AK1)-(AK1*T/ALAM(1,N))
     1*COSF(ALAM(1,N)*T/AK1))/RF(N)
      RETURN
      END
      FUNCTION RF(N)
      COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
     1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
      DIMENSION ALAM(2,0/50),GAM(2,0/50)
      IF(N-1) 10,20,10
10    XXXX=0.0
      GO TO 30
20    XXXX=D(N)*E(1,0)*H
30    CONTINUE
      TERR=T-(AK1/(2.*ALAM(1,N)))*SINF(2.*ALAM(1,N)*T/AK1)
      RF=(BI(0,ALAM(1,N)*R2)*BK(0,ALAM(1,N)*R1)
     1-BI(0,ALAM(1,N)*R1)*BK(0,ALAM(1,N)*R2)
     2-(AKR1*AK1*AK1/(S*AKP*ALAM(1,N)*ALAM(1,N)))
```

```
3*(-ALAM(1,N)*BI(0,ALAM(1,N)*R2)*BK(1,ALAM(1,N)*R1
4-ALAM(1,N)*BI(1,ALAM(1,N)*R1)*BK(0,ALAM(1,N)*R2)
5-XXXX/R1))*TERR/2.
 RETURN
 END
 FUNCTION C1(N)
 COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
 DIMENSION ALAM(2,0/50),GAM(2,0/50)
 C1=(3.1415926*H1*TH*BJ(0,GAM(1,N)*R1))
1/(((AKZ1*GAM(1,N)/AK1)*COSH(GAM(1,N)*T/AK1)+H1*SINH(GAM(1,
2*T/AK1))*(BJ(0,GAM(1,N)*R1)+BJ(0,GAM(1,N)*R2)))
 RETURN
 END
 FUNCTION C2(N)
 COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
 DIMENSION ALAM(2,0/50),GAM(2,0/50)
 C2=(3.1415926*H2*TH*BJ(0,GAM(2,N)*R2))
1/(((AKZ2*GAM(2,N)/AK2)*COSH(GAM(2,N)*T/AK2)+H2*SINH(GAM(2,
2*T/AK2))*(BJ(0,GAM(2,N)*R2)+BJ(0,GAM(2,N)*R3)))
 RETURN
 END
 FUNCTION B2(N)
 COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
 DIMENSION ALAM(2,0/50),GAM(2,0/50)
 TERR=T-(AK2/(2.*ALAM(2,N)))*SINF(2.*ALAM(2,N)*T/AK2)
 B2=((930./TERR)*(AK2/ALAM(2,N))**2*(SINF(ALAM(2,N)*T/AK2)-
1(ALAM(2,N)*T/AK2)*COSF(ALAM(2,N)*T/AK2)))
2/(T*(BI(0,ALAM(2,N)*R2)*BK(0,ALAM(2,N)*R3)
3-BI(0,ALAM(2,N)*R3)*BK(0,ALAM(2,N)*R2)))
 RETURN
 END
 FUNCTION Q(N)
 COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
 DIMENSION ALAM(2,0/50),GAM(2,0/50)
 Q=(AKR1*2.*SINF(ALAM(1,1)*T/AK1)/(3.1415926*R2))
1*((GAM(1,N)/AK1)*COSH(GAM(1,N)*T/AK1)
2+(H1/AKZ1)*SINH(GAM(1,N)*T/AK1))/(P(N)
3*((GAM(1,N)/AK1)**2+(ALAM(1,1)/AK1)**2))
 RETURN
 END
 FUNCTION G(N)
 COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
 DIMENSION ALAM(2,0/50),GAM(2,0/50)
 G=(AKR2*SINF(ALAM(1,1)*T/AK1)
1*(-GAM(2,N)*BY(0,(GAM(2,N)*R3))*BJ(1,(GAM(2,N)*R2))
2+GAM(2,N)*BJ(0,(GAM(2,N)*R3))*BY(1,(GAM(2,N)*R2)))
3*((GAM(2,N)/AK2)*COSH(GAM(2,N)*T/AK2)
4+(H1/AKZ1)*SINH(GAM(2,N)*T/AK2)))/(P(N)
5*((GAM(2,N)/AK2)**2+(ALAM(1,1)/AK1)**2))
