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EXTERNAL INSULATIONS
Contract NAS9-10583

Final Study Report
May 17, 1971

Colspan, Inc. T. M. Flynn

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External Insulation Systems

for

Cryogenic Storage Systems

Contract NAS 9-10583

FINAL STUDY REPORT
(TYPE I DATA)
May 17, 1971

Prepared for: NASA/Manned Spacecraft Center
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

External insulation systems have been studied quite extensively in the past few years. However, there has been no single source which evaluated these various studies and assessed the relative merits and/or deficiencies of each concept. The purpose of this present effort was to bring together all of the available information in a single place as well as to provide the basis for determining the areas in which future development should be undertaken.

The purpose of this, the final report, is to highlight the early parts of the study, to summarize their results by way of a guide to this final effort, and to present in detail the final evaluations, analyses and conclusions.

1.0 INTRODUCTION

1.1 Objective

The purpose of this work was to provide a single source manual that would serve for the evaluation of external insulation concepts and that would also provide a basis for determining future development areas.

This manual contains: (a) a complete and current bibliography of the field of external insulation concepts; (b) a synopsis of each relevant or useful publication found; (c) a systematic, visible, and methodical means of evaluating one concept as compared to another to reduce the field to a manageable size for further study; (d) an analytical method of evaluating the reduced field to produce sufficient self-evident knowledge to reduce the field further and finally (e) a thorough analytical evaluation of the remaining field that will result in sufficient understanding and knowledge to determine the areas in which future developments should be taken.

1.2 Tasks

The program was divided into four discrete areas with a deliverable item, a report, to mark the completion of each. They were:

(a) Initial Research Phase - The purpose of this phase was to perform a literature search, construct an accessible bibliography, provide a synopsis of the relevant reports found, and finally to categorize the literature according to the insulation materials or insulation concepts employed. The purpose of this phase was to build the technological base for the future phases and to assure an effective utilization of the technological equity built up in this field.

(b) Initial Study Phase - The point of this phase was to make a systematic, methodical, and reproducible selection of those concepts found in Phase I which were the most promising and warranted further analytical study and development. Criteria included, but were not limited to: best thermal characteristics, applicability to intended use, maintainability, reliability, and others. The field was narrowed to five (5) concepts for further analytical study during the Interim Study portion of the program.

A result was not only the selection of five concepts, but the design and execution of a systematic, visible, and methodical means of evaluating future concepts. Therefore, this program was not limited to only current concepts, but may be applied

to all future concepts as they arise. It is important to note that the method described in the report was not only used by the present contractor to narrow the field to five, but also may be used by NASA to evaluate future concepts to help determine which merit further analytical study or development.

(c) Interim Study Phase - In the third program phase preliminary thermal analysis, support analysis, producibility, operability and other factors were considered for the five systems chosen above. Three systems, a shingle with substrate, fiberglass, and blanket were chosen for detailed analysis in the fourth phase. In the third phase also development work on mathematical models for that analysis was nearly completed, and summaries of the mathematical models and programming were presented.

(d) Final Study Phase - Phase IV carried the work to completion by analyzing all five promising concepts, resulting in a rational and self-evident documented choice of concepts for further development. This additional analysis, encompassing a shingle and a continuously wrapped system, was made possible by an extension of contract scope.

This effort, the substance of this final report, includes an assessment of the merits, deficiencies, and further development requirements of the systems selected in the preceeding phases. Support systems were analyzed together with parameters of maintenance, reliability, and other factors that might limit or compromise any of the concepts. A complete analytical study of each selected insulation system was made and this work comprises the bulk of this report.

2.0 INITIAL RESEARCH

2.1 Bibliography

The bibliography was produced with the aid of several National Documentation Centers to insure that it was both complete and current at the time it was prepared. Among the data centers used were the following:

2.1.1 The Cryogenic Data Center of the National Bureau of Standards at Boulder, Colorado

This center is renowned for comprehensive past and current work in cryogenic literature processing. This data center enters approximately 8,000 papers per year entirely from the field of cryogenics. It conducts approximately 120 major searches per year, and provides a current awareness service to 700 paid subscribers and another on superconducting

devices to 150 paid subscribers per year. It searches 200 journals cover-to cover, 3 title announcement periodicals, and 20 abstract journals. By this means, it covers about 300,000 titles.

This was by far the most valuable resource for the study.

2.1.2 The Science Information Exchange of the Smithsonian Institution, Washington, D. C.

This center was interrogated to discover research still in progress but not yet published. This is the nation's only library of research in progress and is indispensable for finding the location and purpose of such research. It catalogs about 100,000 unpublished summaries/yr. which can be searched by modern computer techniques to extract those current research summaries relevant to the program.

2.1.3 The Defense Documentation Center, Defense Supply Agency, Alexandria, Virginia

This center was interrogated as a means of double-checking the above two sources.

This is the central facility within the Department of Defense for processing and supplying scientific and technical reports of defense-sponsored research, development, test, and evaluation (RDT&E) efforts. It maintains 800,000 reports, and like the other centers was computer searched to obtain the technological base for the study.

2.1.4 The NASA Scientific and Technical Information System

This information system summarizes, indexes, and stores the results of worldwide aerospace research and development activities. The NASA information bank now contains more than half a million documents, and it too was searched along with the others principally to assure thoroughness and completeness.

2.1.5 Other

In addition to the national documentation centers, private libraries of the authors were used, chiefly as a check upon the completeness of references supplied by the various centers. Also, a very useful bibliography and set of reprints were supplied by the Technical Contract Monitor at the time, Mr. M. L. Davis, of the Power Generation Branch at the NASA Manned Spacecraft Center, Houston, Texas. Mr. Davis' help is acknowledged sincerely.

2.1.6 Search Request

A complete literature search was requested of each of the centers described. The specific request was:

Please perform a literature search on the topic of:

EXTERNAL INSULATION SYSTEMS FOR CRYOGENIC STORAGE SYSTEMS

Cryogenic storage systems for the extended space missions of the future will require more fluid capacity than current systems, and thus new design and developmental techniques will need to be evaluated. We wish to investigate high performance external insulation systems for use on flight-weight cryogenic gas storage systems. By "external insulation" we mean anything added to a cryogenic storage system for the purpose of thermally protecting it from its environment. This definition excludes the vacuum annulus of a dewar. The fluids stored are hydrogen and oxygen.

This statement was deliberately designed to include all possible relevant key words to insure a complete, valid computer search, and was sent to each of the Centers.

2.1.7 Search Results

In the course of the study, approximately 440 leads were found in the literature and 220 of these were deemed of sufficient interest to warrant acquiring hard copies and studying. One hundred ninety-two synopses were prepared. The complete bibliography, directions for its use, availability of original sources, etc., is presented in the:

"EXTERNAL INSULATIONS"
Contract NAS9-10583

Bibliography, Synopsis and Category Report
July 2, 1970

This report is available from:

National Technical Information Service
Springfiled, Virginia 22151

as Report N71-16865, for a price of $3.00/copy or $0.90/microfiche.

2.2 Categories

A major principle that guided this study was that the results actually be useful (useable) later to anyone having a need. The main idea was to make a critical review and evaluation of the field that would stand up for a long time; that would pull together in one place all that was known about external cryogenic insulation. It was meant to be a benchmark study that later investigators could accept without further searching. In fact, it was designed to be a starting point for future research in this field.

To arrive at this result it was not sufficient that a bibliography be prepared and synopses be displayed. One ought to be able to categorize the findings so that later workers could enter the system painlessly at any level of sophistication or interest and extract what was needed.

Accordingly, major category determinations were based on the information found in the bibliography and in the synopses. Typically, these were based on concepts, materials, and techniques.

Ironically, the categories were themselves categorized. As noted, large numbers of documents were assimilated, and one hundred ninety-two synopses were prepared. Because the technological base was so broad, it was decided to prepare two types of categories. The first dealt with materials and concepts; the other dealt with specific properties necessary to assess the utility of the insulation. These two categories are described below.

2.2.1 Material/Concepts Categories

The categories selected are eleven in number and are:

1. Publication Categories - such as review, patent, analytical, experimental, etc.

2. Materials Categories - such as superinsulation, foam, cork, etc.

3. Shroud Mount

4. Vapor Cooled or Refrigerated

5. Continuous Wrap

6. Blankets, Panels, or Shingles

7. Pumped, Evacuated, or Cryopumped

8. Purged or Gas Filled

9. Perforations, Pump Channels

10. Installation - includes bonding, sealing, taping, penetrations, and supports

11. Mission Studies, Economic Studies

(For a complete description, please see the Bibliography/Synopsis/Category Report mentioned above.)

A typical page from the category section follows. It shows how one could enter the system to extract all review papers (coded as "RV" under "Publication"), or all continuous wrapped forms (coded as "X" in "Continuous Wrap Column).

PUBLICATION	MATERIALS	Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIES
				TECHNIQUES/APPLICATIONS						
Swalley (1964) NBS-17 S-46	EI	SI			X		X			X	
Van Vliet (1965) NBS-27 S-47	AT	MC			X					X	
Key (1964) NBS-28 S-91	TB	HC					X			X	
Taylor (1966) NBS-30 S-48	TB	HC						X			
Cohen (1965) NBS-31 S-49	EI	SI			X		X			X	
Parmley (1966) NBS-32 S-50	TB	SI				X	X			X	
McIntire (1948) NBS-33 S-51	RV	FM								X	
Dawson (1965) NBS-34 S-52	PA	IN				X					
Getty (1966) NBS-35 S-53	TB	SI					X				
Nast (1966) NBS-36 S-54	TB	SI						X	X		
Hertz (1966) NBS-37 S-55	TB	CA								X	
Anderson (1965) NBS-38 S-90	AT	SI			X		X		X		

2.2.2 Assessment Categories

After cataloging was accomplished, it became very useful to catalog and abstract the technologies that were apparent from the search and synopses. The result of this condensation is the Assessment Categories that follow.

The whole point was simply to make the study as useful as possible by entering the system under a specific technique and summarizing that whole sub-field.

The effect is to profive an index and abstract of the technological base deemed pertinent and applicable to the intent and scope of this program, in addition to an index and abstract of the literature itself.

It was decided to summarize the field according to thirteen pigeonholes. Each became, in effect, a small handbook on that particular technology. The thirteen sub-field chosen were:

1. Cork Insulation
2. Honeycomb External Insulation
3. Foam
4. Continuous Wrapped Multiple Reflective Shield
5. Multiple Reflective Layer External Insulation
6. Multiple Reflective Layers on a Purged Fiberglass Substrate

7. Cryopumped Multiple Polyurethane Foam Spaced Reflective Shields in a Shingle Configuration
8. Purged Multiple Reflective Shields in a Shingle Configuration
9. Purged Multiple Reflective Shields in Shingle Configuration Mounted on a Purged Fiberglass Substrate
10. Purged External Reflective Layer Insulation in Panels with Special High Flow Spacers
11. Internally Mounted Polyurethane Foam Insulation (for a baseline)
12. Helium Purged Micro-Quartz High Temperature Cryogenic Insulation
13. Shroud Mounted Insulation

Each of these thirteen small handbooks would have "chapter.headings" such as the following:

1. Density
2. Effective thermal conductivity
3. Porosity
4. Absorptivity, including any sealing requirements
5. Radiant heat transfer properties

6. Environmental compatibility, including fluid compatibility and susceptibility to ground-hold, boost, and spaceflight environments.

7. Mechanical properties, including any support requirements

8. Useful life

9. Bonding methods, including any problems associated with bonding

10. Forming methods, including any problems associated with forming

11. Reusability

12. Ground hold requirements

13. Approximate cost

14. Availability, e.g. major manufacturers

15. Notes: any other property or information considered necessary and/or helpful in assessing possible uses of an external insulation scheme

The result was a set of "handbooks" on thirteen different cryogenic external insulations. Each "handbook" has the fifteen chapters described above.

The purpose was to assemble all of the information available in the Synopses for the purposes of assessing the information, enabling pattern recognition, and providing a systematic basis for choosing one scheme over another.

3.0 INITIAL STUDY

Systematic, methodical decisions were made to determine which concepts found in the Bibliography/Synopses/and Category Report were the most promising and warranted further analytical study and development. Selection criteria included, but were not limited to: best thermal characteristics, applicability to intended use, maintainability, reliability, and others. The field was narrowed to five (5) concepts for further analytical study during the Interim Study portion of the program.

3.1 Objectives

The objective of the selection process was not only the selection of five concepts, but a systematic, visible, and methodical means of evaluating future concepts. Indeed, the introduction into this technological field of a formal decision analysis scheme which is systematic, rational, and open ended is regarded as a major contribution of this study.

Therefore, this evaluation was not limited only to current concepts, but may be applied to all future concepts as they appear. It is important to note that the method described below was not only used by the present contractor to narrow the field to five, but also may be used by NASA to evaluate future concepts and thus determine those which merit further analytical study or development.

The reasons used for rating each concept are clearly displayed. The reader who may disagree with the ranking can match his reasons against those used.

The intent of this process is to provide a framework in which reasoned argument can be used to quantitatively intercompare competitive external insulation schemes. It is suggested that such a method also provides a relatively time invariant means of evaluating new approaches, and can have broader utility in other areas of technology where ever quantitative intercomparison of differing technical systems is required.

3.2 Approach

The approach is essentially that of Kepner and Tregoe as explained in The Rational Manger. It is used for administrative purposes by approximately 150,000 business managers, and has recently been applied successfully by the principal authors to other technical problems. The essential scheme is outlined below:

1. Select "alternatives." These are essentially the various means of achieving the same end. In this case, they are the exterior insulation schemes found in Phase I. (The synopses yield the "information" described below.) Alternatives will be listed as volume headings, left to right, in a matrix, e.g.

"The Rational Manager", C.H. Kepner and B.B. Tregoe, McGraw-Hill, 1965.

Alternatives:
Multilayer 1
Multilayer 2
Foam 1
Foam 2
etc.

2. Select "criteria." These will be such judgement factors as: best thermal characteristics, application, maintainability, reliability, etc.

3. Rank "criteria" into two categories; "Musts" and "Wants."

4. "Musts" are GO, NO-GO criteria. They are usually not subject to weighting. Either an alternative passes, or it fails. This is the first "sieve" of the decision process. If an alternative does pass, it may then if required be weighted in the "Musts." then these criteria may be evaluated comparatively to determine the relative qualities of the "GO" alternatives.

5. "Wants" are highly desirable characteristics. They are the other criteria that are not crucial GO, NO-GO parameters. These are now ranked among themselves on a scale of 10 to 1 according to their relative importance. This ranking was done in cooperation with the Technical Monitor.

6. "Musts" and "Wants" nor form the horizontal rows in the matrix:

Alternatives / Must/Wants	A 1	A 2	A 3	A 4
Must 1	GO	GO	NO-GO	GO
Must 2	NO-GO	GO	GO	GO
Must 3	GO	GO	GO	GO
. . .				
Want 1		info.		info.
Want 2		info.		into.
Want 3		etc.		etc.
. . .				
Total score =		xxx		yyy

Eliminated from further consideration as having failed NO-GO.

Eliminated for failing NO-GO criteria.

Product of criteria weights and alternative "scores"

7. Use the "Information" described in (1) above in the boxes formed by Musts/Wants and Alternatives to decide Go or No-Go. All No-Go's are eliminated from further consideration, as these criteria (Musts) are not subject to "trimming" (by definition).

8. Now proceed to the "Wants." Use only one "want" (i.e., one row) at a time, and rate each "Alternative" with respect to the other "alternatives" in the same row, using the same "information." The score of an alternative is the product of the "Alternatives Rank" and the "Want Ranks."

For example, suppose the "Want Ranks" are

Want 1: 10

Want 2: 8

Want 3: 7

The "Wants" in this case, might be:

Want 1: undiminished effectiveness during lifetime

Want 2: ease of on-site application

Want 3: comparative cost

Now suppose the respective alternatives are types of insulation as:

A1: (Superinsulation) -1

A2: S.I. - 2

A3: Foam -1

A4: Foam -2

Rank these with respect to one another in a given row. For example, with respect to "Want1," the rankings might be:

A1: 10

A2: 8

A3: 6

A4: 3

The score then is the product: (Want Rank) x (Alternative Rank), i.e.,

	Rank	A_1 Rank	A_2 Rank	A_3 Rank	A_4 Rank
Want 1:	10	x10 = 100	x 8 = 80	x 6 = 60	x 3 = 30.

Proceed as above through all the "Wants." The total score of an "Alternative" is the sum of all the sub-scores in its column.

These scores thus provide the ranking of one alternative against another. The higher the score, the more desirable the alternative. Closely scoring alternatives may be re-examined on an ad hoc basis.

This method provides a systematic, visible, and methodical scheme for comparing alternatives. Its merit lies in plugging in the information in the boxes for unbiased evaluation. Another merit is the systematic and visible ranking. Finally, it is open-ended with respect to both "Wants" and "Alternatives" as they occur in the future, and thus it may be used indefinitely in the future as new concepts and criteria appear after this study.

To provide a truly balanced choice, a second matrix of "Adverse Consequences" is usually added to the first. Here, the promising "Alternatives" form the rows, and possible "Adverse Consequences" form the columns. Typically, these are health of employees (exposure to dust), patent royalties (unexpected costs), new facilities (unexpected costs), additional training (unexpected costs), modification of existing facilities (costs), etc.

Adverse Consequences are rated according to the product of their probability of occurring and their seriousness if they do occur.

An absolute certainty of an occurrence is given a probability of 10 (e.g., the probability of certain new facilities being required for a new insulation system is a 9 or a 10.).

The seriousness of such a development might not be high (little relative extra cost, S=3 or 4); or the seriousness might be high if it did occur (health hazard, S=9 or 10).

The weight of the Adverse Consequence is then the product, P x S. The total Adverse Consequence score for a given Alternative is then the sum of its sub-scores. This total score (a negative, or adverse connotation) must now be considered against the total positive score obtained in the Must/Want matrix to reach a balanced decision.

In the selection process used, a separate "Adverse Consequences" matrix was not formulated. Instead, Adverse Consequences were considered, and reduced the scores of the concepts in the original matrix. The reduction reasons are clearly shown in the matrix, resulting in a simpler, more efficient, and more easily comprehended system of rating. A separate Adverse Consequences procedure would have yielded about twice as many pages to be intercompared, greatly impeding the interested reader. Nevertheless, the complete process is described here should new criteria appear in the future that would call for the complete formal process.

3.3 Initial Study Results

Table I lists the concepts selected to provide the "musts" and "wants" of the Kepner-Tregoe selection scheme. These categories were chosen in conjunction with the technical monitor to display the important handling, performance and reliability characteristics of the various insulation designs as affected by the mission requirements.

The above criteria and their definitions were compared to each of the three sets of mission requirements to define their relative importance. First the "musts" were defined by determining those properties which are essential to assuring the missions success, (i.e. "Susceptibility to ground-hold, boost and space flight environment" is a "must" for all cases because the insulation

TABLE I

CONCEPT SELECTION CRITERIA
("Musts and Wants")

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

will not perform its intended function and will cause a mission failure if it is damaged after the countdown begins). Some insulations fail on a "must" apriori while others pass but may be rated relative to each other, based on the degree of confidence with which each passes.

After the "musts" were selected the remainder of the criteria were inter-compared among themselves in pairs to provide a relative importance ranking. With the relative ranking completed, category weight factors were assigned to reflect the importance of each item quantitatively. Each "must" received a weight of 15, the highest value assigned. The "wants" were then weighted from 10 downward to their comparative desirability as opposed to the mandatory nature of the "must".

External Insulations were categorized first according to type, e. g.

1. Superinsulation
2. Foams
3. Honeycomb
4. Fiberglass
5. Cork
6. High Temperature

Each type was then subdivided where ever applicable according to (a) material, (b) combination of materials, and (c) mounting method. Thus one can generate all types of external insulations (quite a large number) by forming all possible rational combinations of a relatively small field of materials and methods.

Some combinations are at once not acceptable, elg. foil no spacer.

The field can be further reduced at once as some materials are better suited for only one kind of storage e.g., useful only for long term, intermediate, or short term storage.

Therefore, the initial selection leaves these insulations and their field of application to be subjected to the decision analysis.

Type/Material	Long Term	Intermediate	Short Term
I. Superinsulation	X	X	X
II. Foams			
Polyurethane			X
III. Honeycomb			
Foam			X
Evacuated			X
Purged			X
Evacuated/purged		(X	X)*
IV. Fiberglass			X
V. Cork			X

*Intermediate and short term storage can be considered together here

A typical table and arguments follow to illustrate the method. It is for "Superinsulation Long Term Storage, continuous wrap vs. blankets.

For the complete results, please see:

"EXTERNAL INSULATIONS"
Contract NAS9-10583

Initial Study Report
August 2, 1970"

This document can be obtained only by writing to:

Dr. John R. Wilson
Colspan Environmental Systems, Inc.
P. O. Box 3467
Boulder, Colorado 80303

Short term:

1. Coated reflective shingles on a substrate

2. Fiberglass

Intermediate:

1. Coated reflective shingles with embossed or tufted spacers

Long term: (Can be considered for intermediate)

1. Blankets of coated reflectors with net spacers

2. Continuous coated reflectors with net spacers

For a complete description and detailed arguments, please see the "Initial Study Report" cited above.

Application: Long Term Storage

TABLE II

Criteria	Alternative: Foil Continuous Wrap Net Embossed Scores repeated from preceding table				Blankets/Panels Net	Blankets/Panels Embossed/Tufted Thermal shorts due to no spacer.
Musts						
1. Thermal Performance	15	10	8	Uses seams compared to continuous wrap	9	7
2. Life	15	10	9	No difference	10	9
3. Repeatability	15	3	3	Machine controlled, jigs possible	6	6
4. Environment	15	6	6	Positive mount. Not all fails when some degrades	8	8
Wants						
5. Ground Hold	10	10	10	No appreciable difference. Much easier to pump than continuous wrap.	10	10
6. Operability	9	4	4	Configuration is easier to work with, fixalbe	7	7
7. Weight	8	8	9	Slightly heavier than continuous wrap due to mounting considerations.	7	8
8. Spacecraft	7	7	7	Can mount in place or as prefab modules	8	8
9. Reliability	6	9	9	Has been proven to work well once it has been mounted properly.	9	9
10. Maintainability	5	2	2	Panels can be changed. Hard to interlock Net gives strength.	7	6

TABLE II, (Continued)

12.	Reusability	3	5	5	Repairable, but still difficult to handle.	6	6
13.	Lab/Relization	2	3	3	Predictable. Tests on one panel, a sub unit, rahter than whole assembly.	5	5
14.	Cost	1	2	1	Can be set up jigged, one error does not ruin a whole assembly.	4	3
Weighted Score: Multiplying Rank by weight and adding as before.							
			811	757		925	868

4.0 INTERIM STUDY

In that program phase, preliminary thermal analysis, support analysis, producibility, operability and other factors were considered for the five systems. A shingle alone, shingle with substrate, fiberglass, blanket, and continuously wrapped were the systems chosen for detailed analysis in the final phase. Development work on mathematical models for that analysis was nearly completed by the end of that phase, and is now complete. Summaries of the mathematical models and programming are presented in the Appendices of this report.

Below are basic, simplified descriptions of the five external insulation systems selected for further evaluation and study. These are presented for the convenience of the casual reader. For a detailed discussion of these systems, one may turn immediately to Section 5.0, FINAL STUDY. These descriptions, reproduced from the Initial Study Report, provide the basic framework or reference for analysis and evaluation.

4.1 Short Term Insulations

The short term mission requires the usage of large quantities of cryogen in six 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.

4.1.1 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 cryopumping and fractionation of air in the insulation. The shingled superinsulation 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 insure 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 multilayer subassemblies. Special shapes and cut outs 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 reinstallation. They may be shop or launch pad mounted.

4.1.2 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 reentry 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.

4.2 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.

4.2.1 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 descreased 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.

4.3 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.

4.3.1 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 is 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 predesigned 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. Their increased lateral conductivity results in much poorer repeatability of joint and penetration designs.

4.3.2 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 diffcult to replace.

Performance repeatability is hard to achieve with this insulation because each penetration must be accommodated individually during installation and the system usually cannot be prefabricated by shop procedures. Continuously wrapped insulations are difficult to support as firmly as blankets and thus may shift and/or be damaged during ground 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."

4.4 Summary of Interim Study Report

4.4.1 Tankage

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.

A summary of the tank design appears in the following table (Table III).

4.4.2 Comparison of the Materials/Concepts

The purpose of the Interim Study was to begin to develop analytical techniques and to verify them. Such interim results appear in the following tables (Table IV, Table VII).

For the complete description of the development of the analytical tools, please see:

EXTERNAL INSULATIONS
Contract NAS9-10583

Interim Study Report
November, 2, 1970

TABLE III

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, $H_2/0_2$(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		1.76	29
Loaded Wt H_2, lbs.	152,590	157,780	62,800	60,585	58,470
Loaded Wt 0_2, lbs.	2,276,650	2,284,500	864,700	861,350	858,200
Support OD, in, $H_2/0_2$	3.81/7.5	3.75/7.5	3.3/7	4.1/6.5	4.1/6.5
Support ID, in, $H_2/0_2$	3.5/5	3/5	3/5	4.0/5.5	4.0/5.5
Support Length, in, $H_2/0_2$	36/36	36/36	36/36	36/36	36/36
Number of Supports	12	12	6	12	12
1 Fill Pipe, in, $H_2/0_2$	4p/6p	4p/6p	3p/4p	3p/4p	3p/4p
1 Vent Pipe, in, $H_2/0_2$	5p/8p	5p/8p	4p/5p	4p/5p	4p/5p
1,2 Use line, in	7 ps	7 ps	4ps, 2pm	4ps, 2pm	4ps, 2pm

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

TABLE III, (Cont'd)

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	
Cylinder Thickness, in		0.0263	0.0526		0.0263	
Structural Wt, $H_2/0_2$ (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 Wt H_2, lbs.	10,460	11,178	10,088	522	539	26
Loaded Wt 0_2, lbs.	143,950	145,050	143,500	7202	7228	360
Support OD, in, $H_2/0_2$	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, $H_2/0_2$	2.6/4.0	2.00/5.0	1.5/4.0	2.00/2.00	2.00/2.00	0.75/1.25
Support Length, in, $H_2/0_2$	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, $H_2/0_2$	2T/3P	2T/3P	2T/3P	1T/1.5T	1T/1.5T	1/4T/1/2T
1 Vent Pipe, in, $H_2/0_2$	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

Which is available from:

National Technical Information Service
Springfield, Virginia 22151 as

Report N72-16600
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Table IV gives the approximate insulation weight of the five tanks.

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 V and VI. Table V pertains to the ground hold condition and Table VI presents the estimates of performance while evacuated in space. 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 VII presents estimates of this pump-out time for the various insulations. The numbers presented there are probably optimistic since a detailed out-gassing 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(one day) or intermediate missions(two week)as quickly as the shingles. On the other hand, these pump-out times are essentially insignificant in six month missions.

TABLE IV

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 V

GROUND-PURGED THERMAL PERFORMANCE, BTU/hour

Tanks/ Insulations	Fiberglass		Fiberglass-Shingles		Dimplar		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	511	1,000	823	1,000	823

TABLE VI

GROUND-PURGED THERMAL PERFORMANCE, BTU/hour

Tanks/ Insulations	Fiberglass		Fiberglass-Shingles		Dimplar Shingles		Net Spaced Blankets		Continuous	
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 VII

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

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 semi-permeable material. The purge gas contributes 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 performance 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 nonrepeatable installation factors become a large portion of the heat leak in this 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 "Superfloc") should probably be considered in a blanket design, where its lateral conductivity is not so detrimental and its pump-put characteristics can be full 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 nonaluminized 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.

Five Materials/Concepts were selected for further study in the final phase of this program. Space does not permit a listing hereof the merits of the chosen systems, which are (1) Fiberglass (2) Shingles alone, (3) Shingles on a purged substrate, (4) Blankets, and (5) Continuous wrap. The reasons for these choices will be briefly summarized.

At first only three were selected, as required by the contract:

(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 at first eliminated because they provide slightly poorer thermal performance. There are some missions for which they are appropriate, however.

Similarly continuous systems were at first 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.

However, it became clear that the bulk of the development work would have been for the evaluation of the three systems, but that it would be cost effective to actually perform the complete analysis on all five systems. Accordingly, all five were carried into the final phase, which follows immediately.

5.0 FINAL STUDY

5.1 Detailed Description of Five Systems

5.1.1 Fiberglass

The functional element of this system is a matted web of fibers of glass. The fibers provide a long conductive path for heat flowing toward the tank, but act only minimally to block radiative heat input. The variations of the system arise from variations in the materials, methods of attachment to the tankage, and manner of preventing gas (usually atmospheric) condensation in the functional element.

The composition and physical form of the material may be varied. The fibers are usually manufactured of borosilicate glass by a highly developed, efficient industrial process. For systems requiring performance at temperatures typically encountered under harsh aerodynamic conditions, borosilicate glass degrades, but can be replaced by fibers of quartz. Some physical forms are: felt mats cut into rectangular pieces of relatively large size and arbitrary thickness, and long fiber bundles. The high temperature versions are often merely short chopped fiber.

Although the felt mats could be restrained in place by an external barrier, usual practice is to bond them directly to the tank wall with suitable adhesives. Epoxies are widely used. When this approach is followed, attention must be given to joints between adjacent pieces of material. If the material is not lapped in some fashion at the joints, regions of direct radiative heat transfer are left, and high boil-off penalties are sustained. Jointing techniques include simple overlaps, beveled laps, or interlayered laps.

With the functional element i. e. the felt mat attached to the tank, consideration must be given to stopping gas condensation in the insulating material at the cold tank wall. Condensation of gases causes high rate heat transfer to the vessel. If oxygen is one of the gases condensed, a potentially hazardous situation is created. In the case of a leaking hydrogen vessel, the hazard is obvious. However, hydrocarbons in bonding agents, lubricants, etc.,

can oxidize explosively on impact if sufficient oxygen is present. These problems make it desirable to exclude gas condensation altogether in the thermal protection system. Many methods for accomplishing this have been evolved. Most employ an air-excluding jacket to surround the insulation system.

Maximum insulation efficiency is attained if all gas is excluded from the insulating element. The removal of gas from the material requires an external barrier, surrounding the material, to prevent the entry of additional gas after initial evacuation. Such a barrier can be rigid and metallic, or it can be flexible such as a laminate of plastic films and metal foils. The systems weight penalty is less if the latter is used, although the blessing is a mixed one. A flexible evacuation jacket usually is supported only by the underlying insulating material, in order to gain a large weight saving over the metal shroud system. As evacuation proceeds, two undesirable effects appear in such a scheme. The insulation material compresses under the force of atmospheric pressure on the jacket, and the jacket wrinkles as the enclosed volume is reduced by compression. Insulation compression increases the heat transfer rate to the tank. Wrinkles in the jacket have usually led to gas leaks in the membrane, defeating the purpose of the system. Some light-weight vacuum jacket support systems have been proposed, and the continuing development of better jacket materials makes these systems more attractive for future applications.

Because of these problems, it is often desirable to utilize an insulation material purged with a noncondensible gas. The entry of atmospheric gas is then prevented in part by an external barrier in the form of a purge jacket needed to control the effluent and in part by the purge effluent itself. The only purging gas suitable for this purpose is helium, unfortunately. Helium permits very rapid conductive heat transfer, but it will not condense when used as a purge for hydrogen or oxygen storage systems, since its liquefaction temperature is the lowest known.

The external purge barrier may be impermeable, and may be made of Mylar, Aclar, or Tedlar, with several inlets and vents of controlled geometry for the purge gas. As well, the jacket may be fabricated of impremeable material with a controlled pattern of porosity produced by mechanical puncture. A typical example is woven fiberglass cloth. The purge barrier has some additional side benefits; it can provide additional mechanical strength and durability to the external surface of the insulation. Typically, the purge membrane is bonded to the outer surface of the fiberglass felt with an adhesive. For the woven barriers, epoxies are preferred.

The introduction of the purge gas into the insulation medium and its proper venting, are complex subjects. In general, the purge system should be tailored specifically to the application, and few general guidelines have been established.

Following is a discussion of fiberglass matting external insulation systems.

5.1.1.1 Merits

Fiberglass has many merits. It is a lightweight, low density, durable material. Its desirable physical properties include its inorganic nature, implying low outgassing except for the bonding agents employed; and nonflammability. It is environmentally stable, with low water absorptivity, and has long life. It will withstand reentry with but limited protection. It is inexpensive, easily fabricated, and can be refurbished satisfactorily. It is easier to mount to the tank than any other system (except foams). In space, micrometeorite punctures present little hazard to the insulation system proper. Although tankage leaks degrade its thermal performance, under the proper conditions it can cause the leak to plug. However, foams are superior in this regard. Thermally, fiberglass functions better on a conductivity basis than foams, but worse than powder insulations. Fiberglass is an isotropic insulating material, noncompacting in use, which provides repeatable performance with simple penetration treatment. Purge systems used during ground hold require relatively limited apparatus and support services, and the purge jacket often is easily maintained.

5.1.1.2 Deficiencies

The deficiencies of fiberglass insulating systems fall into three areas:

(1) The material has poor (limited) thermal performance capability, compared to powders and superinsulations.

(2) It cannot be opacified in its present form, and becomes increasingly transparent to radiation as the warm boundary temperature is raised. Its thermal performance is subject to degradation from adhesive outgassing and from purging. It is subject to atmospheric gas condensation within the insulation, and purging is necessary to prevent this. Gas condensation increases boil off and hazard.

(3) The material requires support for large inertial loads, and although it is superior to laminar insulations in this regard, it is inferior to foam. Good joints in the material can be difficult to make, and the repair of the material can be hampered severly if an outer bonded purge barrier is used. The mounting technique, while simpler than powders or superinsulations, is inferior to foams.

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Purging systems can add a weight penalty to the system in the form of piping manifolds for the introduction of purge gas. Reliability problems can be experienced with purge jackets (leaks) and the jacket must be vented properly in space. The latter usually imposes further weight penalty.

5.1.1.3 Further Development Required

Further development of fiberglass external insulation is feasible in two areas:

(1) The thermal performance of the material could be enhanced significantly if ways were possible to opacify it. There are several conceivable ways in which this might be achieved. One way is to aluminize a portion of the fibers upon manufacture, and then combine these with normal material in such proportions as to avoid thermal shorting. Another way is to add small quantities of metal fibers or whiskers. Metal powders are not suited for this purpose.

(2) Further work on purging systems with attempts to reduce the piping weight and increase the reliability of purge

jackets is required. However, the elimination of the purging system with the introduction of a lightweight, supported, and reliable vacuum jacket is more desirable.

5.1.1.4 Support Systems

Because of the isotropic nature of fiberglass material, support systems for the fully insulated tank are not restricted. In general, penetration treatment with fiberglass is straightforward as long as careful attention is given to material junctures. All of the common systems, employing struts, bands, or other configurations may be used. Advantage is often taken of support penetrations for the introduction of purge gas. In this fashion, additional purge jacket penetrations are avoided.

5.1.1.5 Maintenance and Reliability

Most fiberglass maintenance problems fall into the area of repair and refurbishment, while the reliability problems usually concern the purging system. Repair of damaged portions of fiberglass is accomplished by cutting away the damage and bonding additional material into the gap. Repair is completed by patching the purge jacket. The concentration of adhesive in a given region can produce a localized highly conductive area if caution is not observed. Small leaks in the purge jacket are not generally of serious consequence, unless located in a position to deprive the remainder of the

system of gas flow. The maintenance of complicated penetration geometries in leak free condition can be difficult, and repairs to such regions are often unreliable. Unfortunately, these problems must be met in each system as they occur.

5.1.1.6 Limitations/Compromises

The basic limitation of fiberglass is thermal performance. The only avenue of improvement here seems to be opacification. The basic compromise of the materials properties occurs through the use of helium purging systems. The indicated improvement is the substitution of a reliable evacuation jacket system.

5.1.2 Coated Reflective Shingles on a Substrate

This system has two functional elements; one, a purged sublayer lying next to the tank, and two, a series of radiation shields in shingle configuration attached to the outer surface of the sublayer. The discussion of the fiberglass system applies directly to the sublayer of this system, and the merits and deficiencies transfer directly. The new element, which must be considered in detail, is the external shingle layer.

Although foils may be employed for the shingles, metallized plastic films have many more attractive properties. The use of foils leads to additional weight and to more and difficult attachment problems including the support of the nonintegral spacer, and to insulation failure at high acoustic loading levels. Metal coated plastic shingles, on the other hand have none of these disadvantages. The shingles, attached to the sublayer purge jacket, effectively opacify the sublayer, thus preventing radiative heating of the cryogen vessel. The sublayer, which acts as the shingles support eliminates the requirement for low temperature shingle attachment and provides a longer path for heat reaching the tank by conduction.

The shingle mat is typically Mylar, the trade name for the du Pont polyester, polyethylene terepthalate, which is aluminized by vacuum evaporation on one side. Mylar is light and has high tensile strength. It has low tear resistance and is subject to tear propagation. Aluminum deposited by evaporation adheres fairly well to Mylar in the absence of water vapor or liquid, or sterilizing agents such as ethylene oxide. The presence of these substances in any appreciable quantity causes the immediate removal of the metal coating. To insure against this, aluminized Mylar should not be exposed to atmospheres of greater than 60 per cent relative humidity. If this goal cannot be met, it is mandatory that a dry gas shingle purge be used to prevent catastrophic insulation failure. Some other metallic coatings are not subject to this problem in such a severe form. Gold is an example. However, it is difficult to obtain good mechanical adhesion for gold films thermally deposited on

Mylar. Silver, another commonly used metal, tarnishes unless treated carefully. Attempts to overcoat metallic films to provide protection from these problems have so far been unsuccessful. For these reasons, and for reasons of expense, aluminum is typically the choice of the reflecting element.

There are other problems with aluminized Mylar. Handling the material with unprotected hands degrades its emissivity more than is generally recognized. Space workers ought to know better, but the literature is nonetheless full of pictures of bare hands on aluminized mylar. Silver films are degraded by sulphur bearing rubber gloves.

Manufacturers of metallized coatings do not always meet the user's requirements. On custom orders, one often finds unusable portions of the material throughout the roll as supplied. The problems one can expect range from thin coating, to coating spalling, to holes in the substrate material.

One of the greatest technological problems with aluminum thermal deposition processes is an inability to deposit metal of the required thickness. To provide correct theoretical opacity to incident radiation, the metal film should be at least 570 Angstroms in thickness. To the fabricator, this amounts to 0.5 ohms/square, according to the commonly used resistance monitoring technique. The emittance of such a film should typically approach 0.02. Instead, the coatings which can be produced have usually a minimum resistance of 1 ohm/square, and an emittance of 0.03, 50% higher than the optimized value.

In spite of this, aluminized Mylar is widely used. It can be used to temperatures as high as 325°F, but degrades rapidly above that point. Mylar is quite flammable and burns freely in air. The polyimide, Kapton, while heavier than an equivalent thickness of Mylar, has a useful service temperature approaching 825°F. It is often used as a single layer external protective film for a Mylar system.

The fabrication of shingles is normally accomplished by cutting the material around a thin metal template with the proper dimension. Shingle dimensions are chosen from the tank geometry in each case, and have relatively low mechanical tolerance. Frequently one pattern can be used for the bulk of the material required, leading to fabrication cost savings. Typical shingle lengths are 28 to 36 inches. The shingle pieces usually have better support against inertial loading than other systems such as blankets or continuous wrap systems, which of necessity use larger sized Mylar components.

Once fabricated, shingles are bonded directly by one of several techniques to the sublayer purge jacket. These include adhesive bonding, or taping of each individual shingle, or preassembly of layers of shingles in a pad, which is then bonded to the jacket. The shingle pad is typically fastened together at one end, much as a pad of paper. The pad can be formed using adhesive, or ultrasonic fusion of the shingle ends. The latter is

preferred, for the prevention of outgassing. Since the bond line at the purge jacket is not subject to the extreme cold of the tank, many low vapor pressure adhesives are suitable for shingle attachment.

The treatment of penetrations in shingle systems is greatly simplified, as the shingles can be cut to overlap and can be fitted around the piping or support. If desired, buffer material can be used, but the laterally conductive paths from the penetration are interrupted by the shingle structure and with proper design, adequate penetration performance is easily attained. Joints between shingles are also less critical than those in other multilayer systems, and only sufficient, nominal overlap (6 inches) is required to achieve full performance of the system. A carefully installed shingle system exhibits a thermal performance which is degraded no more than 50 per cent over a comparable parallel layer multilayer system, due primarily to lateral conductive heat leak.

As a result of the structure, shingles are easy to repair or refurbish, at least to the subassembly level. Tankage leaks can degrade the substrate completely, but the shingles will still function and degrade only locally at points of sublayer leakage. Any gas which might leak into the shingles vents immediately to space, and normally the performance of only a single shingle is lost. The same property, again a result of the structure, allows the rapid evacuation of the shingle layer once the vacuum of space is

reached. To prevent undesirable decompression effects, a net or other container encloses the shingle layer and controls the position of the loose shingle ends.

Since atmospheric gas condensation in the shingle layer is not a problem, the shingle layer of a composite system is seldom purged. If the last ounce of performance must be wrung from the system, it can be purged with hot dry nitrogen. This technique, while bearing a weight penalty, allows the most rapid achievement of ultimate thermal performance in space. Additional discussion of shingle purge systems may be found in the section dealing with the shingle system alone.

5.1.2.1 Merits

Coated shingles with a purged sublayer exhibit good thermal performance characteristics. The system is easily fabricated, has long life if properly protected from moisture and harsh reentry conditions, and is easily refurbished. The mounting of the system to the tank is relatively simple and the insulation is well supported against launch stress. The shingles are not affected by high acoustic fields if plastic film shingles are used. Tankage leaks do not significantly degrade the performance of the shingle layer. The complete thermal protection system functions better (lower conductivity) than foams, fiberglass, or powders, and has none of the handling drawbacks

of the latter. The material does not compact in either prelaunch or space operation and provides very repeatable performance with simple penetration treatment. Purge systems used for the sublayer during ground hold are reliable and limited in size and complexity. The purge jacket is protected by the shingle layer and is thus not subject to damage.

5.1.2.2 Deficiencies

Deficiencies in this system arise from the materials, the structure, and the purging system. The deficiencies of the sublayer have been outlined earlier. The materials limitations inherent with plastic film components are well known. Mylar burns freely and completely in air as already noted. Moisture is readily absorbed by the film, and causes reflector failure and extended evacuation time. Plastic materials and adhesives outgas, reducing the achievable thermal performance. External protection and possibly meteorite shielding are required if any harsh mechanical or thermal environment will be encountered.

Structurally, shingle compression must be avoided to maintain optimum thermal performance. The crevices of the shingles can store trapped condensed moisture from the atmosphere, and although the vent path is direct, these crevices can be slow to empty even residual gas to the

vacuum of space. Although the shingles are easily repaired, damage to the insulation sublayer requires complete removal of shingles and substrate membrane in the damaged region before repair can be effected.

The sublayer purge tubing manifold adds a weight penalty to the system. The sublayer purge membrane integrity must be preserved through launch and hence the tolerable jacket pressure differential is limited.

5.1.2.3 Further Development Required

Development appropriate to the improvement of the sublayer performance was discussed earlier. The aspect of shingle technology requiring further development is in the production of lower emissivity, more durable shingle coatings.

5.1.2.4 Support Systems

In general, since tankage using this system will probably be large (propellant storage) the most appropriate support systems will be struts of the type described in Section 5.2.4 of this report or conventional cone (ring) mounting. Neither system requires special treatment for use with this thermal protection system.

5.1.2.5 Maintenance and Reliability

Damage to this system is likely to occur as a result of handling, and the shingles should bear the brunt of this. Replacement of shingles is straightforward. Repair of the sublayer requires removal of a portion of the shingles and the purge jacket. This is required in the case of tankage leaks for example. If properly protected, this system is long lived, and easily refurbished from mission to mission.

5.1.2.6 Limitations/Compromises

The thermal performance of this scheme is limited, but significantly better than fiberglass. It should compete favorably with powder systems. Ground hold performance is of course compromised by purging and by the nonevacuation of the shingles.

5.1.3 Coated Reflective Shingles with Embossed or Tufted Spacers

The functional element of this system is a shingle layer attached to the exterior of the tank wall by bonding or by pins.