 RETURN
 END
 FUNCTION F(N)
```

```
 COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
1AKP,S,H1,H2,TH,H, AKR1,AKR2,AKZ1,AKZ2
 DIMENSION ALAM(2,0/50),GAM(2,0/50)
 F=((-AKR2/R2)*((ALAM(1,1)/AK1)*SINF(ALAM(2,N)*T/AK2)
1*COSF(ALAM(1,1)*T/AK1)-(ALAM(2,N)/AK2)*
2COSF(ALAM(2,N)*T/AK2)*SINF(ALAM(1,1)*T/AK1)))
3/(((ALAM(2,N)/AK2)**2-(ALAM(1,1)/AK1)**2)*P(N)
 RETURN
 END
 FUNCTION P(N)
 COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
 DIMENSION ALAM(2,0/50),GAM(2,0/50)
 X=T-(AK1/(2.*ALAM(1,1)))*SINF(2.*ALAM(1,1)*T/AK1)
 P=(AKR1*X*D(1)/2.)*(-ALAM(1,1)*BI(0,ALAM(1,1)*R1)*BK(1,ALAM(1,
1*R2)-ALAM(1,1)*BI(1,ALAM(1,1)*R2)*BK(0,ALAM(1,1)*R1))*E(N,1)
2-AKR2*((-ALAM(2,N))*BI(0,ALAM(2,N)*R3)*BK(1,ALAM(2,N)*R2)
3-ALAM(2,N)*BI(1,ALAM(2,N)*R2)*BK(0,ALAM(2,N)*R3))
4*((ALAM(1,1)/AK1)*SINF(ALAM(2,N)*T/AK2)*COSF(ALAM(1,1)*T/AK1)
5-(ALAM(2,N)/AK2)*COSF(ALAM(2,N)*T/AK2)*SINF(ALAM(1,1)*T/AK1))
6/(((ALAM(2,N)/AK2)**2-(ALAM(1,1)/AK1)**2))
 RETURN
 END
 FUNCTION E(N,M)
 COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
 DIMENSION ALAM(2,0/50),GAM(2,0/50)
 E=(BI(0,ALAM(2,N)*R3)*BK(0,ALAM(2,N)*R2)
1-BI(0,ALAM(2,N)*R2)*BK(0,ALAM(2,N)*R3))
2*((-ALAM(2,N)/AK2)*COSF(ALAM(2,N)*T/AK2)*SINF(ALAM(1,M)*T/AK1)
3+(ALAM(1,M)/AK1)*SINF(ALAM(2,N)*T/AK2)*COSF(ALAM(1,M)*T/AK1))
4/(1.*((ALAM(2,N)/AK2)**2-(ALAM(1,M)/AK1)**2))
 RETURN
 END
 FUNCTION D(N)
 CALCULATES D CONSTANTS
 COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
 DIMENSION ALAM(2,0/50),GAM(2,0/50)
 TERR=T-(AK1/(2.*ALAM(1,N)))*SINF(2.*ALAM(1,N)*T/AK1)
 D=2./(TERR*(BI(0,ALAM(1,N)*R1)*BK(0,ALAM(1,N)*R2)
1-BI(0,ALAM(1,N)*R2)*BK(0,ALAM(1,N)*R1)))
 RETURN
 END
```

```
PROGRAM  "PAP"
PENETRATION ANALYSIS PROGRAM
COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
1AKP,S,H1,H2,TH,H,AKR1,AKR2,DUMMY
DIMENSION ALAK(2,0/50),GAM(2,0/50),SUM(0/50),ALL(0/50),ANN(0/50
1B1(0/50),A2(0/50),SUM1(0/50),SUM2(0/50),A1(0/50)
TYPE 10001
ACCEPT 10, T
TYPE 10002
ACCEPT 10,R1
TYPE 10003
ACCEPT 10,R2
TYPE 10004
ACCEPT 10,R3
TYPE 10005
ACCEPT 10,S
TYPE 10006
ACCEPT 10,AL
TYPE 10007
ACCEPT 10,AKP
TYPE 10008
ACCEPT 10,AKR1
TYPE 10009
ACCEPT 10,AKZ1
TYPE 10010
ACCEPT 10,AKR2
TYPE 10011
ACCEPT 10,AKZ2
TYPE 10013
ACCEPT 10,H1
TYPE 10014
ACCEPT 10,H2
TYPE 10015
ACCEPT 10,TH
TYPE 10016
ACCEPT 10,DLEG1
TYPE 10017.