Shingles mounted directly to the cryogen tank have properties somewhat different from the shingles with substrate considered earlier.

The materials and fabrication of the shingle elements are similar to those of the earlier system. The only exception, the spacer elements, are incorporated into the shingle material by embossing with rollers or by the use of flocking techniques with mechanical or electrical provision for orientation of the flock fibers.

Because of reliability problems with long adhesive bonds which experience thermal cycling from ambient to cryogenic temperatures, pins are the preferred method of attaching shingles to the tank. In this method, studs are welded or bonded to the material of the tank wall. In the case of metal, welded pins, a nylon shell is sometimes bonded over the pin. Since aluminized Mylar can in no sense be considered a structural material, it is usual to form the individual shingles into the stronger pad structure which is ultrasonically bonded at the attachment end. Holes are then punched to fit the pins.

In order to avoid propagation of tears at the punched boundary, a heated (1000°F) tool is often used to cut the holes. At this temperature, the Mylar shrinks back from the tool as it parts, thickening slightly, and forming a tear resistant "grommet" around the hole. This technique, considered

superior by many, is not widely used and is even disparaged by some fabricators. The shingle pads are mounted on the pins, and retained by nylon clips. Each attachment is covered by the next pad installed. The system is easily demounted and repaired.

A system using shingles only is subject to atmospheric gas cryocondensation at the cold tank surface and this represents the system's major engineering complication. There are of course two methods to prevent this. Evacuation of the shingle system on the ground is not an easy matter and has undersirable consequences. A conventional unsupported flexible vacuum jacket causes drastic shingle compression and consequently large conduction heat leak (typically double the nonevacuated rate) in the evacuated state. As well, the recovery from compression after boost can be unsatisfactory, although for tufted materials, this is not a major problem. For these reasons, a helium shingle purge system is often utilized during the ground hold phase.

While purged systems avoid the problems of evacuation jackets, they are not without drawbacks. The purge tube manifolding adds both weight and a conductive path through the insulation. The manifolding path is difficult to optimize and large variations in ground hold performance can result from similar purge routing. The integrity of the purge jacket must be maintained throughout boost, until the tank is well above the atmosphere. Most jacket materials will support only a low pressure differential and hence, require a complex venting system to survive launch.

In orbit, although a properly vented shingle system evacuates rapidly, the shingles exhibit some peculiarities in this regard. The shingle pad structure will support long lived pressure gradients in the directions vertical, horizontal and normal to the shingle layers. The source of these gradients can be adhesive outgassing and trapped moisture or tankage leaks venting through the purging manifold. (Leak venting internal to the tank has not prevented this in some cases.) Measurements have shown a pressure differential of two orders of magnitude within the shingle pad rising from the loose end to the attached end. Compared to the operating pressure in the insulation interior, an order of magnitude pressure increase has been observed at the surface of shingles in immediate proximity to the outer purge membrane. High flow spacer shingle types perform better in this regard.

These pressure differentials degrade the insulation performance severely, and should be considered carefully during the design phase. There is an overdrawn tendency to view shingles intuitively as a rapid, easy venting system, but this is not necessarily so.

5.1.3.1 Merits

The merits enumerated for the shingle/substrate system carry over directly to shingles discussed above. Shingles alone have slightly poorer ground hold thermal performance than shingles/substrate but are superior to blankets and continuous wrap systems in this respect. Embossed/tufted

shingles exhibit superior compression recovery properties (and hence thermal performance) over the ordinary shingles, if evacuated and protected from handling damage. This renders them slightly more attractive than shingles/substrate from the point of ground hold operations.since the jacket is accessible for maintenance. In addition, the space compression recovery which is best for tufted shingles, allows a more rapid approach to the ultimate system working pressure than that exhibited by conventional material shingles. In systems purged prior to launch, lack of prelaunch shingle compression reduces the evacuation time still further.

5.1.3.2 Deficiencies

The chief deficiency of shingle-only systems is that a direct lateral conductive path to the cold tank wall is provided. This problem, in one form or another is common to all multilayer thermal protection systems, and makes the proper insulation of penetration piping somewhat difficult. If annular isotropic buffer insulation is not used around piping, it is difficult to prevent the penetration from thermally shorting to the tank. Generally speaking, materials deficiencies cited for the shingle/substrate system transfer directly to the shingle-only system.

The purge manifold adds a large weight penalty as well. The routing of the purge piping is a matter of cut and try and it follows that the optimization of a

shingle purging system is difficult. Finally, the pressure differential which the purge jacket can support during ascent is limited, and an explosive decompression failure can occur. The thermal protection capacity of the system is destroyed, since proper shingle orientation is lost under these circumstances.

5.1.3.3 Further Development Required

The system performance could be improved somewhat by the development of a noncompressive ground hold evacuation system. High flow spacers have proved to be a valuable development. The "Superfloc," tufted variety appears to have properties superior to Dimplar. As long as conductive metallic shingle elements are used, probably little else can be done to improve this system.

5.1.3.4 Supports

Because of the high lateral conductivity of this insulation system, tension supports of poorly conducting material such as filament wound fiberglass epoxy struts, or epoxy glass tension bands are the indicated choice. Metallic mounts often result in unacceptable thermal performance.

5.1.3.5 Maintainance and Reliability

Shingles are protected by the purge jacket and are easily repaired should the necessity arise. Refurbishment is also minimal and would normally be required only in the event of moisture entry into the shingles, exposure to excessive heat, and so forth. Shingle reliability is good.

5.1.3.6 Limitations/Compromises

The thermal performance of this system is limited by lateral conductive heat leak to the cryogen vessel. Performance is further compromised by purging during ground hold.

5.1.4 Blankets of Coated Reflectors With Net Spacers

The functional element of this external insulation system is a panel of stacked layers of aluminized Mylar, all of the same shape, mounted next to the outer tank wall on some support mechanism. The modular nature of the panels, or blankets, makes possible a long term high thermal performance system which can be removed for maintenance.

The materials used for blanket systems are the same as those for super-insulation systems, namely; foils, coated plastic films, glass webs, (i.e., Dexiglass or Tissuglass) silk, nylon or dacron netting; and thin, rigid or flexible polyurethane foams.

Blankets are made by cutting materials to size, and forming on production jibs of various types. The jib can be an actual tank, or a fiberglass/epoxy cast of a tank. Often, jigs are made of wood, or suitably sealed plaster. For very large tanks, jigs are not required. The blankets are essentially flat and can be laid on large tables. The method of assembly of the blanket depends on the support mechanism. Several of the more common are described below.

Supports may be classified into (one) those using a rope or line as the structural element, and (two) those using tank bonded pins as the primary support. For the rope support systems, the blankets are frequently quilted loosely with dacron thread to prevent layer shifting during handling. In use, the blanket is folded over the rope and clipped to it by a fastener. When pins are used for blanket support, similar jig pins are used to align layers properly as the blanket is fabricated. The blanket can be removed piecewise if stitched in groups of layers, and each layer group can be secured to the tank pins with a fastener which preserves the separation of the groups. Other techniques, such as the "button and string" mount are merely variations of this basic technique.

Before fabrication, careful thought must be given to blanket penetration and seam design. Penetrations are typically insulated with patches of the same material, which are terminated on the piping in a manner which preserves the temperature gradient through the blanket. Occasionally, annular plugs of another material such as fiberglass or foam are used to insulate the blanket from the penetration. This method offers greater repeatability but somewhat lower thermal performance than the former.

Many methods for forming blanket seams have been developed and some are illustrated in Fig. 5. Variations of the interleave schemes offer best performance. In the sawtooth scheme, a strip of Mylar, folded accordion fashion, is stitched lightly to the blanket edge. Scalloped cuts are made in the folds to permit blanket evacuation or purge.

Since the support of blankets against compression is firmer than that of shingles, and because there are no lateral conductive paths direct to the tank, blanket ground hold thermal performance is enhanced greatly by evacuation. The obvious place to evacuate blankets is at the seams, which is another reason for giving careful consideration to blanket seam geometry. Blankets are evacuated by pumping out the system through a manifold laid into ducts left at blanket seams. Open ducts are patched and sealed at installation. Unpumped joints are merely spliced and sealed, as shown earlier. Loose blanket edges are frequently held in place by tape or netting, and the whole system is encased in a flexible jacket.

For purged operation, the same general procedure is used except that purge gas is introduced into the piping manifold. The outer impermeable jacket is frequently replaced by an open weave purging jacket. If the blanket system is mounted on a sublayer insulation, hot purge gas (250°F) is used to insure against moisture entry into the insulation. The exposure of aluminized Mylar to heat invariably shrinks the material. Blankets which shrink either overstress their mounting perforations and tear under load, or suffer layer compression and consequent reduction in their thermal performance. For exposure to 250°F for prolonged time, a 5 per cent change in blanket size has been observed.

5.1.4.1 Merits

Blanket systems provide the closest approach to the thermal performance of continuously wrapped systems, but without the near impossible maintenance and repair problems associated with the latter. Additionally, blankets deliver this performance repeatably (with consistent and reliable penetration treatment). The design of the blanket allows some standardization in penetration geometry and penetration insulation can be prefabricated using standard shop practices.

5.1.4.2 Deficiencies

The high lateral conductivity of blankets makes penetration and seam treatment of great importance to system thermal performance. Because

of the insulation mounting apparatus, the system has fairly high weight, compared to continuous or shingle systems. The labor cost for the system is high, but probably less than that of a continuous system. Blanket performance is degraded by compression (and therefore vacuum jackets must be carefully designed.) If the blanket is purged, the decompression must be closely controlled during launch to avoid catastrophic insulation disruption. Blanket mounting studs open radiation windows to the tank and must be optimized carefully for both number and location. Prelaunch evacuation is slow due to tortuous gas flow paths. Attempts to reduce this time by adding blanket perforations help, but system performance degrades quickly if too many perforations are used. In addition, perforations must be laboriously placed by hand, again to avoid direct radiation windows. Micro meteorite protection in space is desirable.

5.1.4.3 Further Development Required

Means for the control of lateral conductivity in blanket systems should be investigated thoroughly. Some patented methods for interrupting the conductive medium have been described in the literature and further development along this line is indicated. Better vacuum jacket suspension methods and blanket support mechanisms are also needed, to prevent the compression effects mentioned earlier. Metal shrouds have been used for this purpose, but they add a weight penalty.

5.1.4.4 Support Systems

The best support systems for use with blankets are again the low conductivity tension members. The reader is referred to "NASA 37"* of the Bibliography/Synopsis/Category report of this contract for a description of these and thermally decoupled support systems for orbital use.

5.1.4.5 Maintenance and Reliability

Blankets are easily maintained although system repair must be accomplished on a modular basis. This leads to higher cost if module inventory must be maintained. Generally, the system is reliable, with mounting failure probably the most likely failure mode. Accordingly, the simplest most rugged mounts are desired. Rope suspension systems are usually more reliable than bonded fasteners since the structural member can be anchored solidly.

5.1.4.6 Limitations/Compromises

The chief thermal limitations of blanket systems arise from the many penetrations and high lateral conductivity. Seams are necessary for evacuation and can be closed satisfactorily. The system is compromised chiefly by the many holes put through it.

*All references are reported in the form used in the Bibliography/Synposes/Categcry report.

5.1.5 Continuous Coated Reflectors with Net Spacers

The functional element of this system is a continuous wrapped segment of doubly aluminized Mylar, with nylon net spacer.

The net material is typically of monofilament construction. The doubly aluminized Mylar has been described previously.

This system is intended for small ($< 5\ ft^3$) tankage and is applied to the tank by hand wrapping. The first layer of net is anchored to tank fixtures and the Mylar is secured to the net by hand stitching as the task proceeds. The net is actually the structural element of the system. Adhesive tape and extensive tucking are used to force the material to conform to the tank shape. It is mandatory that noncontaminating gloves be worn by the installers when handling these materials.

Penetrations are accommodated by cutting and patching the material as they are encountered. It is obvious that a high caliber of workmanship must be maintained throughout this operation. For this reason, continuously wrapped tankage exhibits variable performance and generally poor repeatability.

The system must be evacuated during ground hold, if the cryogen is to be preserved past launch. Since the layers trap gas very well, one seam is left

to allow gas to vent to the evacuation ports. The seam must be well patched and sealed before the vacuum jacket is installed. Vacuum jackets for small tanks are relatively easy to maintain, so that the evacuation of this system is generally accomplished quite reliably.

5.1.5.1 Merits

For small tankage, with unfavorable surface to volume ratio, continuous reflector systems provide the best thermal performance attainable. Lack of seams is in part responsible for this. The system is very lightweight since little structural material is involved. The system is easily evacuated and thus moves to the space environment with little or no loss of operating capability.

5.1.5.2 Deficiencies

It is difficult to find two identical continuous wrap systems which exhibit the same performance. This is due in part to the treatment of insulation penetrations, but apparently also to many unknown factors. Lack of structural elements make the material susceptible to damage during boost, when seams and gaps may be opened through relative shifting of the insulation. The installed system is also quite susceptible to handling damage on the ground and must be protected since repair implies stripping the tank and

beginning the installation again. In orbit, micro meteorite shielding should be provided. The evacuation of the system during ground hold proceeds quite slowly, due to the tortuous gas flow paths through the insulation material. Due to the complicated installation, these are the most costly systems, on a comparative basis. Penetration insulation in this system is not standardized and depends critically on workmanship.

5.1.5.3 Further Development Required

There appears to be little that can be done to improve this particular approach to external insulation. Probably only improved materials can make the largest contribution. The major system deficiency which appears prominently in penetration performance, is lateral conductivity. Little can be done at present to alleviate that problem, but it is the one which should be attacked in order to improve all multilayer systems.

Some standardized approach to penetration treatment should be pursued to isolate and identify the influence of insulation parameters not now under control.

5.1.5.4 Support Systems

Only low conductivity support members should be employed with this system, with thermal decoupling in orbit employed if indicated. Of these

systems, tension bands are probably the best supports at present, since their path through the system can be made long and they have small area. Strut type tank mountings, which penetrate the insulation material directly, are to be avoided unless their cross section is very small.

5.1.5.5 Maintenance and Reliability

Maintenance and repair of continuously wrapped systems is confined to the evacuation jacket. Fortunately, with careful handling, the system is comparatively reliable.

5.1.5.6 Limitations/Compromises

Although these systems exhibit excellent thermal performance, they are expensive, difficult to install, and mechanically unsound. Their otherwise excellent performance is compromised mainly by penetrations and other indeterminate factors.

5.2 Parametric Study

5.2.1 How to Use the Parametric Curves

The following types of parametric results have been computed, and are displayed in graphical and tabular form in this section:

1. Curves showing the temperature distribution and heat leak (Q) for some selected cases of penetration piping.

2. Curves showing the heat leak which can be expected for the five chosen external insulation system types:

   a. on the ground

   b. at the end of transition to evacuated (space) performance

   c. in space

   d. for various tank volumes

   e. for hydrogen or oxygen

   f. for various insulation thicknesses

   g. for various tankage L/D ratios

3. Given in tabular form are mechanical parameters such as:

   a. tank type (sphere; cylinder, spherical heads)

   b. tank weight

   c. insulation system weight

   d. support number and size

   e. pipe identification, number, and sizes

   f. tank dimensions

   g. tank area

The curves are oriented in sections by type of insulation system. One merely has to identify the type of system whose performance he desires to

inspect. Upon turning to the section dealing with that system, he may locate easily the curve or table dealing with the aspect of system performance he desires. Values for the points plotted are shown in the tables. Other values may be read from the curves, or found by interpolation between curves.

An example will easily show how this process can be used:

The rate of heat transfer to a 4000 cubic foot fiberglass insulated oxygen tank operating in space is desired. Turning to page 84 one finds the proper graph. The values from that graph show 1800 Btu/hr, 1300 Btu/hr, and 1050 Btu/hr for fiberglass thicknesses of 1, 2, and 3 inches respectively. On the preceding page, one finds the heat leak while the tank sits waiting for launch: 9.5×10^4 Btu/hr, 4.5×10^4 Btu/hr, and 3.3×10^4 Btu/hr, again for 1, 2, and 3 inch insulation. The mechanical parameters of the tank are found on page 107.

5.2.1.1 Summary

The results presented in the next section illustrate the performance characteristics of the five systems when installed on tankage representative of that in common use. The results are <u>not</u> exhaustive, as the scope of the work was limited in time. From the results displayed, one can infer the trend of most items of interest.

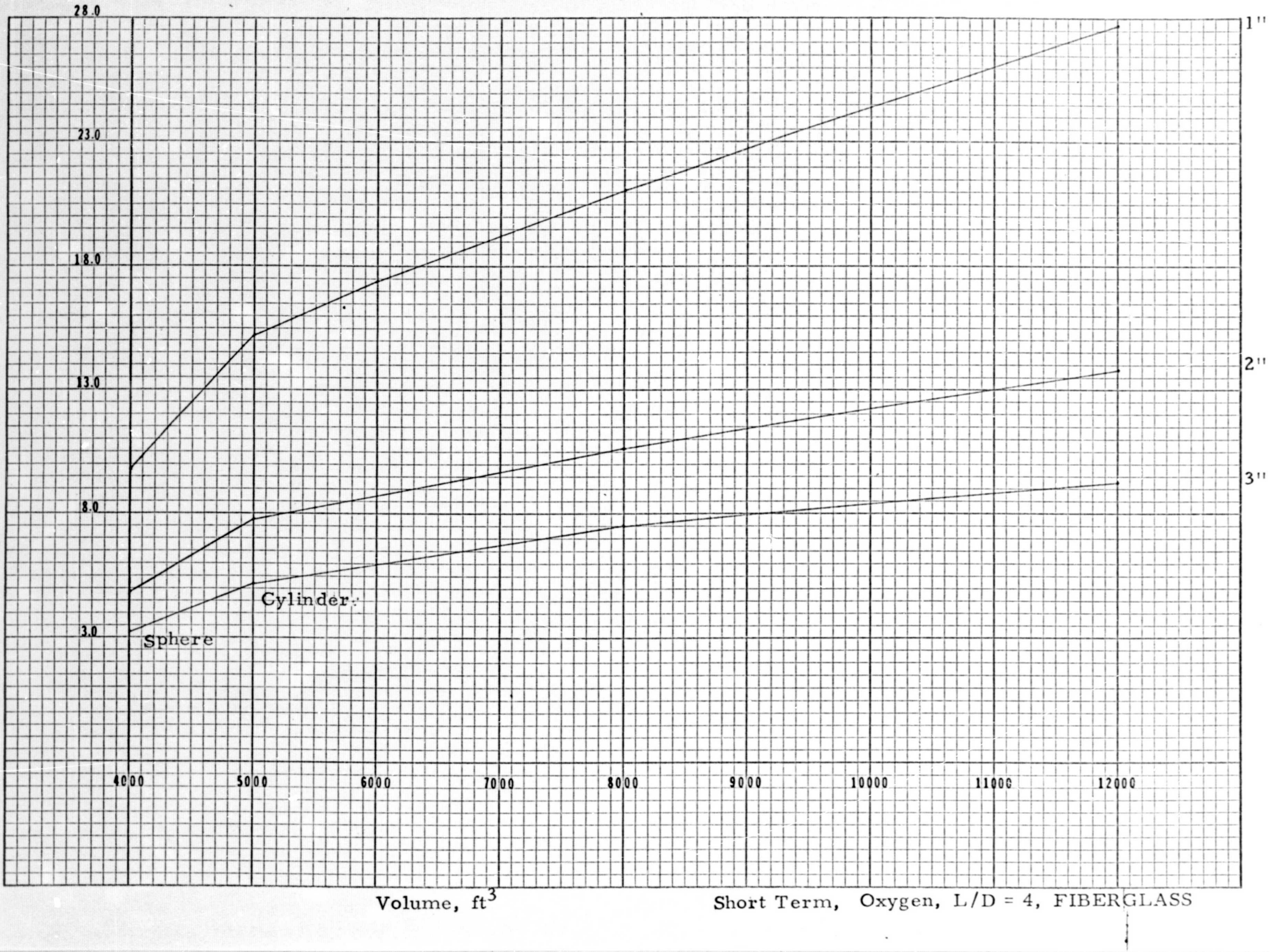
The units of the tables, not repeated there for lack of space, are given here and should be read thoroughly before examining the results.

Tank Type:	1 indicates sphere 2 indicates cylindrical tank with hemispherical ends
Tank Radius:	dimension in feet
Cylinder Length:	length of cylindrical portion of tank, in feet. Spheres have zero cylinder length.
Tank Area:	area in square feet
No. of Supports, I. D., O. D.:	number of supports is self explanatory; ID, OD in inches
No. of Instrument Conduits:	self explanatory
Piping; Fill, Use, Vent:	schedule self explanatory, size is diameter in inches
Volume:	fluid volume in cubic feet
Ullage:	per cent of fluid volume

Use Time:	duration of use in hours
Insulation Thickness:	thickness in inches
Insulation Weight:	total insulation weight in pounds
Loaded Weight:	weight of tank and fluid less insulation, in pounds
Q Space:	space heat transfer rate in Btu/hr.
Q Ground:	prelaunch heat transfer rate in Btu/hr.
Pump Down Time:	insulation evacuation time, hours.

5.2.1.2 Complete Results

K+E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



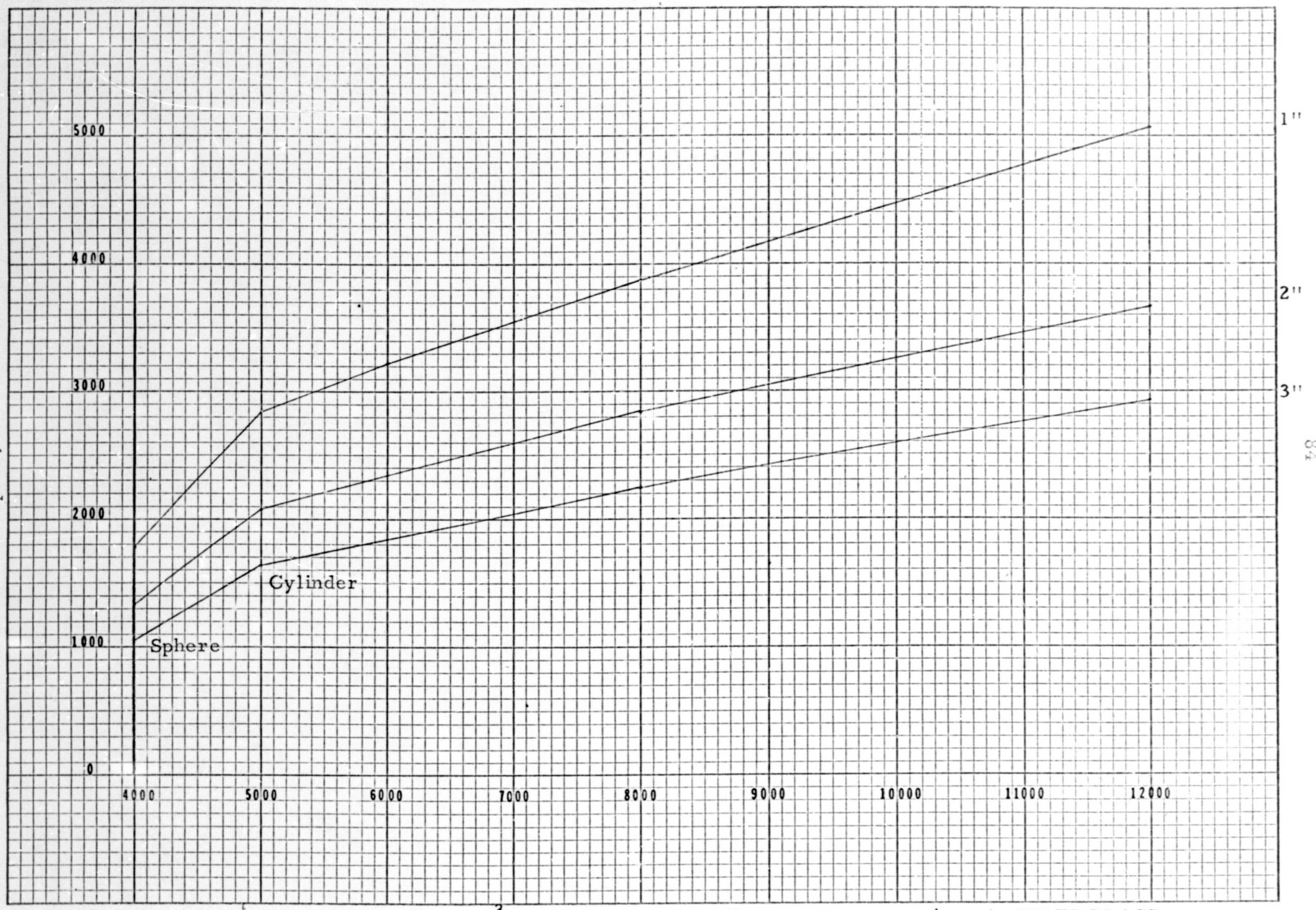
Scale Multiplier: 10^4

Q Ground Hold, Btu/hr

Volume, ft^3

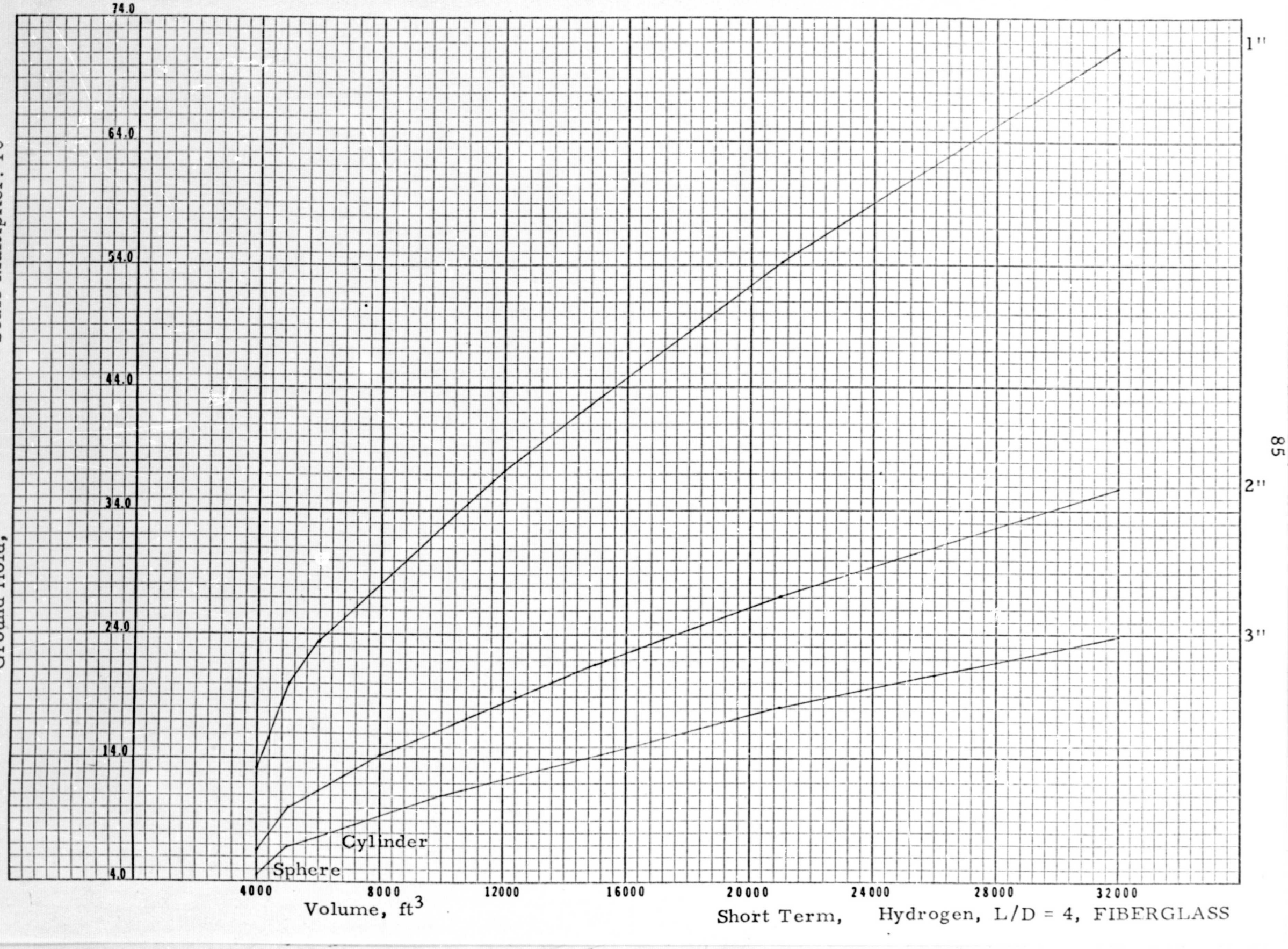
Short Term, Oxygen, L/D = 4, FIBERGLASS

K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

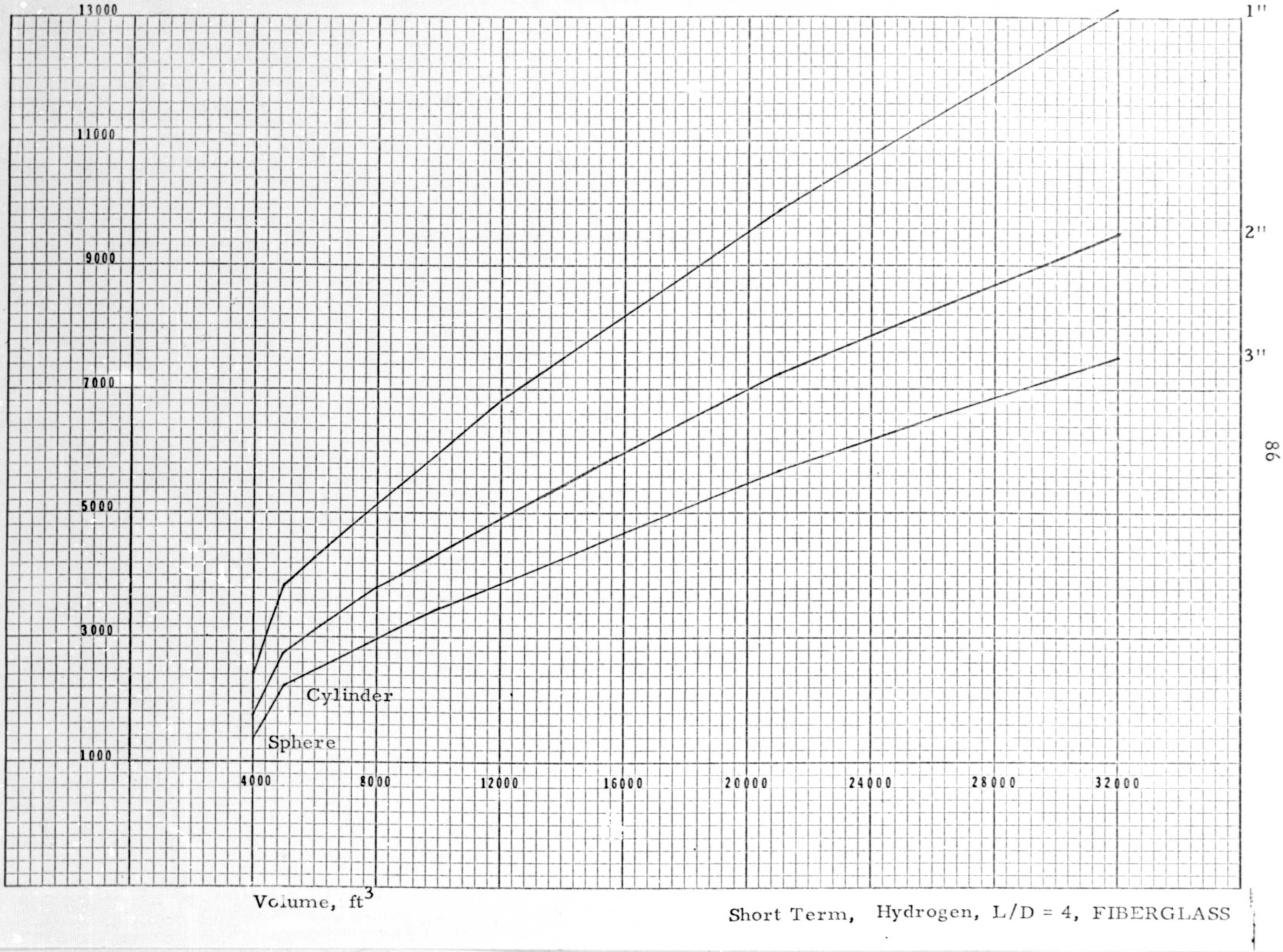


Short Term, Oxygen, L/D = 4, FIBERGLASS

K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

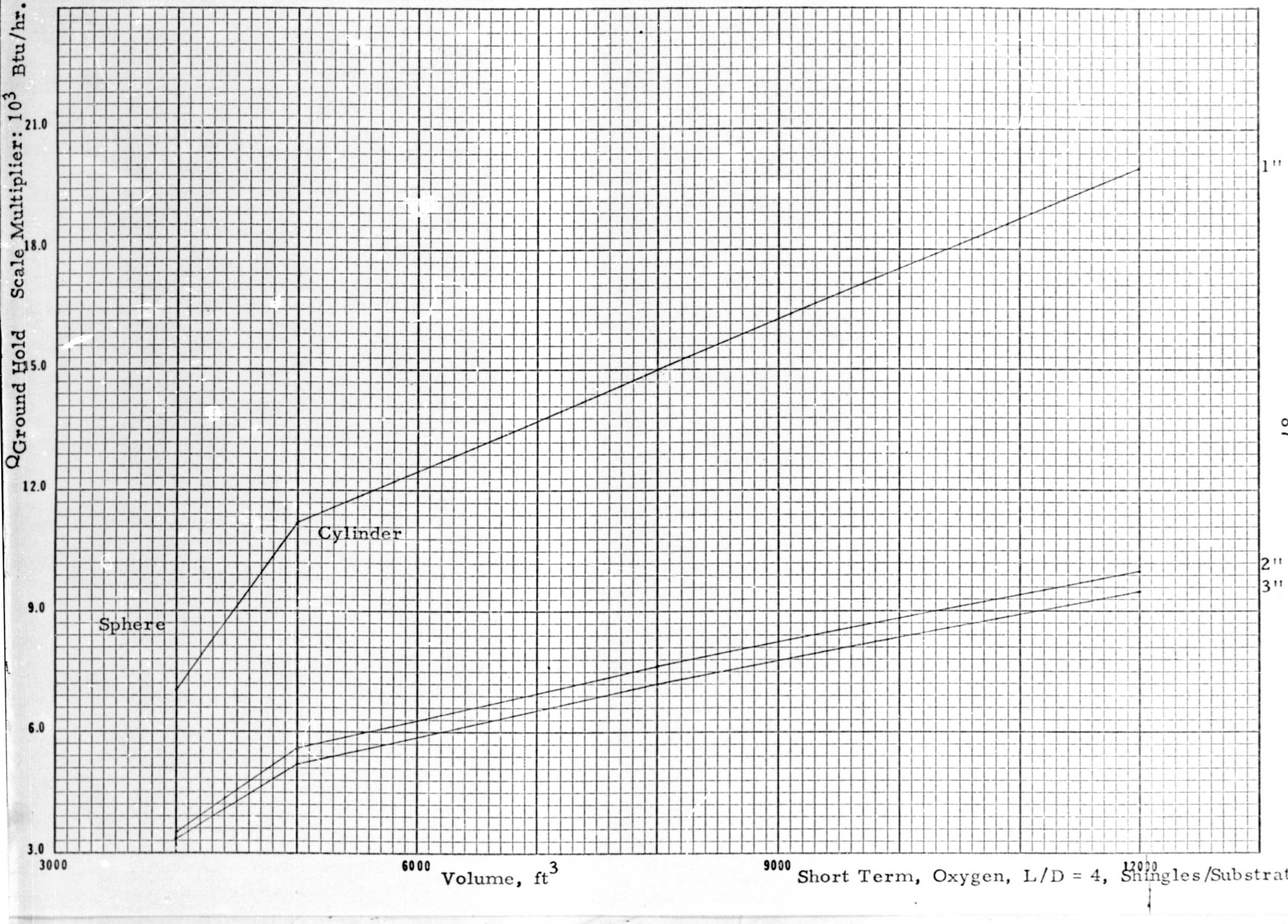


K·Σ 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

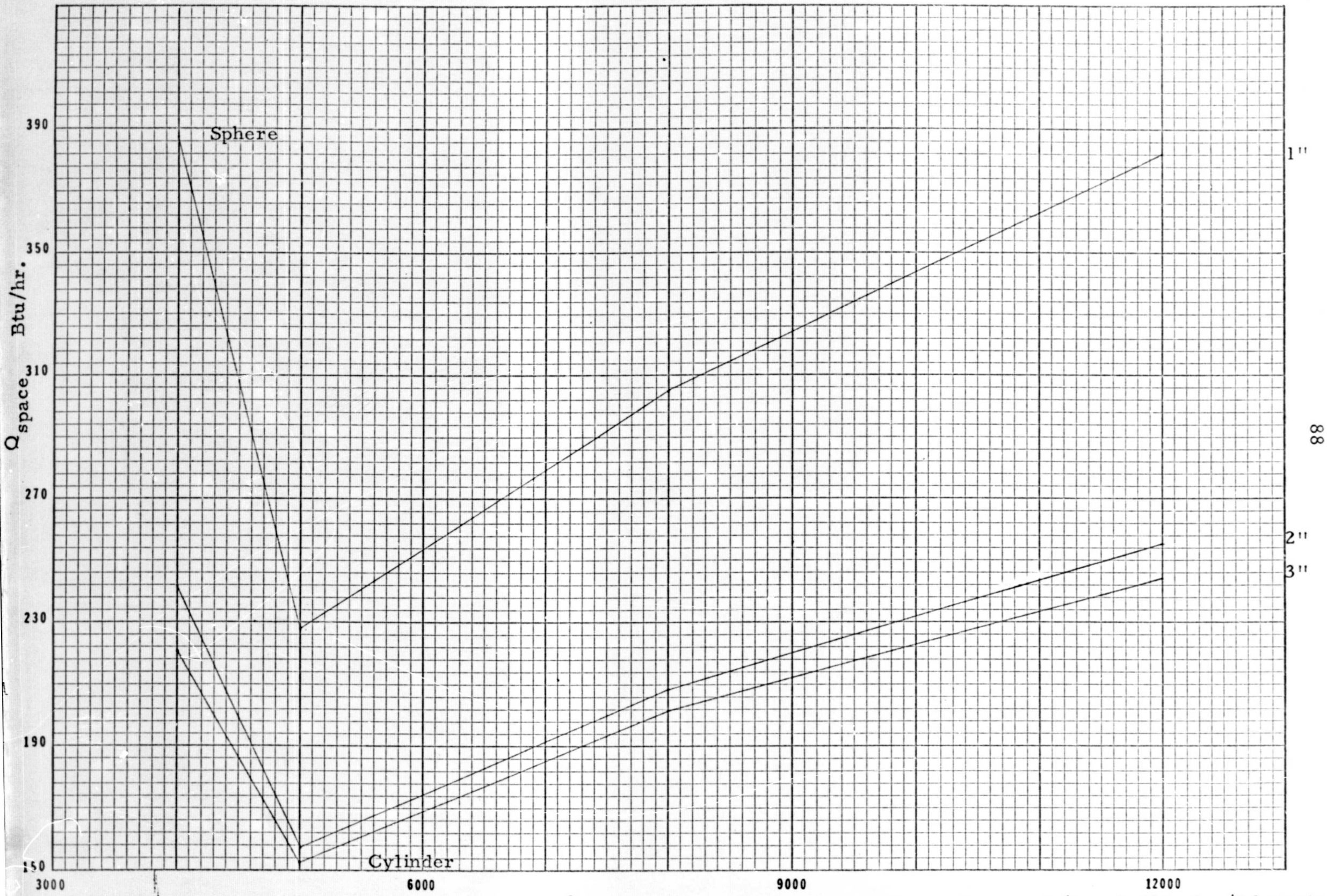


Short Term, Hydrogen, L/D = 4, FIBERGLASS

K+E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

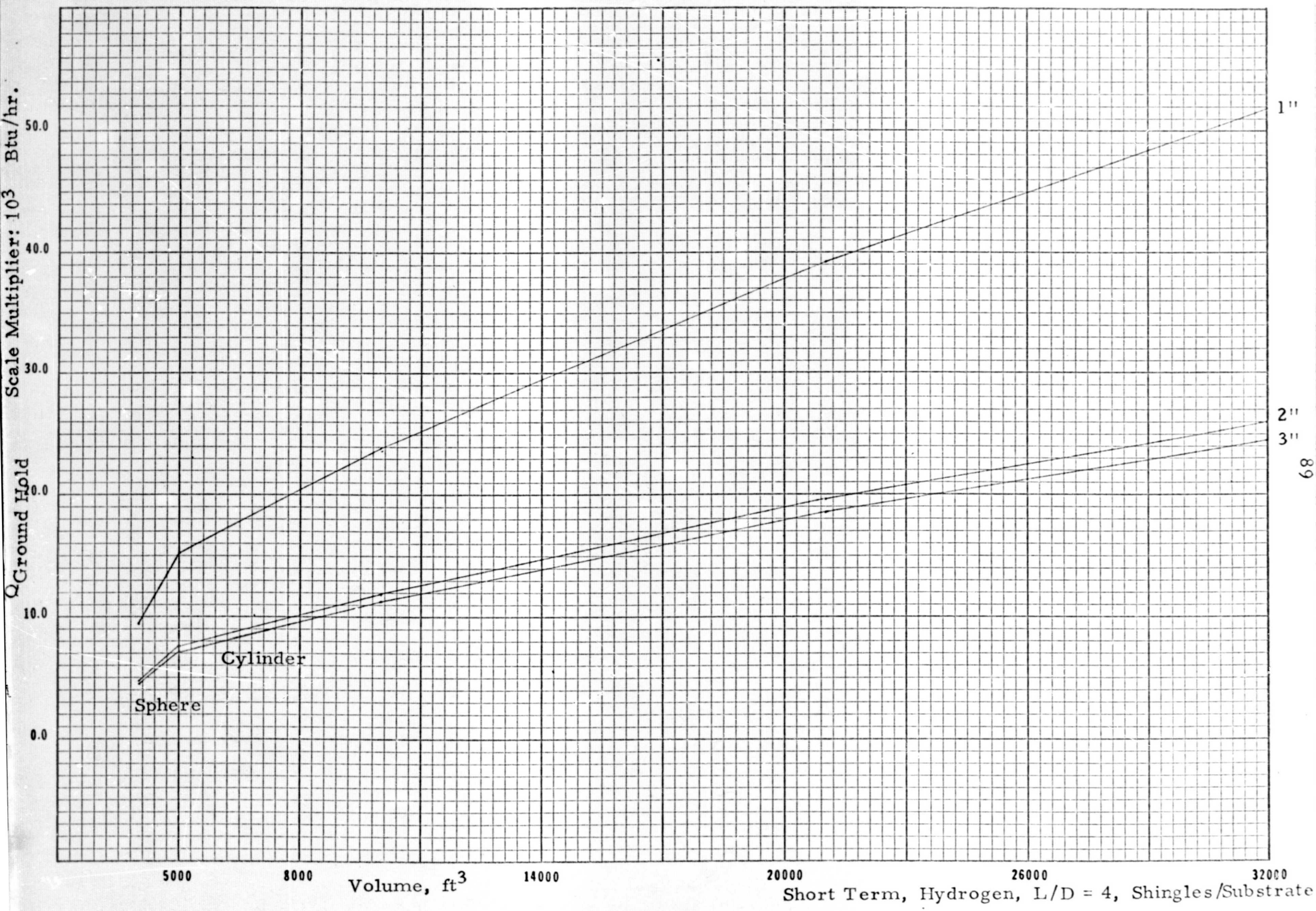


K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