ACCEPT 11,MEIG1
TYPE 10018
ACCEPT 10,DLEG2
TYPE 10019
ACCEPT 11,MEIG2
TYPE 10020
ACCEPT 11,MNL
TYPE 10021
ACCEPT 11,MNLP
TYPE 10022
ACCEPT 11,MNN
TYPE 10023
ACCEPT 11,MNNP
TYPE 10024
ACCEPT 10,CONV
TYPE 10025
ACCEPT 11,MM
TYPE 10026
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      ACCEPT 11,MMA
      TYPE 10027
      ACCEPT 11,MMP
      TYPE 10028
      ACCEPT 11,MNA2
      TYPE 10029
      ACCEPT 11,MNB1
      TYPE 10030
      ACCEPT 11,MNB1P
      TYPE 10031
      ACCEPT 11,MT1
      TYPE 10032
      ACCEPT 11,MT2
      TYPE 10033
      ACCEPT 10,R
      TYPE 10034
      ACCEPT 10,Z
10    FORMAT(F10.5/)
11    FORMAT(I2/)
10001 FORMAT($             T=$)
10002 FORMAT($            R1=$)
10003 FORMAT($            R2=$)
10004 FORMAT($            R3=$)
10005 FORMAT($             S=$)
10006 FORMAT($            AL=$)
10007 FORMAT($           AKP=$)
10008 FORMAT($          AKR1=$)
10009 FORMAT($          AKZ1=$)
10010 FORMAT($          AKR2=$)
10011 FORMAT($          AKZ2=$)
10013 FORMAT($            H1=$)
10014 FORMAT($            H2=$)
10015 FORMAT($            TH=$)
10016 FORMAT($DELTA EIG1=$)
10017 FORMAT($MAXNUMEIG1=$)
10018 FORMAT($DELTA EIG2=$)
10019 FORMAT($MAXNUMEIG2=$)
10020 FORMAT($MAX N OF L=$)
10021 FORMAT($MAX S IN L=$)
10022 FORMAT($MAX N OF N=$)
10023 FORMAT($MAX S IN N=$)
10024 FORMAT($CONV CRIT.=$)
10025 FORMAT($MAX M1 SUM=$)
10026 FORMAT($MAX M2 SUM=$)
10027 FORMAT($MAX N3 SUM=$)
10028 FORMAT($MAX A2 SUM=$)
10029 FORMAT($MAX B1 SUM=$)
10030 FORMAT($MX B1P SUM=$)
10031 FORMAT($MAX T1 SUM=$)
10032 FORMAT($MAX T2 SUM=$)
10033 FORMAT($             R=$)
10034 FORMAT($             Z=$)
      AK1=AKZ1/AKR1
      AK2=AKZ2/AKR2
      EIGENVALUES "1"
      J=1
      ALAM(1,0)=0.0
      ALAM(2,0)=0.0
```

```
      SCALE=AK1/T
      AKX=AK1
      AKZX=AKZ1
      I=1
      HX=H1
1     CONTINUE
      UP=3.2*SCALE
      DEL=3.2*SCALE
5     S=-1.0
      ALAM(I,J)=ALAM(I,J-1)+UP
      A=(ALAM(I,J)*T)/AKX
      B=(ALAM(I,J)*AKZX)/(AKX*HX)
      D1=SINF(A)/COSF(A)+B
      DEL=DEL/2.0
      ALAM(I,J)=ALAM(I,J)-DEL
15    AB=(ALAM(I,J)*T)/AKX
      BA=(ALAM(I,J)*AKZX)/(AKX*HX)
      D2=SINF(AB)/COSF(AB)+BA
      IF(DLEG1 -D2*D2)20,100,100
20    IF(D1*D2)30,40,40
30    S=-S
      DEL=DEL/2.0
      ALAM(I,J)=ALAM(I,J)+S*DEL
35    D1=D2
      GO TO 15
40    IF(D1)50,60,60
50    ALAM(I,J)=ALAM(I,J)+DEL
      GO TO 35
60    ALAM(I,J)=ALAM(I,J)-DEL
      GO TO 35
100   IF(I*J-1)203,103,203
103   TYPE 204
204   FORMAT(S                LAMBDA(I,J)                  $/)
203   CONTINUE
      TYPE 105,(I,J,ALAM(I,J))
105   FORMAT(I2,5X,I2,5X,F10.5/)
      UP=3.2*SCALE
      DEL=ALAM(I,J)+UP-(J*3.1415921+1.571)*SCALE