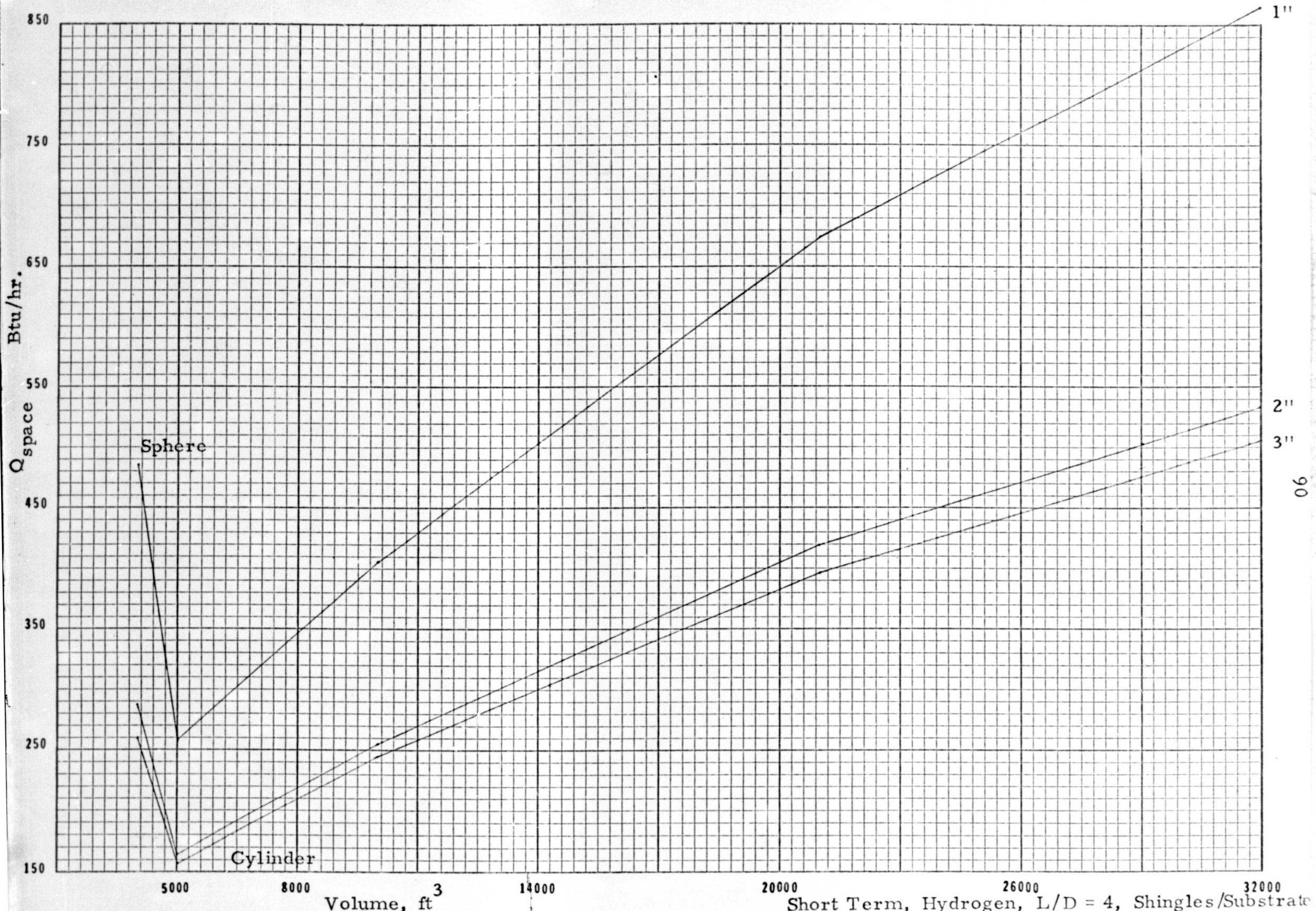


Short Term, Oxygen, L/D = 4, Shingles/Substrate

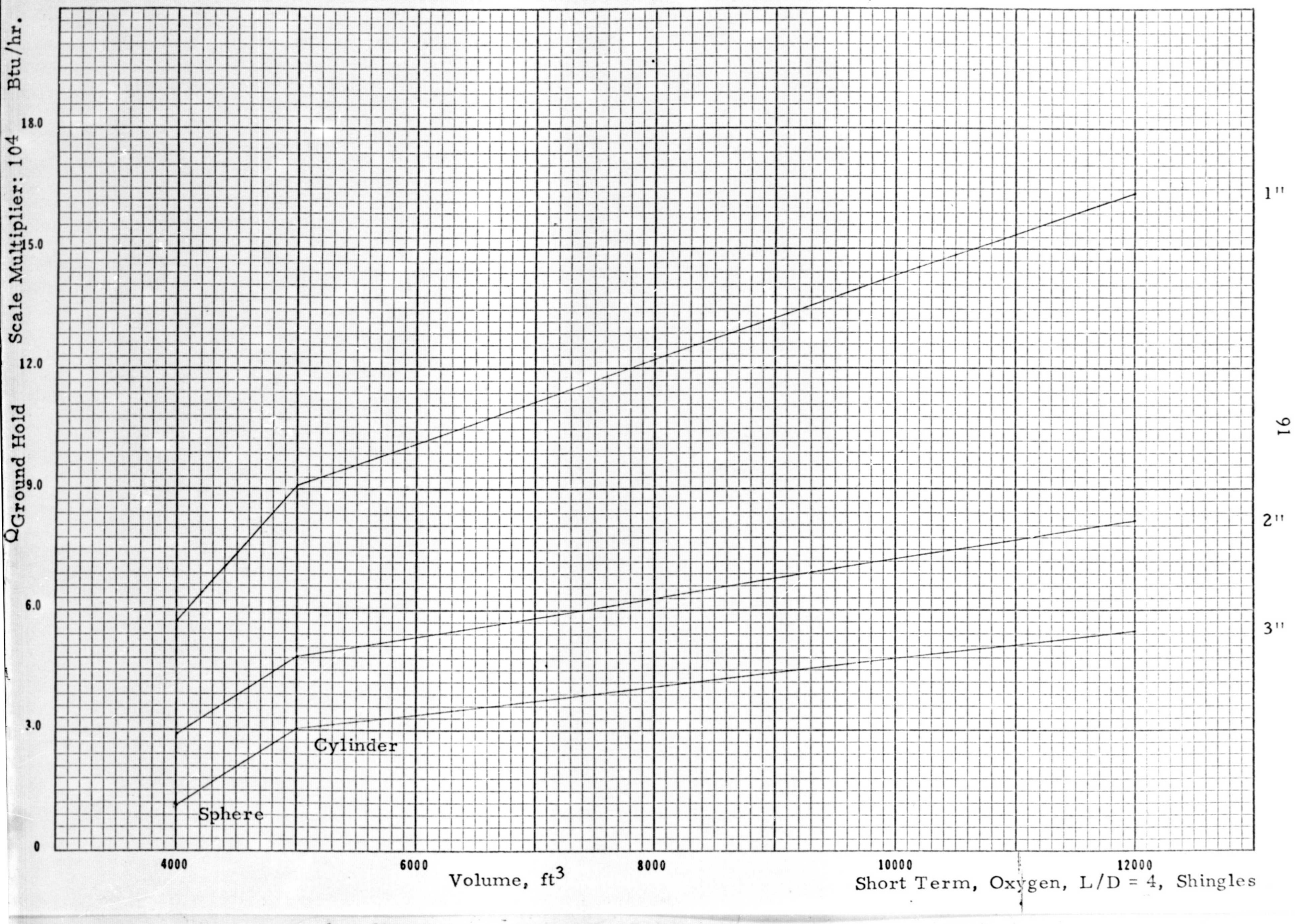
K+E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



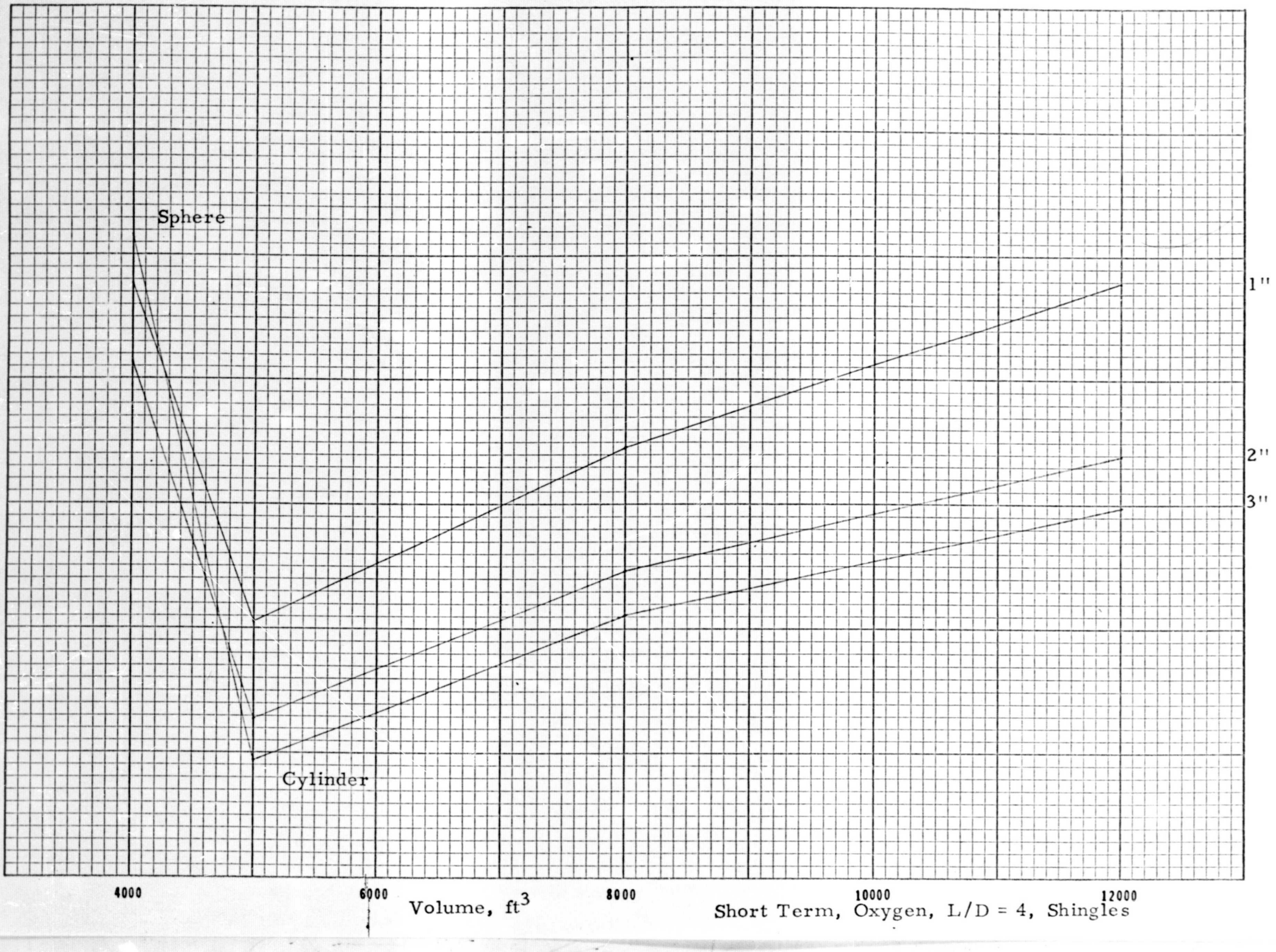
K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

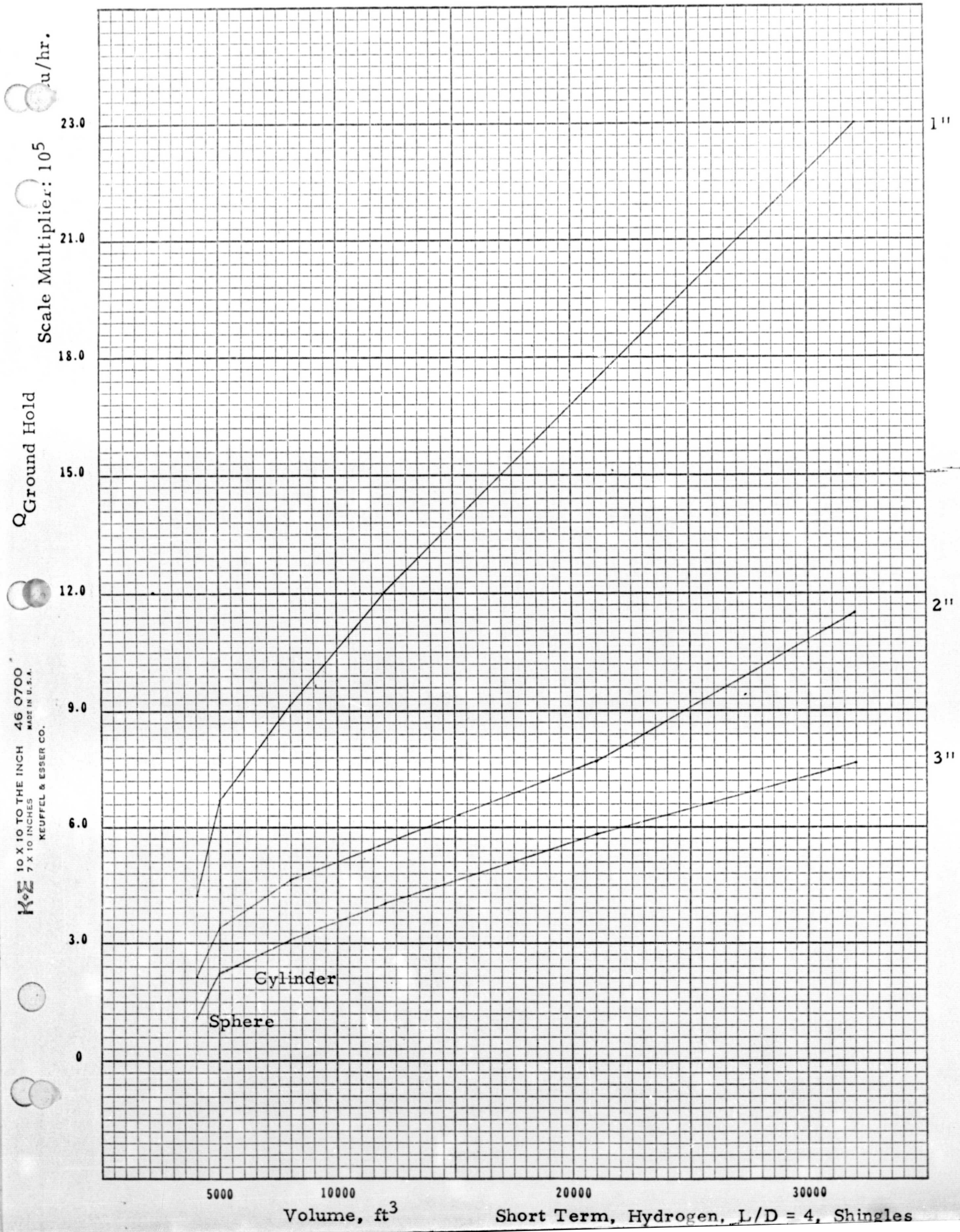


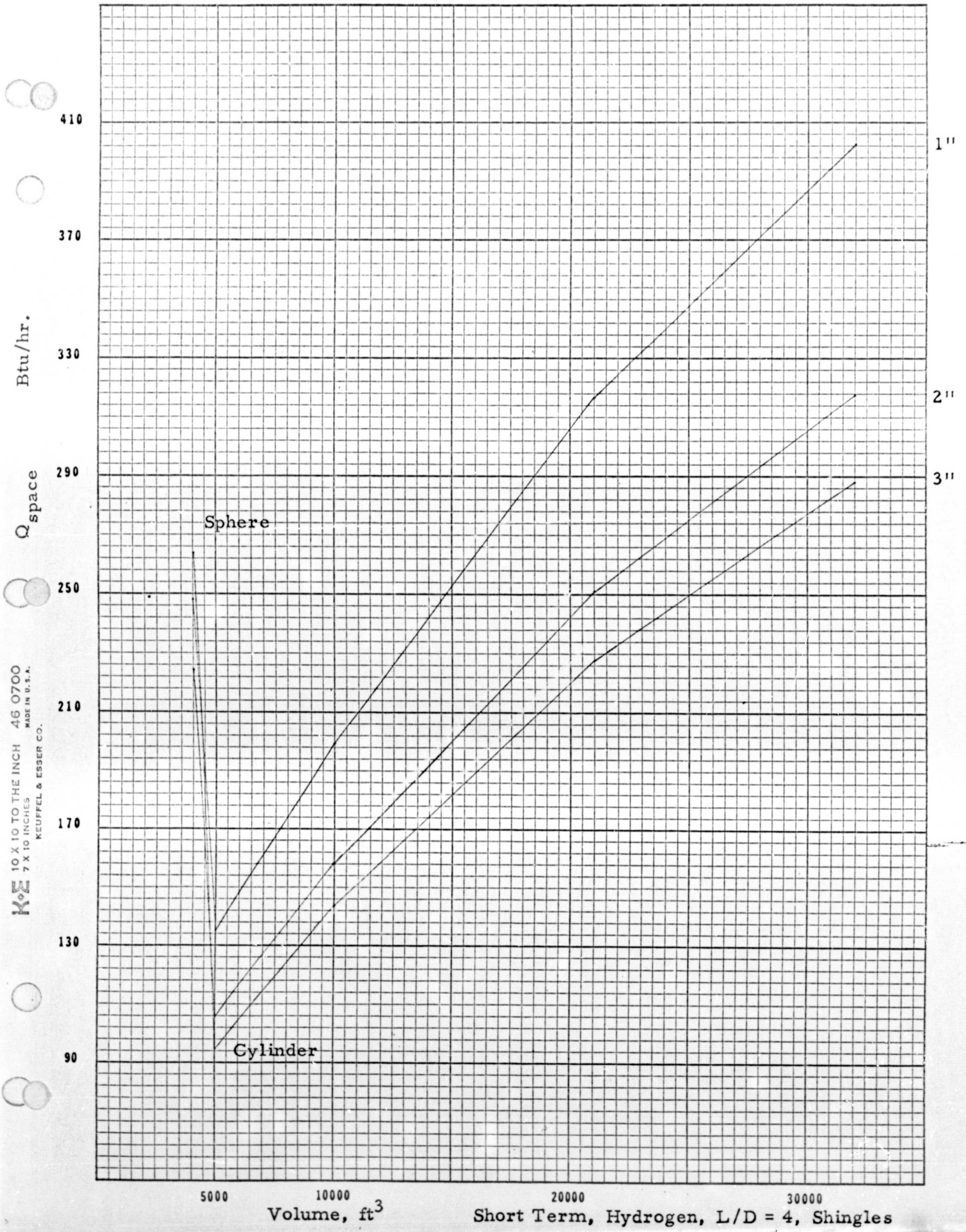
K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



K·E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

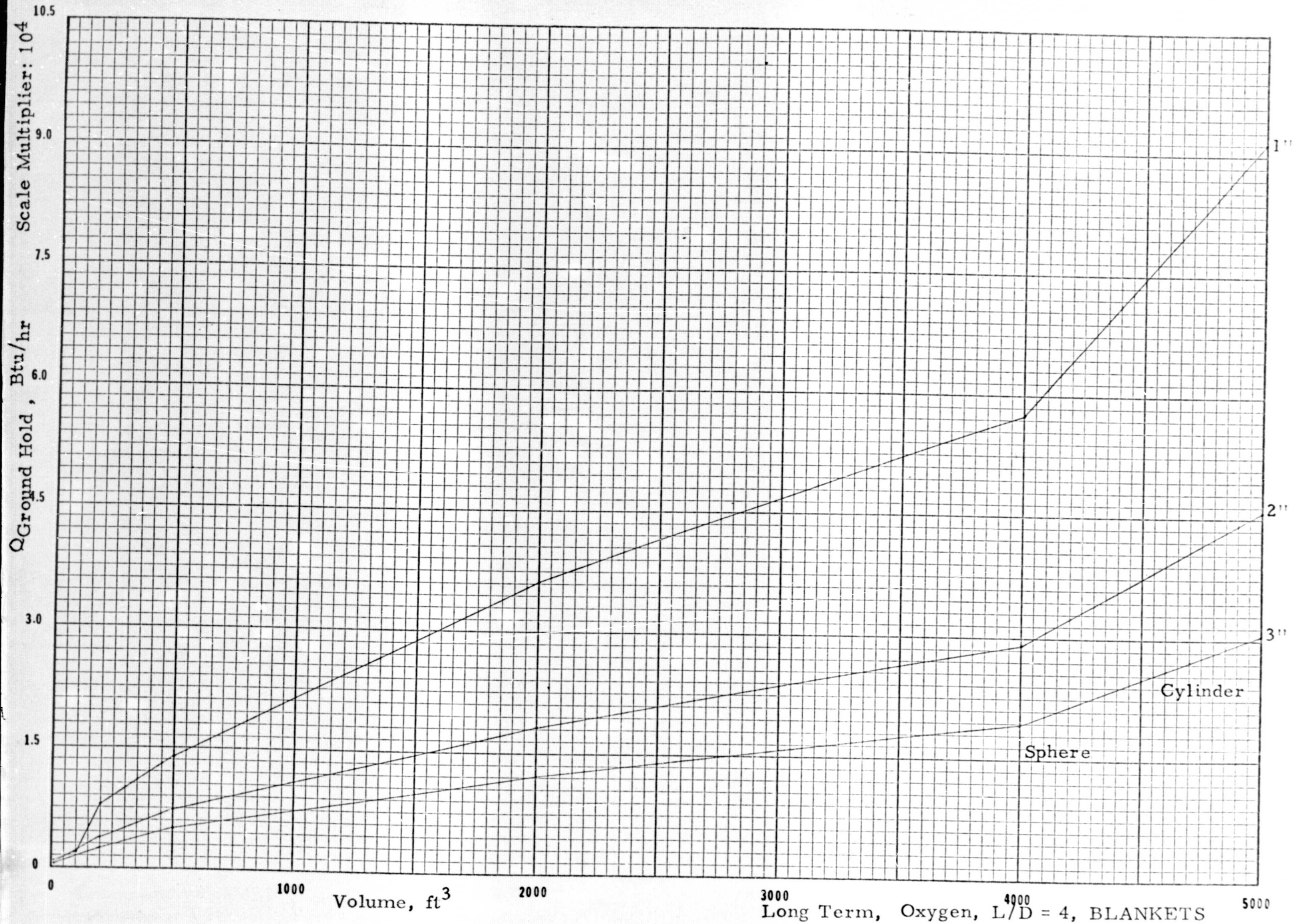



Q Ground Hold
Scale Multiplier: 10^5 Btu/hr.
23.0
21.0
18.0
15.0
12.0
9.0
6.0
3.0
0
1"
2"
3"
Cylinder
Sphere
5000
10000
20000
30000
Volume, ft^3
Short Term, Hydrogen, L/D = 4, Shingles
10 X 10 TO THE INCH 46 0700
7 X 10 INCHES
KEUFFEL & ESSER CO.
MADE IN U.S.A.



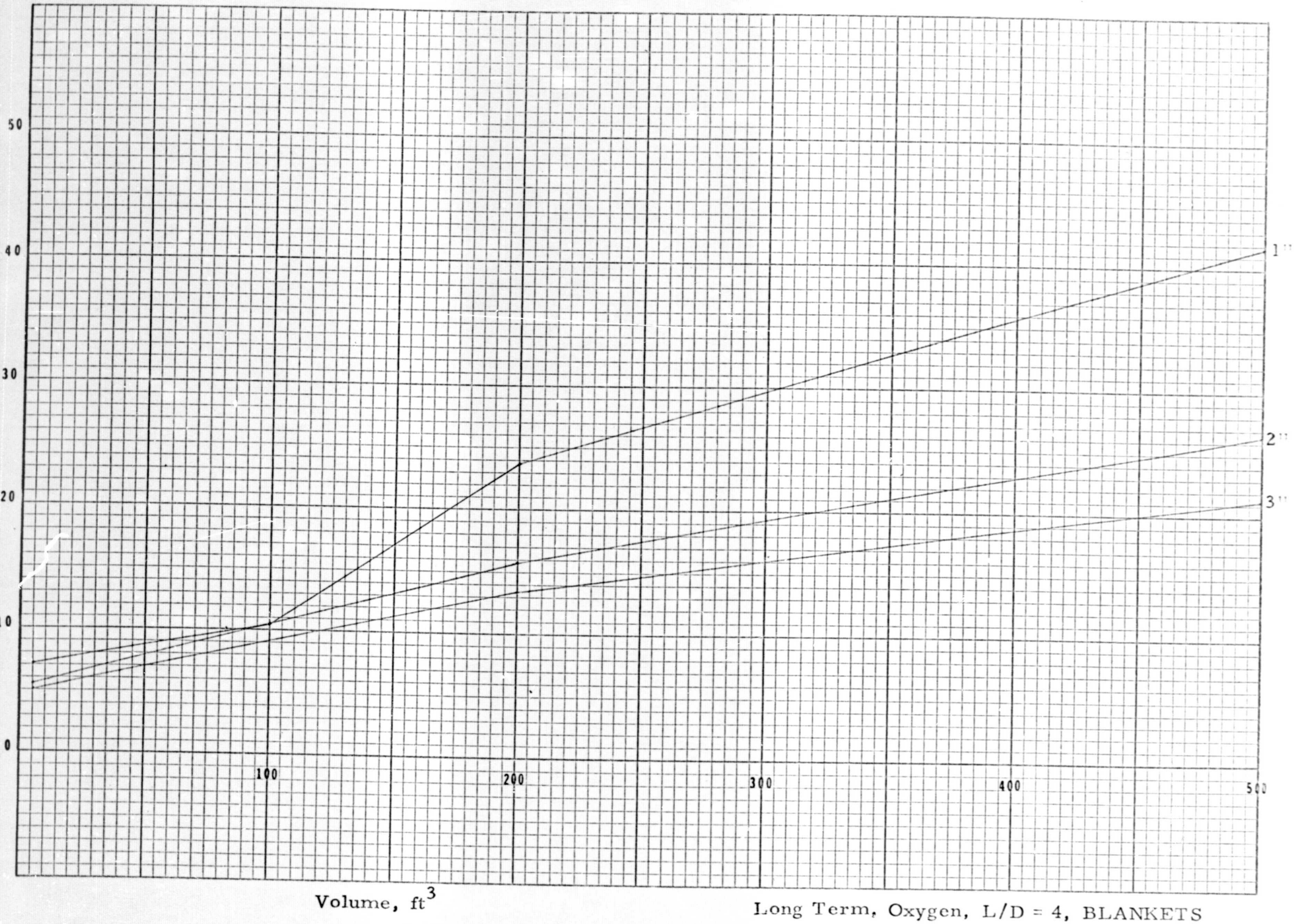
K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

K+E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



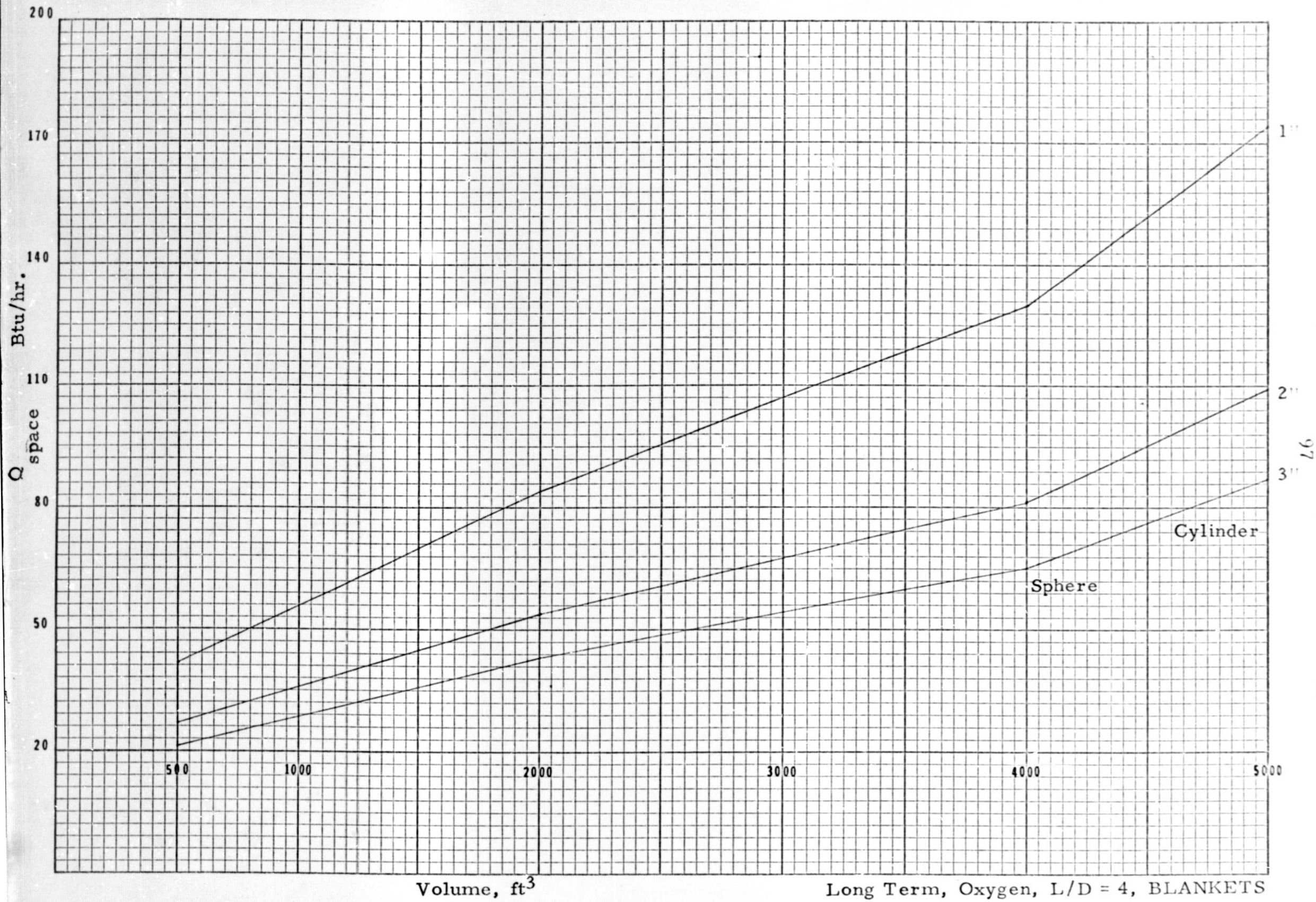
Long Term, Oxygen, L/D = 4, BLANKETS

K+E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



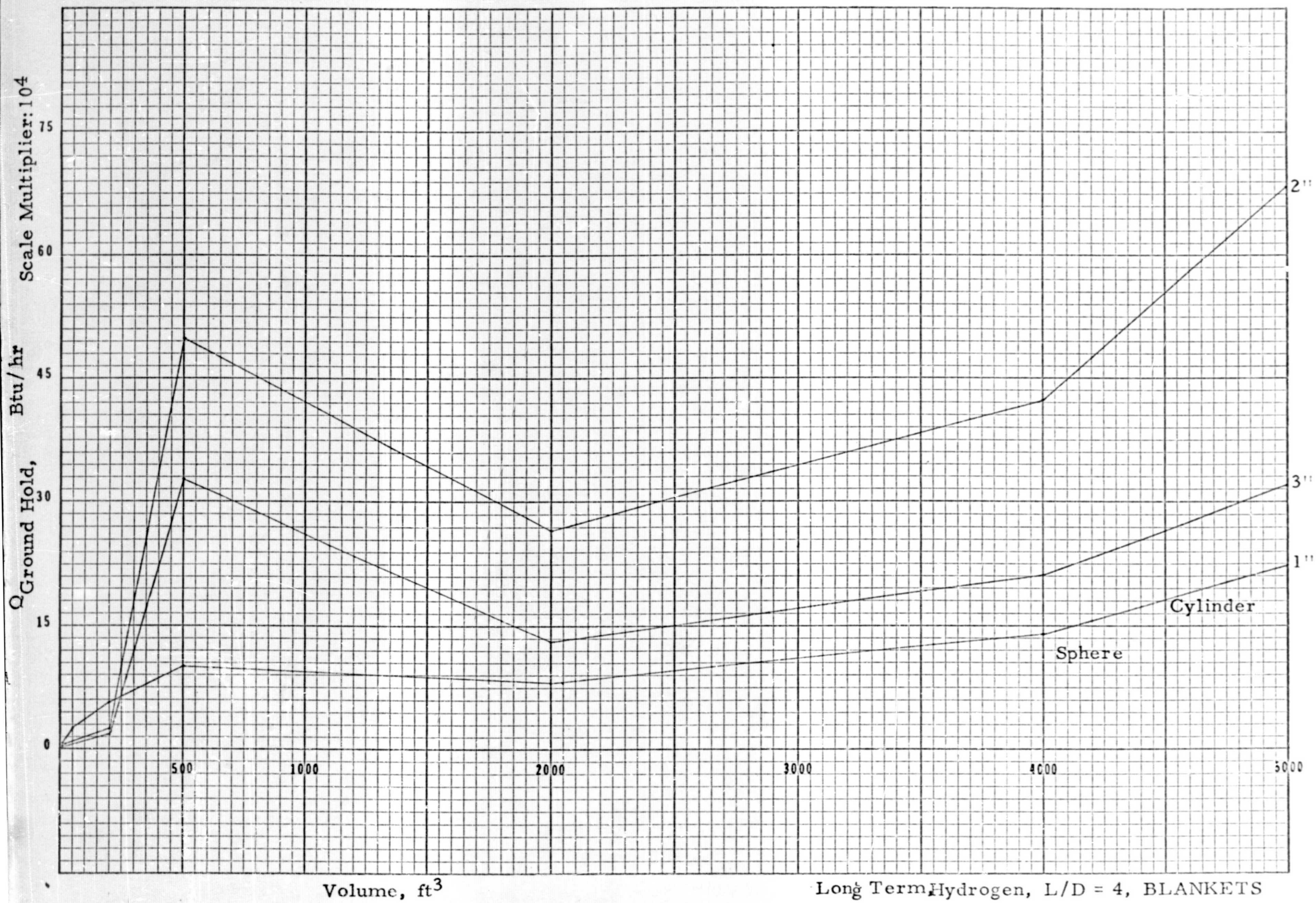
Long Term, Oxygen, L/D = 4, BLANKETS

K+E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U. S. A.
KEUFFEL & ESSER CO.