      J=J+1
      IF(J-MEIG1  )5,5,110
110   I=I+1
      J=1
      AKX=AK2
      AKZX=AKZ2
      HX=H2
      SCALE=AK2/T
      DEL=3.2*SCALE
      IF(I-2)1,1,115
115   TYPE 120
120   FORMAT($EIGENVALUE EQUATION 1 COMPLETES/)
C     EIGENVALUE - 2
      GAM(1,0)=0.0
      GAM(2,0)=0.0
      S=1.0
      III=1
      R1X=R1
      R2X=R2
```

```
31      IF (R1X-R2X) 51,51,41
41      TA=3./(R1X-R2X)
        GO TO 61
51      TA=3./(R2X-R1X)
61      DEL=TA/5.
        I=1
70      GAM(III,I)=GAM(III,I-1)+TA/3
        D1=BJ(0,GAM(III,I)*R1X)*BY(0,GAM(III,I)*R2X)
       1-BJ(0,GAM(III,I)*R2X)*BY(0,GAM(III,I)*R1X)
80      GAM(III,I)=GAM(III,I)+DEL*S
        D2=BJ(0,GAM(III,I)*R1X)*BY(0,GAM(III,I)*R2X)
       1-BJ(0,GAM(III,I)*R2X)*BY(0,GAM(III,I)*R1X)
        IF(D1*D2)90,90,101
90      IF(D2*D2-DLEG2  )200,200,95
95      S=-S
        DEL=DEL/2.
        D1=D2
        GO TO 80
101     D1=D2
        GO TO 80
200     I=I+1
        JJ=I-1
        IF(JJ*III-1)201,198,201
198     TYPE 199
199     FORMAT($              GAMMA(NU,X)                  $/)
201     CONTINUE
        TYPE 202,(III,JJ,GAM(III,JJ))
202     FORMAT(I2,5X,I2,5X,F10.5/)
        S=1.
        DEL=TA/5.
        IF(I-MEIG2  )70,70,1000
1000    IF(III-1)1027,1013,1027
1013    III=2
        R1X=R2
        R2X=R3
        GO TO 31
1027    CONTINUE
        TYPE 1400
1400    FORMAT($EIGENVALUE EQUATION 2 COMPLETE$/)
        H=AKR1*T/(2.*R2*P(1))
        TYPE 2728
2728    FORMAT($H FUNCTION COMPLETE$/)
        SUM(0)=0.0
        DO 310 IJ=1,MNL
        DO 320 IK=1,MNLP
        SUM(IK)=SUM(IK-1)+E(IK,IJ)*(F(IK)*B2(IK)+G(IK)*C2(IK)
       1+O(IK)*C1(IK))
        ASUM=SUM(IK)
        IF ((SUM(IK)/SUM(1))**2-CONV**2)319,319,320
319     MNLP=IK
        TYPE 2727
320     CONTINUE
        ALL(IJ)=D(IJ)*SUMA
        IF (IJ-1)309,303,309
303     TYPE 305
305     FORMAT($FUNC-L(N)   N         L(N)$/)
309     CONTINUE
```

```
      IF ((ALL(IJ)/ALL(1))**2-CONV**2)308,308,310
308   MNL=IJ
      TYPE 2727
2727  FORMAT($::::::****CONVERGED****::::::$)
310   TYPE 315,(IJ,ALL(IJ))
315   FORMAT(10X,I2,5X,F10.5/)
      SUM(0)=0.0
      DO 410 IJ=1,MNN
      DO 420 IK=1,MNNP
      SUM(IK)=SUM(IK-1)+(AKR1*AK1*AK1/(S*AKP*GAM(1,IK)**2))*
     1(-GAM(1,IK)*BJ(1,(GAM(1,IK)*R1))*BY(0,(GAM(1,IK)*R2))
     2+GAM(1,IK)*BJ(0,(GAM(1,IK)*R2))*BY(1,(GAM(1,IK)*R1)))
     3*SINF(ALAM(1,IK)*T/AK1)
     4*((GAM(1,IK)/AK1)*COSH(GAM(1,IK)*T/AK1)
     5+(H1/AKZ1)*SINH(GAM(1,IK)*T/AK1))*C1(IK)
      ASUM =SUM(IK)
      IF ((SUM(IK)/SUM(1))**2-CONV**2)419,419,420
419   MNNP=IK
      TYPE 2727
420   CONTINUE
      ANN(IJ)=((-AKR1*AK1*AK1*ALL(IJ)*ALAM(1,IJ)**2)*(T/2.)