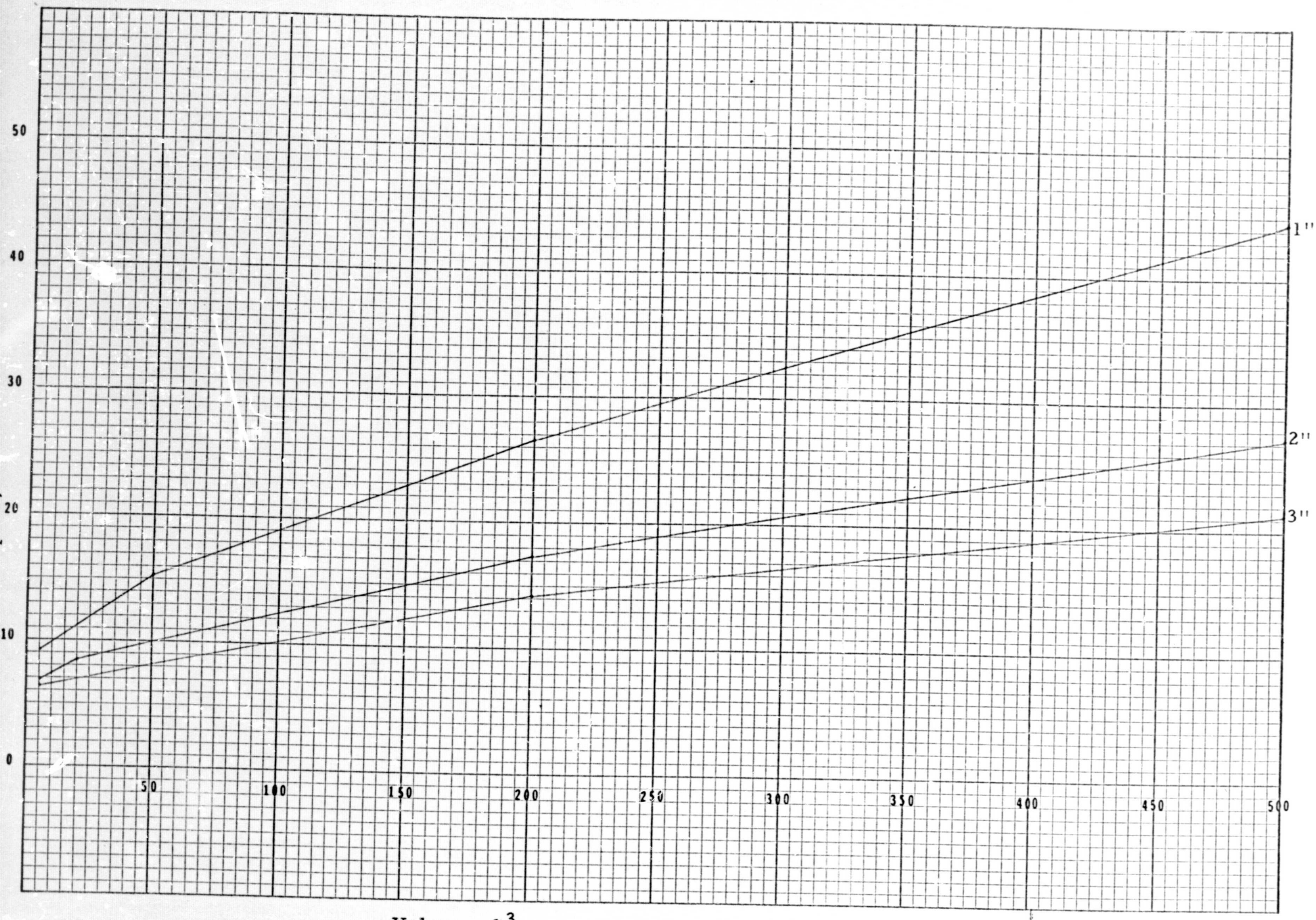
Long Term, Oxygen, L/D = 4, BLANKETS

K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



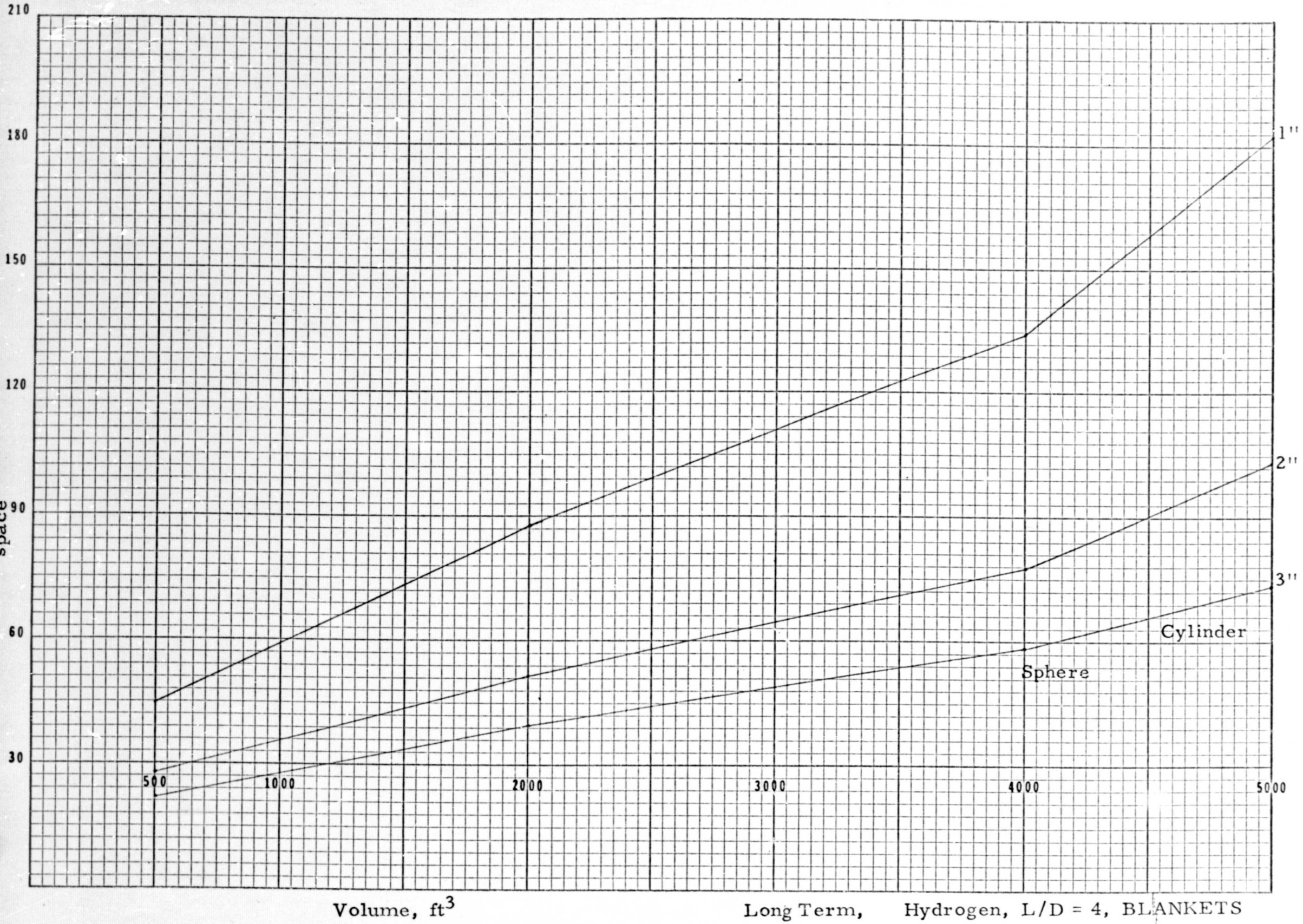
Long Term Hydrogen, L/D = 4, BLANKETS

K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

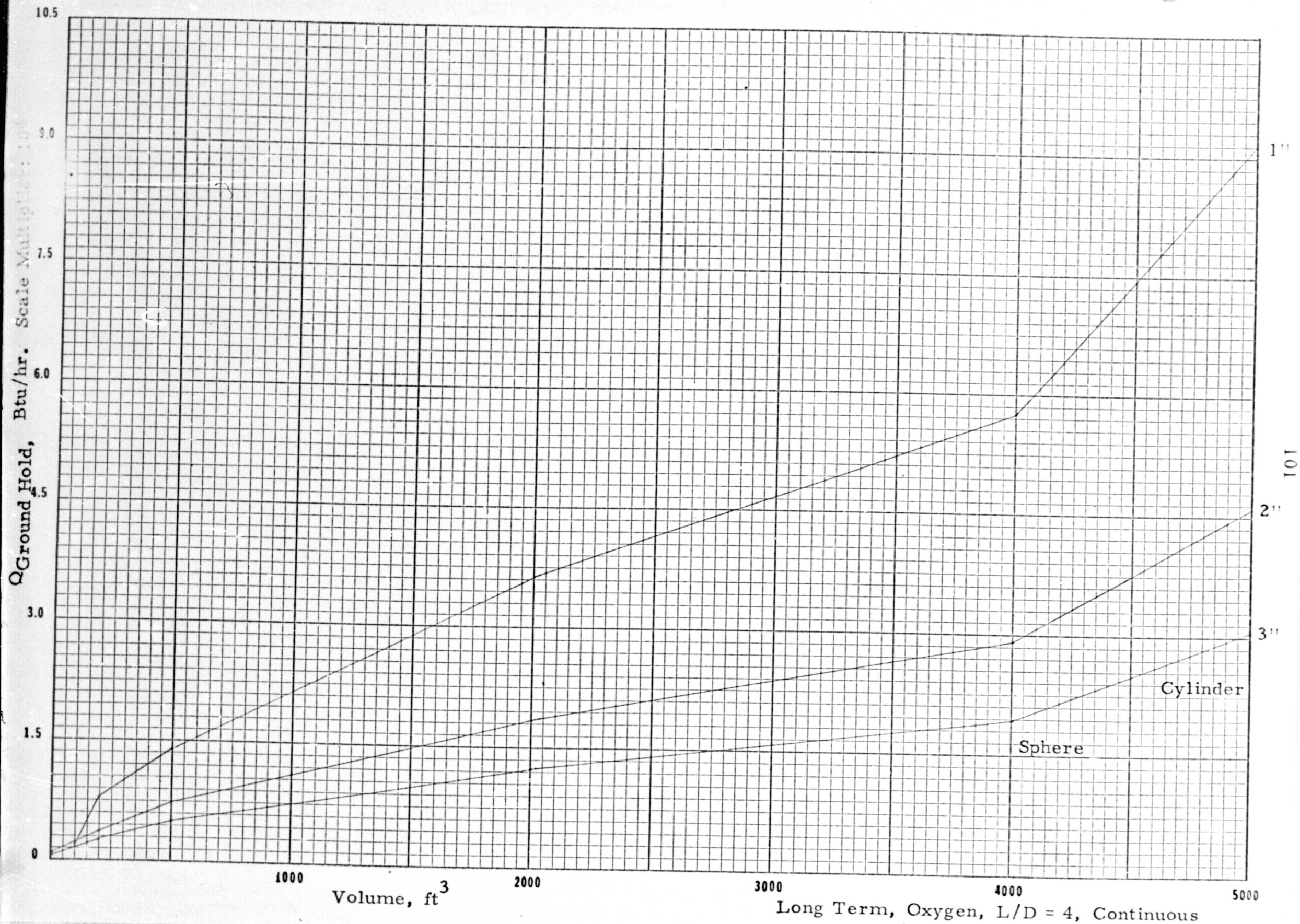


Long Term Hydrogen, L/D = 4, BLANKETS

K+E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

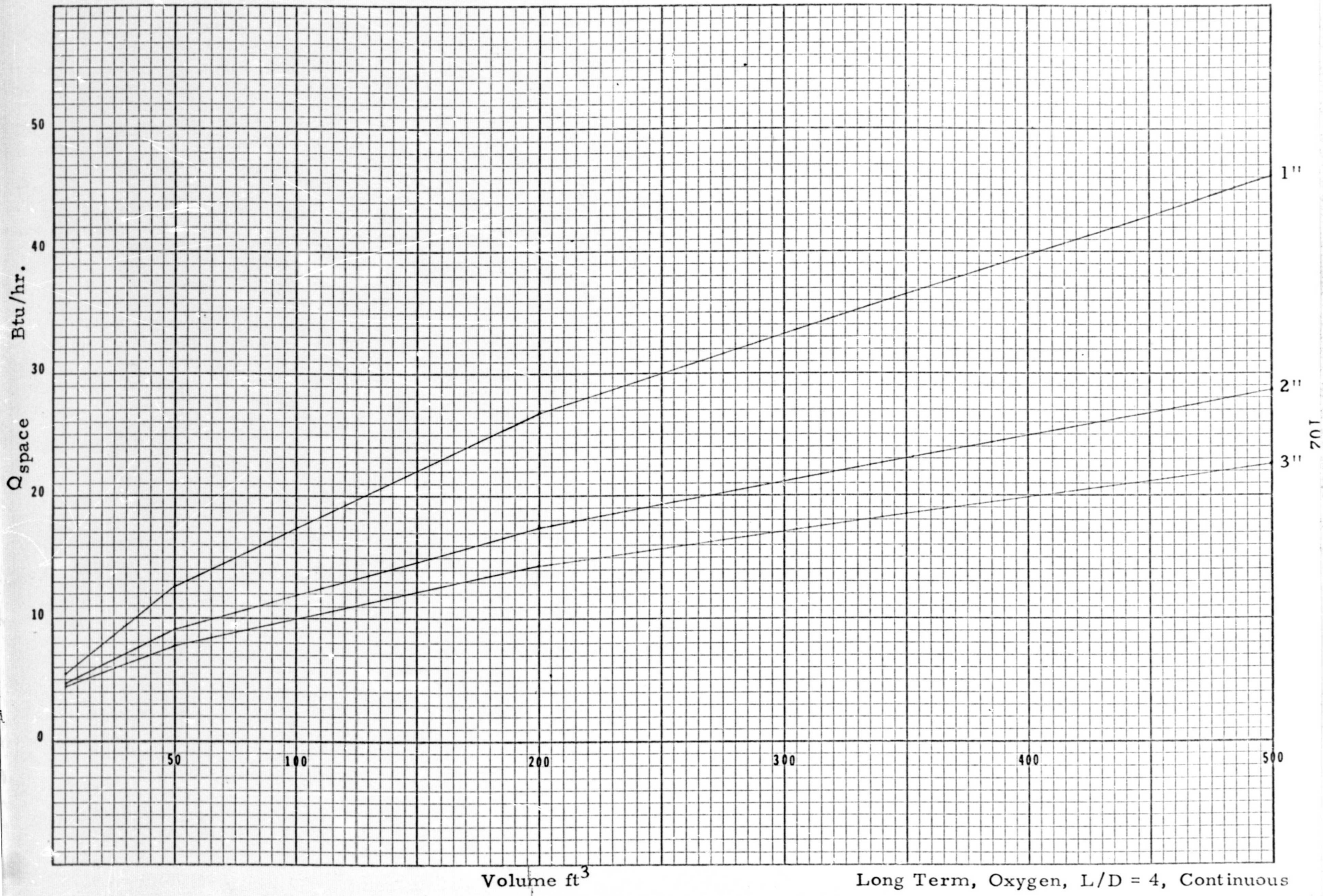


K·E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



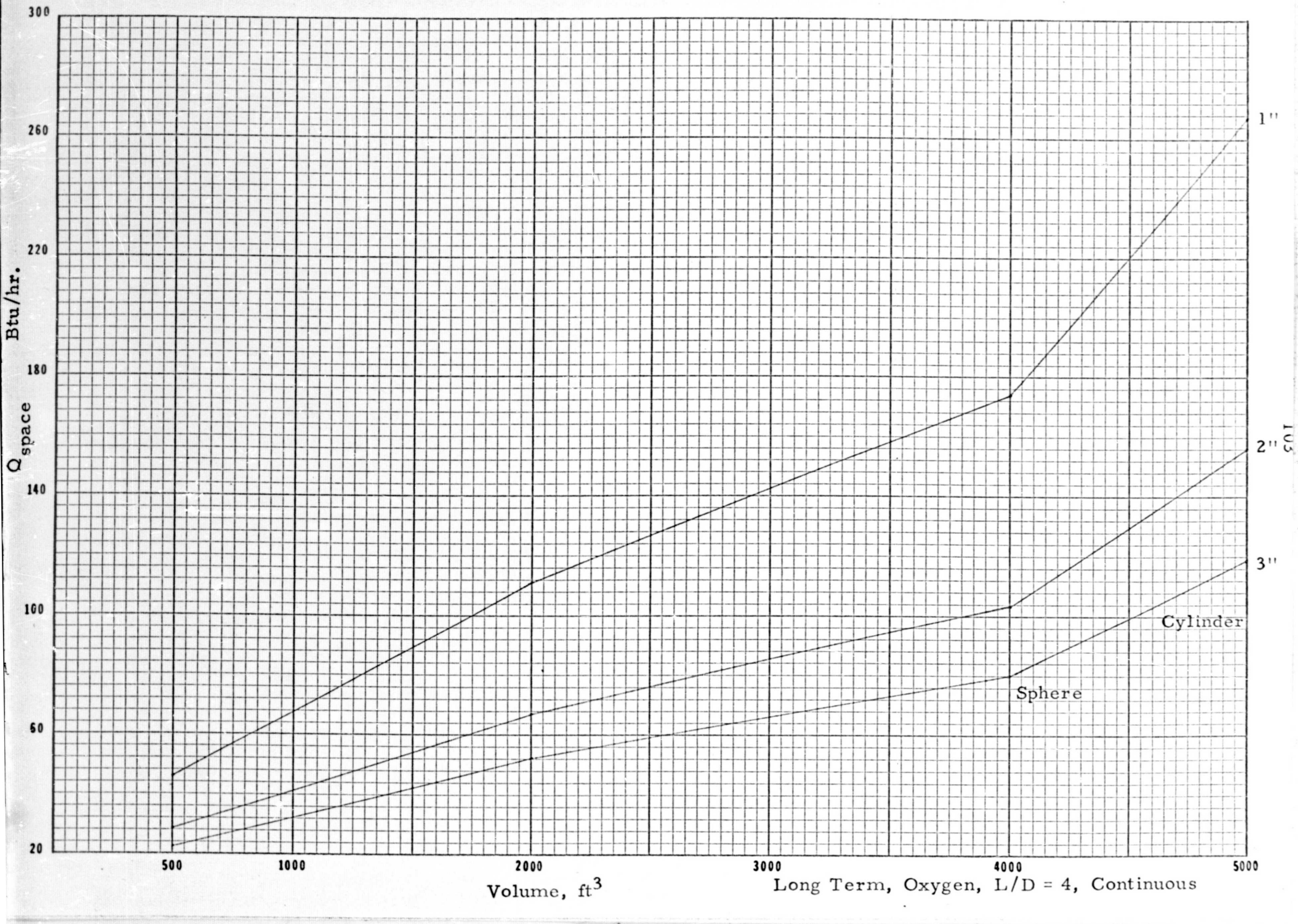
Long Term, Oxygen, L/D = 4, Continuous

K+E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

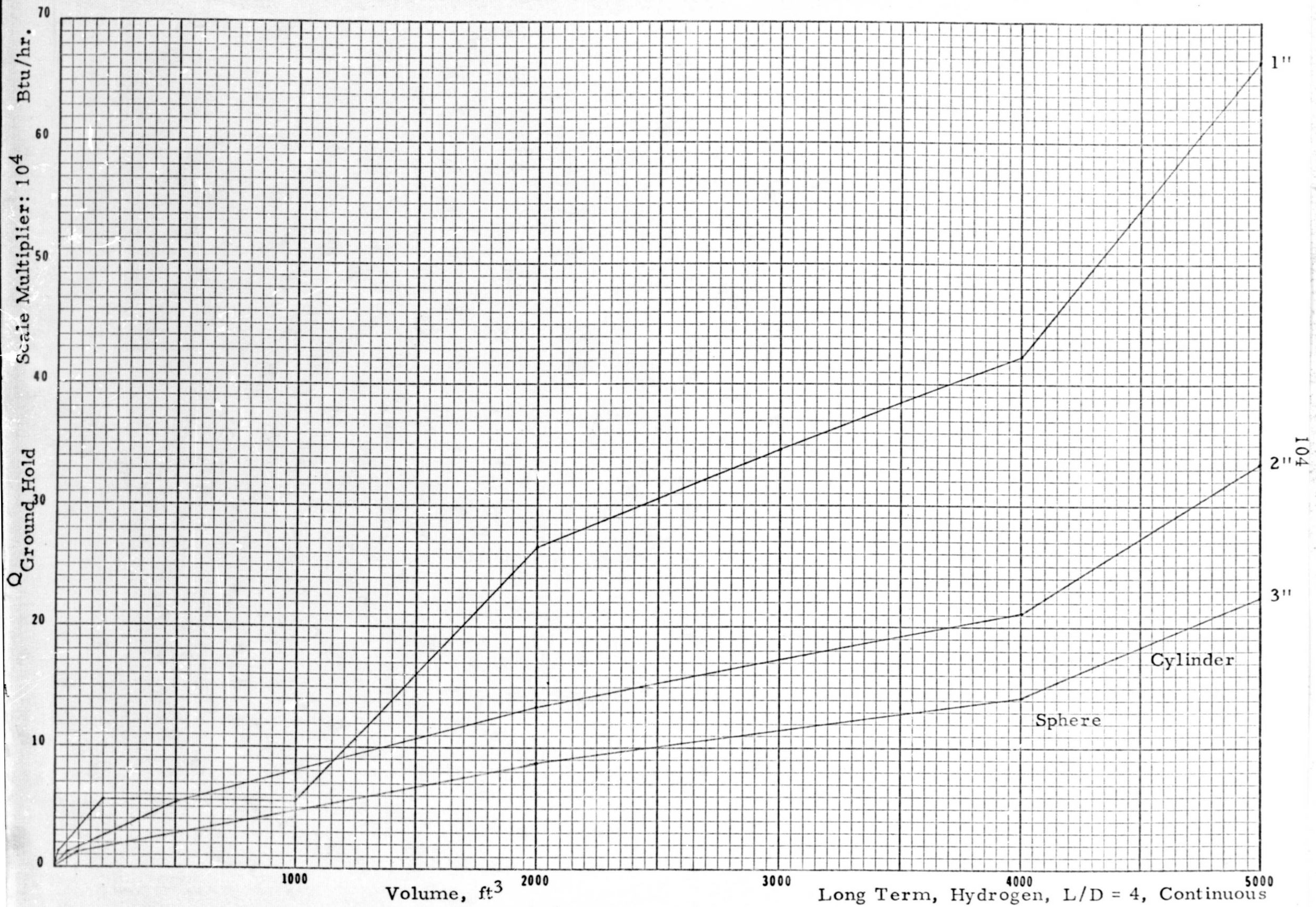


Long Term, Oxygen, L/D = 4, Continuous

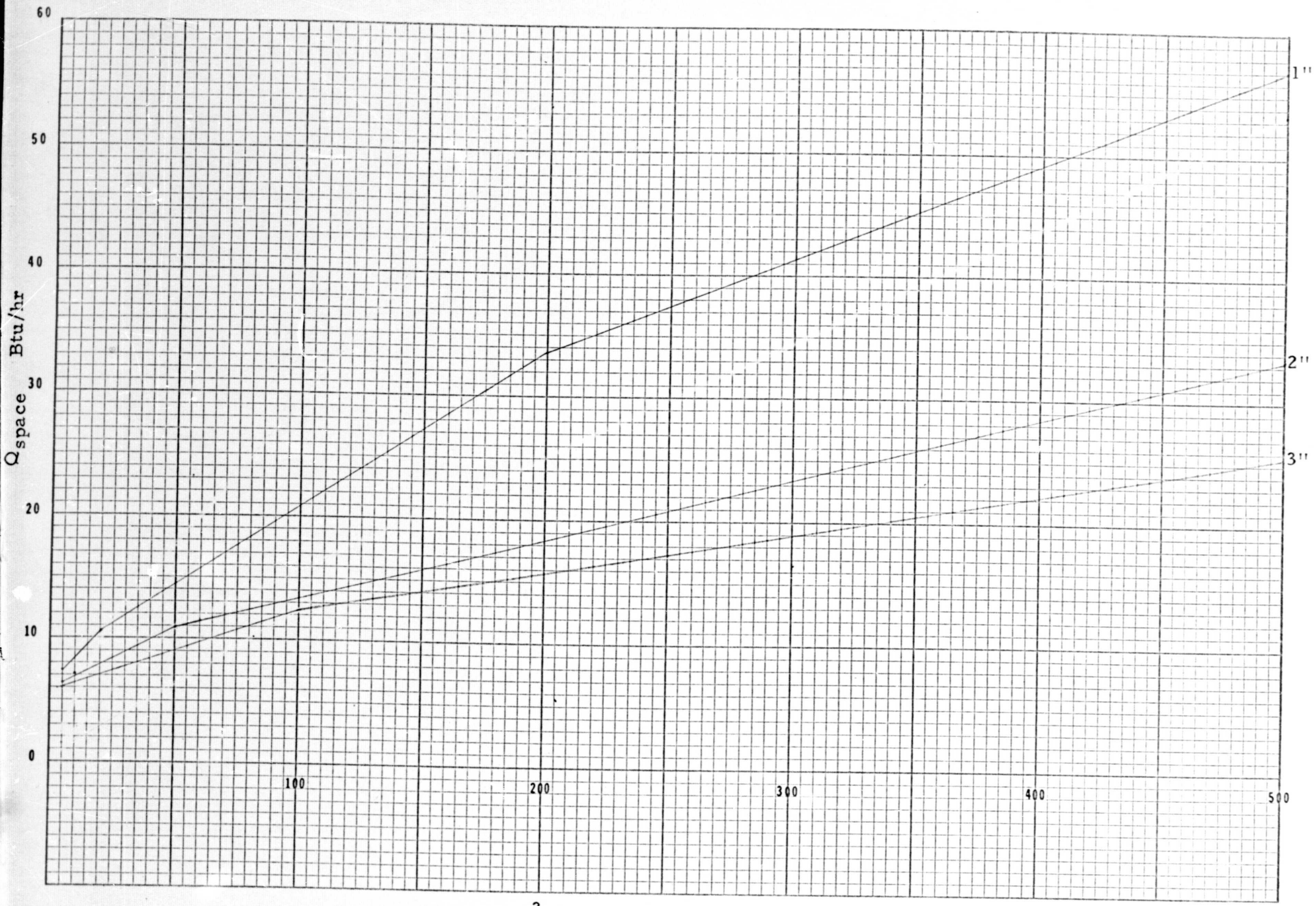
K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



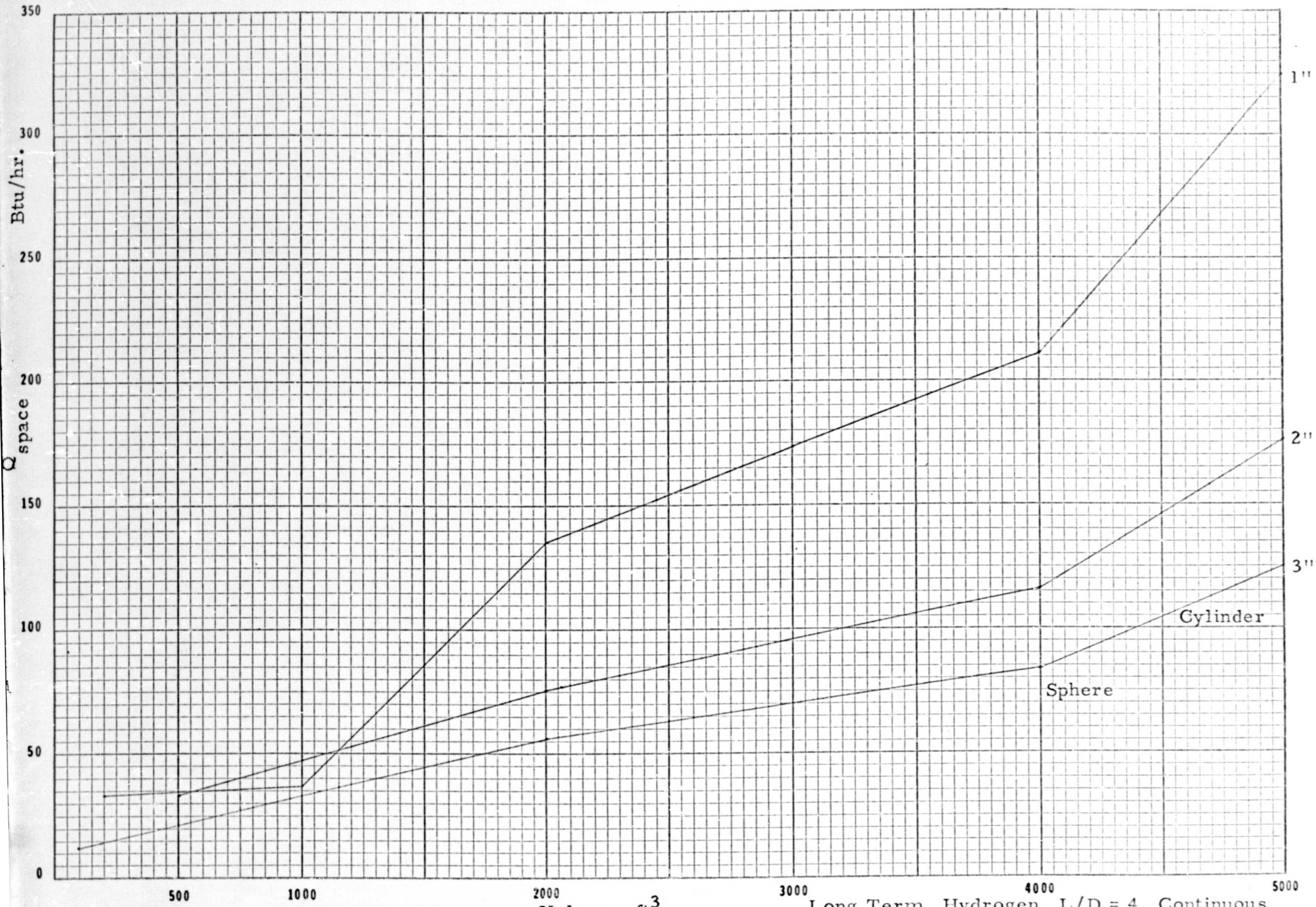
K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



Volume, ft^3

Long Term, Hydrogen, L/D = 4, Continuous

K+E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



Long Term, Hydrogen, L/D = 4, Continuous

INSULATION: FIBERGLASS L/D = 4 Fluid Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	10.2		1298	6	2.63	3.94	1	5	3	5	2 1/2	5	2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
2	5.7	45.9	2058	12	2.95	3.71	1	5	3 1/2	5	2 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"			2324	12	2.86	3.78	2	5	3 1/2	5	2 1/2	5	2 1/2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	6.7	53.6	2815	12	2.68	3.91	"	5	4	5	3	5	3
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"			3267	12	2.48	4.03	"	5	5	5	3	5	3
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	7.7	61.3	3689	12	2.27	4.16	"	5	3 1/2	5	3	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"

INSULATION: FIBERGLASS L/D = 4 Fluid Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
4000	10%	.5	1	121.2	310168	1794	9.75×10^4	19.2
"	"	"	2	229.4	"	1313	4.87×10^4	"
"	"	"	3	337.6	"	1038	3.25×10^4	"
5000	"	"	1	192.1	364810	2844	1.54×10^5	"
"	"	"	2	363.6	"	2083	7.73×10^4	"
"	"	"	3	535.1	"	1646	5.15×10^4	"
6000	"	"	1	216.9	437771	3207	1.74×10^5	"
"	"	"	2		"			"
"	"	"	3		"			"
8000	"	"	1	262.77	583695	3880	2.11×10^5	"
"	"	"	2	497.4	"	2839	1.06×10^5	"
"	"	"	3	732.0	"	2241	7.05×10^4	"
10000	"	"	1		729618			"
"	"	"	2		"			"
"	"	"	3		"			"
12000	"	"	1	344.3	875541	5074	2.77×10^5	"
"	"	"	2	651.8	"	3678	1.38×10^5	"
"	"	"	3	959.2	"	2927	9.23×10^4	"