     1/(S*AKP*R1)-SUM(IJ))/RF(IJ)
      IF(IJ-1)409,404,409
404   TYPE 405
405   FORMAT(SFUNC-N(N)   N        N(N)$/)
409   CONTINUE
      IF((ANN(IJ)/ANN(1))**2-CONV**2)408,408,410
408   MNN=IJ
      TYPE 2727
410   TYPE 315,(IJ,ANN(IJ))
      ASUM=0.0
      ASUM1=0.0
      ASUM2=0.0
      DO 610 IJ=1,MM
      TERM=0.0
      IF(IJ-1)603,607,603
607   TERM=D(1)*E(1,0)*H
603   CONTINUE
      ASUM=ASUM+(AK1/ALAM(1,IJ))**2
     1*(-ALL(IJ)/R1+ANN(IJ)*(ALAM(1,IJ)*(-BI(1,(ALAM(1,IJ)*R2)))
     2*BK(1,(ALAM(1,IJ)*R1))-ALAM(1,IJ)*BI(1,(ALAM(1,IJ)*R1))
     3*BK(0,(ALAM(1,IJ)*R2)))*((SINF(ALAM(1,IJ)*T/AK1)/(T-AL))+
     4(ALAM(1,IJ)/AK1)*COSF(ALAM(1,IJ)*T/AK1))
     5+TERM)
610   CONTINUE
      DO 620 IK=1,MMA
      ASUM1=ASUM1+C1(N)*AK1*AK1/GAM(1,IK)
     1*(-GAM(1,IK)*BJ(1,(GAM(1,IK)*R1))*BY(0,(GAM(1,IK)*R2))
     2+GAM(1,IK)*BJ(0,(GAM(1,IK)*R2))*BY(1,(GAM(1,IK)*R1)))
     3*((1./(T-AL))*SINH(GAM(1,IK)*T/AK1)-(GAM(1,IK)/ K1)
     4*COSH(GAM(1,IK)*T/AK1))
620   CONTINUE
      DO 630 IL=1,MKP
      TERM=0.0
      IF (IL-1)623,625,623
625   TERM=D(1)*O(1)*E(1,0)*H
623   CONTINUE
```

```
      ASUM2=ASUM2+(AK1/ALAM(1,IL))**2*(-TERM/R1
     1+O(IL)*(-ALAM(1,IL)*BI(0,(ALAM(1,IL)*R2))*BK(1,(ALAM(1,IL)*R1))
     2-ALAM(1,IL)*BI(1,(ALAM(1,IL)*R1))*BK(0,(ALAM(1,IL)*R2)))
     3*((1./(T-AL))*SINF(ALAM(1,IL)*T/AK1)+(ALAM(1,IL)/AK1).
     4*COSF(ALAM(1,IL)*T/AK1)))
630   CONTINUE
      AM=(-TH+AKR1*SUM(MM)/(S*AKP)-AKR1*SUM1(MMA)/(S*AKP))
     1/(-AL/(T-AL)-AKR1*SUM2(MMP)/(S*AKP))
      TYPE 637
637   FORMAT($FUNCTION M CALCULATED$/)
      DO 710 IIJ=1,MNL
      A1(IIJ)=ANN(IIJ)+O(IIJ)*AM
710   CONTINUE
      TYPE 712
712   FORMAT($ FUNCTION A1(N) DEFINEDS/)
      DO 451 IL=1,MNA2
451   A2(IL)=F(IL)*B2(IL)+G(IL)*C2(IL)+O(IL)*C1(IL)
      A2(1)=A2(1)+H*A1(1)
      TYPE 452
452   FORMAT($FUNCTION A2(N) DEFINEDS)
      SUM(1)=0.0
      DO 510 IJ=1,MNB1
      DO 520 IK=1,MNB1P
      SUM(IK)=SUM(IK-1)+E(IK,IJ)*A2(IK)
      ASUM=SUM(IK)
      IF((ASUM/SUM(IK))**2-CONV**2)519,519,520
519   MNB1P=IK
      TYPE 2727
520   CONTINUE
      A2(IJ)=D(IJ)*SUM(I.
      IF(IJ-1)509,505,509
505   TYPE 506
506   FORMAT($FUNC-B1(N) N          B1(N)$
509   CONTINUE
      IF((B1(IJ)/B1(1))**2-CONV**2)508,508,510
508   MNB1=IJ
      TYPE 2727
510   TYPE 315,(IJ,B1(IJ))
      ASUM=0.0
      DO 730 I=1,MT1
      ASUM=ASUM+A1(I)*(-BI(0,(ALAM(1,I)*R))*BK(0,(ALAM(1,I)*R2))
     1+BI(0,(ALAM(1,I)*R2))*BK(0,(ALAM(1,I)*R)))
     2*SINF(ALAM(1,I)*Z/AK1)
     3+B1(I)*(-BI(0,(ALAM(1,I)*R))*BK(0,(ALAM(1,I)*R1))
     4+BI(0,(ALAM(1,I)*R1))*BK(0,(ALAM(1,I)*R)))
     5*SINF(ALAM(1,I)*Z/AK1)
     6+C1(I)*(BY(0,(GAM(1,I)*R2))*BJ(0,(GAM(1,I)*R
     7-BJ(0,(GAM(1,I)*R2))*BY(0,(GAM(1,I)*R)))
     8*SINH(GAM(1,I)*Z/AK1)
      TYPE 731,(I,ASUM)
731   FORMAT(ST--S,I2,5X,F10.5)
730   CONTINUE
      T1=ASUM
      TYPE 736,T1
736   FORMAT($......T1=$,F10.5)
      TYPE 732
732   FORMAT($ T1 COMPLETE$)
```

```
      ASUM=0.0
      DO 740 I=1,MT2
      ASUM =ASUM+A2(I)*(-BI(0,(ALAM(2,I)*R))*BK(0,(ALAM(2,I)*R3))
     1+BI(0,(ALAM(2,I)*R3))*BK(0,(ALAM(2,I)*R)))
     2*SINF(ALAM(2,I)*Z/AK2)
     3+B2(I)*(-BI(0,(ALAM(2,I)*R))*BK(0,(ALAM(2,I)*R3))
     4+BI(0,(ALAM(2,I)*R3))*BK(0,(ALAM(2,I)*R)))
     5*SINF(ALAM(2,I)*Z/AK2)
     6+C2(I)*(BY(0,(GAM(2,I)*R3))*BJ(0,(GAM(2,I)*R))
     7-BJ(0,(GAM(2,I)*R3))*BY(0,(GAM(2,I)*R)))
     8*SINH(GAM(2,I)*Z/AK2)
 740  TYPE 742,(I,ASUM)
 742  FORMAT($T--$,I2,5X,F10.5)
      T2=ASUM
      TYPE 744,T2
 744  FORMAT($.......T2=$,F10.5)
      END
*

*
-LOG
10/23   10:13

TIME USED 0:1:14 IN 0:34:48  237 DISC UNITS
```