INSULATION: FIBERGLASS L/D = 4 Fluid Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	10.2		1298	6	3.27	3.42	1	5	2	5	1 1/4	5	1 1/2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
2	5.7	45.8	2058	12	3.32	3.38	1	5	2	5	1 1/4	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"			2324	12	3.31	3.39	2	5	2 1/2	5	1 1/4	5	2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	6.7	53.6	2815	12	3.30	3.40	"	5	2 1/2	5	1 1/4	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"			3267	12	3.29	3.41	"	5	3	5	1 1/2	5	2 1/2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	7.7	61.3	3689	12	3.28	3.42	"	5	2 1/2	5	2	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"			4281	12	3.26	3.44	"	5	2 1/2	5	2	5	2 1/2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	9.2	73.9	5357	12	3.22	3.47	"	5	3	5	2 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"

INSULATION: FIBERGLASS L/D = 4 Fluid Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
4000	10%	.5	1	121.2	35651	2409	1.31×10^5	17.3
"	"	"	2	229.4	"	1762	6.57×10^4	"
"	"	"	3	337.6	"	1391	4.38×10^4	"
5000	"	"	1	192.1	29296	3821	2.08×10^5	"
"	"	"	2	363.6	"	2795	1.04×10^5	"
"	"	"	3	535.1	"	2206	6.94×10^4	"
6000	"	"	1	216.9	35155	4309	2.35×10^5	"
"	"	"	2		"			"
"	"	"	3		"			"
8000	"	"	1		46874			"
"	"	"	2	497.4	"	3811	1.42×10^5	"
"	"	"	3		"			"
10000	"	"	1		58592			"
"	"	"	2		"			"
"	"	"	3	849.4	"	3481	1.10×10^5	"
12000	"	"	1	344.3	70310	6820	3.73×10^5	"
"	"	"	2		"			"
"	"	"	3		"			"
15000	"	"	1		87888			"
"	"	"	2	756.3	"	5777	2.17×10^5	"
"	"	"	3		"			"
21000	"	"	1	500.	123042	9891	5.42×10^5	"
"	"	"	2	946.4	"	7223	2.71×10^5	"
"	"	"	3	1393.	"	5690	1.81×10^5	"

INSULATION: FIBERGLASS L/D = 4 Fluid Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2			6177	12	3.19	3.50	2	5	3	5	3	5	3
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	10.6	85.	7094	"	3.15	3.54	"	5	3	5	3	5	3
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"

INSULATION: FIBERGLASS L/D = 4 Fluid Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
26000	10%	.5	1		152336			17.3
"	"	"	2		"			"
"	"	"	3	1606.	"	6558	2.08×10^5	"
32000	"	"	1	662.1	187489	13090	7.18×10^5	"
"	"	"	2	1253.2	"	9533	3.59×10^5	"
"	"	"	3	1844.4	"	7527	2.39×10^5	"

INSULATION: FIBERGLASS L/D = 2 Fluid: Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2	6.9	27.6	1793	12	2.94	3.71	1	5	3 1/2	5	2 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	9.95	39.4	3730	"	1.88	4.34	2						
"	8.07	32.3	2453	"									

INSULATION: FIBERGLASS L/D = 2 Fluid: Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5000	10%	.5	1	167.4	367669	2478.	1.35×10^5	19.2
"	"	"	2	316.8	"	1788.	6.73×10^4	"
"	"	"	3	466.2	"	1434.	4.49×10^4	"
15000	"	"	2	648.9	1103004	3749.	1.4×10^5	"
8000	"	"	2	433.4		2474.	9.21×10^4	"

INSULATION: FIBERGLASS L/D = 2 Fluid: Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2	6.9	27.6	1793.	12	3.32	3.38	2	5	2	5	1 1/4	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	11.5	44.5	4667	"	3.21	3.48	"	5	3	5	2 1/2	5	2 1/2
"	12.8	51.2	6181	"	3.14	3.55	"	5	3 1/2	5	3	5	3

INSULATION: FIBERGLASS L/D = 2 Fluid: Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5000	10%	.5	1	167.4	31203	3328.	1.82×10^5	17.3
"	"	"	2	316.8	"	2435.	9.07×10^4	"
"	"	"	3	466.2	"	1921.	6.05×10^4	"
21000	"	"	2	824.6	131047	6293.	2.36×10^5	
32000	"	"	2	1092.	199688	8327.	3.13×10^5	

INSULATION: FIBERGLASS L/D = 8 Fluid: Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2	4.7	74.5	2452	12	2.95	3.71	1	5	3 1/2	5	2	5	2 1/2
"	"	"	"	"	"	"	1	"	"	"	"	"	"
"	"	"	"	"	"	"	1	"	"	"	"	"	"
"	6.7	107.4	3730	12	1.91	4.33	2	5	4	5	3 1/2	5	3
"	5.45	87.1	3354	12	2.68	3.90	2	5	4	5	2 1/2	5	3

INSULATION: FIBERGLASS L/D = 8 Fluid: Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5000	10%	.5	1.	228.9	363050	3387	1.84×10^5	19.2
"	"	"	2	433.2	"	2480	9.2×10^4	"
"	"	"	3	637.6	"	1959	6.14×10^4	"
15000	"	"	2	901	1089147	5122	1.92×10^5	"
8000	"	"	2	592.6	580879	3380	1.26×10^5	"

INSULATION: FIBERGLASS L/D = 8 Fluid: Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2	4.66	74.5	2452	12	3.32	3.38	1	5	2	5	1 1/2	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	7.5	120	6382.6	"	3.22	3.47	2	5	3	5	2 1/2	5	2 1/2
"	8.6	138	8451	"			"						

INSULATION: FIBERGLASS L/D = 8 Fluid: Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5000	10%	.5	1					19.2
"	"	"	2	433	28123	3331	1.24×10^5	"
"	"	"	3					"
21000	"	"	2	1127.6	118115	8605	3.23×10^5	"
32000	"	"	2	1493		11380	4.27×10^5	"

INSULATION: SHINGLES/SUBSTRATE **L/D** = 4 **Fluid**: Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	10.2		1298	6	2.63	3.94	1	5	3	5	2 1/2	5	2
2	5.7	45.9	2058	12	2.95	3.71	2	5	3 1/2			5	2 1/2
	6.7	53.6	2815		2.68	3.91		5	4	5	3	5	3
	7.7	61.3	3689	12	2.27	4.16		5	3 1/2	5	3	5	2 1/2

INSULATION: SHINGLES/SUBSTRATE L/D = 4 Fluid: Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
4000	10%	.5	1	233.8	31068	387.3	7.06×10^3	27.5
"	"	"	2	454.7	"	241.7	3.53×10^3	"
"	"	"	3	621.4	"	220.4	3.33×10^3	"
5000	"	"	1	372.	36409	228.0	1.12×10^4	26.96
"	"	"	2	723.4	"	157.3	5.6×10^3	"
"	"	"	3	989.1	"	152.3	5.28×10^3	"
6000	"	"	1					
"	"	"	2					
"	"	"	3					
8000	"	"	1	507.6	533695	305.3	1.5×10^4	27.3
"	"	"	2	987.	"	208.7	7.66×10^3	"
"	"	"	3	1349.	"	201.2	7.22×10^3	"
10000	"	"	1					
"	"	"	2					
"	"	"	3					
12000	"	"	1	664.	875541	382.	$2. \times 10^4$	27.5
"	"	"	2	1290.	"	255.	1×10^4	"
"	"	"	3	1764.	"	244.	9.46×10^3	"

INSULATION: SHINGLES/SUBSTRATE L/D = 4 Fluid: Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	10.2		1298.	6	3.27	3.42	1	5	2	5	1 1/4	5	1 1/2
1	"		"	"	"	"	"	"	"	"	"	"	"
1	"		"	"	"	"	"	"	"	"	"	"	"
2	5.7	45.8	2058	12	3.32	3.37	"	5	2	5	1 1/4	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"			2324	"	3.31	3.39	2	5	2 1/2	5	1 1/4	5	2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	6.7	53.6	2815	"	3.30	3.40	"	"	"	"	"	"	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	7.2	57.7	3267.	"	3.29	3.41	"	5	3	5	1 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	7.7	61.3	3689	"	3.28	3.42	"	5	2 1/2	5	2	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"			4281	"	3.26	3.44	"	"	"	"	"	5	2 1/2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	9.2	73.9	5357	"	3.22	3.47	"	5	3	5	2 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"

INSULATION: SHINGLES/SUBSTRATE L/D = 4 Fluid: Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
4000	10%	.5	1			485.	9.5×10^3	
"	"	"	2			288.9	4.75×10^3	
"	"	"	3			260.3	4.48×10^3	
5000	"	"	1			259.8	1.51×10^4	
"	"	"	2			164.5	7.53×10^3	
"	"	"	3			157.9	7.10×10^3	
6000	"	"	1					
"	"	"	2					
"	"	"	3					
8000	"	"	1					
"	"	"	2					
"	"	"	3					
10000	"	"	1	588.3		406.9	2.39×10^4	
"	"	"	2	1144.		255.5	1.19×10^4	
"	"	"	3	1563.		243.1	1.13×10^4	
12000	"	"	1					
"	"	"	2					
"	"	"	3					
15000	"	"	1					
"	"	"	2					
"	"	"	3					
21000	"	"	1	961.7		676.9	3.92×10^4	
"	"	"	2	1869.8		418.8	1.96×10^4	
"	"	"	3	2554.7		396.8	1.85×10^4	

INSULATION: SHINGLES/SUBSTRATE L/D = 4 Fluid: Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2			6177	12	3.19	3.50	2	5	3	5	3	5	3
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	10.6	85.2	7094	"	3.15	3.54	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"

INSULATION: SHINGLES/SUBSTRATE L/D = 4 Fluid: Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
26000	10%	.5	1					
"	"	"	2					
"	"	"	3					
32000	"	"	1	1271.		864.8	5.19×10^4	
"	"	"	2	2472.		533.2	2.60×10^4	
"	"	"	3	3377.		504.8	2.44×10^4	

INSULATION: SHINGLES/SUBSTRATE L/D = 2 Fluid Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2	6.9	27.6	1793	12	2.94	3.71	1	5	3 1/2	5	2 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	9.95	39.4	3730	"	1.88	4.34	2	5	4 1/2	5	3 1/2	5	3
"	8.07	32.3	2453	"									

INSULATION: SHINGLES/SUBSTRATE L/D = 2 Fluid Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5000	10%	.5	1	323.5	367669	196.3	9.75×10^3	27.3
"	"	"	2	629.0	"	138.1	4.88×10^3	"
"	"	"	3	859.8	"	132.7	4.6×10^3	"
15000	"	"	1	1301.7	1103004	261.1	1.01×10^4	27.5
8000	"	"	2	858.4		178.2	6.67×10^3	27.55

INSULATION: SHINGLES/SUBSTRATE L/D = 2 Fluid Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2	6.9	27.6	1793	12									
"	"	"	"	"									
"	"	"	"	"									
"	11.5	44.5	4667	"	3.21	3.48	2	5	3	5	2 1/2	5	2 1/2
"	12.8	51.2	6181	"	3.14	3.55	"	5	3 1/2	5	3	5	3

INSULATION: SHINGLES/SUBSTRATE L/D = 2 Fluid Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5000	10%	.5	1	323.5	31203	217.1	1.31×10^4	20.4
"	"	"	2	629.	"	138.6	6.46×10^3	"
"	"	"	3	859.8	"	131.5	6.2×10^3	"
21000	"	"	2	1627	131047	383.0	1.71×10^4	-
32000	"	"	2	2151	199688	465.	2.26×10^4	-

INSULATION: SHINGLES/SUBSTRATE L/D = 8 Fluid Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2	4.7	74.5	2452	12	2.95	3.71	1	5	3 1/2	5	2	5	2 1/2
"	"	"	2452	"	"	"	1	"	"	"	"	"	"
"	"	"	"	"	"	"	1	"	"	"	"	"	"
"	6.7	107.4	3730	"	1.91	4.33	2	5	4	5	3 1/2	5	3
"	5.45	87.1	3354	"	2.68	3.90	2	5	4	5	2 1 2	5	3

INSULATION: SHINGLES/SUBSTRATE L/D = 8 Fluid Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5000	10%	.5	1	864.7	363050			
"	"	"	2		"	186	6.67×10^{3}	
"	"	"	3					
15000	"	"	2	1786	1089147	367.8	$1.38 \times 10^{4}_{3}$	
8000	"	"	2	1179	580879	254	9.12×10^{3}	

INSULATION: SHINGLES/SUBSTRATE L/D = 8 Fluid Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2	4.66	74.5	2452	12	3.32	3.38	1	5	2	5	1 1/2	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	7.5	120	6382.6	"	3.22	3.47	2	5	3	5	2 1/2	5	2 1/2
"	8.6	138	8451	"			"						

INSULATION: SHINGLES/SUBSTRATE L/D = 8 Fluid Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5000	10%	.5	1					
"	"	"	2	864.7	28123	211.6	8.97×10^3	
"	"	"	3					
21000	"	"	2	2232	118115	533.9	2.34×10^4	
32000	"	"	2	2950		709	3.09×10^4	

INSULATION: SHINGLES L/D = 4 Fluid: Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	10.2		1298.	6	2.63	3.94	1	5	3	5	2 1/2	5	2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
2	5.7	45.9	2058.	12	2.95	3.71	"	5	3 1/2	5	2 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"				"			2						
"				"			"						
"				"			"						
"	6.7	53.6	2815.	"	2.68	3.91	"	5	4	5	3	5	3
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"				"			"						
"				"			"						
"				"			"						
"	7.7	61.3	3689.	"	2.27	4.16	"	5	3 1/2	5	3	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"

INSULATION: SHINGLES L/D = 4 Fluid: Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
4000	10%	.5	1	180.	310168	240.7	5.77×10^4	27.5
"	"	"	2	346.5	"	208.8	2.89×10^4	"
"	"	"	3	513.2	"	228.2	1.93×10^4	"
5000	"	"	1	286.2	364809	113.3	9.15×10^4	26.96
"	"	"	2	551.9	"	123.4	4.58×10^4	"
"	"	"	3	817.6	"	146.5	3.05×10^4	"
6000	"	"	1					
"	"	"	2					
"	"	"	3					
8000	"	"	1	390.2	583695	148.7	1.25×10^5	27.3
"	"	"	2	752.35	"	159.2	6.26×10^4	"
"	"	"	3	1114.4	"	188.6	4.17×10^4	"
10000	"	"	1					
"	"	"	2					
"	"	"	3					
12000	"	"	1	510.1	875541	174.3	1.64×10^5	27.5
"	"	"	2	983.2	"	186.9	8.20×10^4	"
"	"	"	3	1456.4	"	228.9	5.47×10^4	"

INSULATION: SHINGLES L/D = 4 Fluid: Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	10.2		1298.	6	3.27	3.42	1	5	2	5	1 1/4	5	1 1/2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
2	5.7	45.8	2058.	12	3.32	3.37	"	5	2	5	1 1/4	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"			2324	"	3.31	3.39	2	5	2 1/2	5	1 1/4	5	2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	6.7	53.6	2815	"	3.30	3.40	"	"	"	"	"	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"			3267.	12	3.29	3.41	"	5	3	5	1 1/2	5	2 1/2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	7.7	61.3	3689	"	3.28	3.42	"	5	2 1/2	5	2	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"			4281	"	3.26	3.44	"	"	"	"	"	"	2 1/2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	9.2	73.9	5357.	12	3.22	3.47	"	5	3	5	2 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"

INSULATION : SHINGLES L/D = 4 Fluid: Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
4000	10%	.5	1	179.7	35650	263.6	4.22×10^5	20.6
"	"	"	2	346.5	"	224.0	2.11×10^5	"
"	"	"	3	513.2	"	248.2	1.41×10^5	"
5000	"	"	1	286.2	29296	94.2	6.69×10^5	20.0
"	"	"	2	551.9	"	106.7	3.34×10^5	"
"	"	"	3	817.6	"	135.5	2.23×10^5	"
6000	"	"	1		35155			
"	"	"	2		"			
"	"	"	3		"			
8000	"	"	1		46874			
"	"	"	2		"			
"	"	"	3		"			
10000	"	"	1	452.2	58592	143.8	1.06×10^6	20.5
"	"	"	2	871.7	"	158.7	5.31×10^5	"
"	"	"	3	1291.2	"	198.9	3.54×10^5	"
12000	"	"	1		70310			
"	"	"	2		"			
"	"	"	3		"			
15000	"	"	1		87888			
"	"	"	2		"			
"	"	"	3		"			
21000	"	"	1	738.5	123042	228.3	1.74×10^6	20.6
"	"	"	2	1423.4	"	251.2	8.70×10^5	"
"	"	"	3	2108.3	"	317.1	5.80×10^5	"

INSULATION: SHINGLES L/D = 4 Fluid Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2			6177	12	3.19	3.50	2	5	3	5	3	5	3
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"	10.6	85.	7094	12	3.15	3.54	"	5	3	5	3	5	3
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"

INSULATION: SHINGLES L/D = 4 Fluid: Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
26000	10%	.5	1		152336			
"	"	"	2		"			
"	"	"	3		"			
32000	"	"	1	976.	187490	288.1	2.30×10^6	20.6
"	"	"	2	1881.	"	317.6	1.15×10^6	"
"	"	"	3	2786.	"	402.2	7.68×10^5	"

INSULATION: SHINGLES L/D = 2 Fluid Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2	6.9	27.6	1793	12	2.94	3.71	1	5	3 1/2	5	2 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	9.95	39.4	3729.8	"	1.88	4.34	2	5	4 1/2	5	3 1/2	5	3
"	8.07	32.3	2453.	"	2.67	3.91	"	5	4	5	3	5	3

INSULATION: SHINGLES L/D = 2 Fluid Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5000	10%	.5	1		367669	100.7	7.98×10^4	27.3
"	"	"	2	479.6	"	103.2	3.99×10^4	"
"	"	"	3	710.4	"	117.8	2.66×10^4	"
15000	"	"	2	990.9	1103004	182.4	8.29×10^4	27.5
8000	"	"	3	654.	588270	131.2	5.45×10^4	27.55

INSULATION: SHINGLES L/D = 2 Fluid Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
2	6.9	27.6	1793	12	3.32	3.38	2	5	2	5	1 1/4	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	11.5	44.5	4667	"	3.21	3.48	"	5	3	5	2 1/2	5	2 1/2
"	12.8	51.2	6181	"	3.14	3.55	"	5	3 1/2	5	3	5	3

INSULATION: SHINGLES L/D = 2 Fluid Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5000	10%	.5	1	248.7	31203	97.4	5.83×10^5	20.4
"	"	"	2	479.6	"		2.91×10^5	"
"	"	"	3	859.8	"	127.0	1.94×10^5	
21000	"	"	2					
32000	"	"	2					

INSULATION: BLANKETS L/D = 4 Fluid: Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	.76		15.1	6	3.348	3.349	1	10	1/8	10	1/8	10	1/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	1.20		38.0	"	3.34	3.35	"	10	3/8	10	1/8	10	1/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	1.63		69.9	"	3.34	3.35	"	10	1/2	10	1/8	10	1/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	2.06		111.	"	3.33	3.36	"	5	3/4	10	1/8	10	1/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	2.60		176.	"	3.32	3.38	"	5	1	10	1/8	10	3/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	3.52		324.6	"	3.26	3.42	"	5	1 1/4	10	1/8	5	3/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	4.44		515.	"	3.18	3.51	"	5	2	10	1/8	5	3/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	5.59		818.	"	3.01	3.66	"	5	2 1/2	10	1/8	5	1 1/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"

INSULATION: BLANKETS L/D = 4 Fluid: Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5	10%	2160	1	17.7	387.7	7.08	6.72×10^{2}	10.5
"	"	"	2	21.7	"	5.5	3.37×10^{2}	"
"	"	"	3	25.6	"	5.0	2.25×10^{2}	"
20	"	"	1		1550.			
"	"	"	2		"			
"	"	"	3		"			
50	"	"	1		3877.			
"	"	"	2		"			
"	"	"	3		"			
100	"	"	1	102.1	7754.	10.3	1.65×10^{3}	10.9
"	"	"	2		"			
"	"	"	3		"			
200	"	"	1	61.6	15508.	23.8	7.84×10^{3}	11.0
"	"	"	2	107.9	"	15.8	3.92×10^{3}	"
"	"	"	3	154.1	"	13.2	2.61×10^{3}	"
500	"	"	1	108.5	38771.	41.7	1.44×10^{4}	11.2
"	"	"	2	193.7	"	26.3	7.22×10^{3}	"
"	"	"	3	278.9	"	21.2	4.81×10^{3}	"
1000	"	"	1		77542			
"	"	"	2		"			
"	"	"	3		"			
2000	"	"	1	249.3	155084	83.7	3.64×10^{4}	11.2
"	"	"	2	464.0	"	53.3	1.82×10^{4}	"
"	"	"	3	678.8	"	43.2	1.21×10^{4}	"

INSULATION: BLANKETS L/D = 4 Fluid: Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	6.39			6			1						
"	"			"			"						
"	"			"			"						
"	7.05		1298	"	2.63	3.94	"	5	3	10	1/8	5	2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
2			2058	"	2.95	3.71	"	5	3 1/2	10	1/8	5	2 1/2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"

INSULATION: BLANKETS L/D = 4 Fluid: Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
3000	10%	2160.	1					
"	"	"	2					
"	"	"	3					
4000	"	"	1	395.4	310168	129.9	5.77×10^4	11.2
"	"	"	2	736.3	"	81.3	2.89×10^4	"
"	"	"	3	1077.2	"	65.1	1.93×10^4	"
5000	"	"	1	624.8	364810	174.6	9.15×10^4	"
"	"	"	2	1165.1	"	109.0	4.58×10^4	"
"	"	"	3	1705.4	"	87.1	3.05×10^4	"

INSULATION: BLANKETS L/D = 4 Fluid: Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	.76		15.1	6	-	-	1	10	1/8	10	1/2	10	1/8
"	"		"	"	-	-	"	"	"	"	"	"	"
"	"		"	"	-	-	"	"	"	"	"	"	"
"	1.20		37.97	"	100	1	"	10	1/8	10	1/8	10	1/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	1.63		69.9	"	3.347	3.349	"	10	1/4	10	1/8	10	1/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	2.06		111.0	"	3.34	3.35	"	10	3/8	10	1/8	10	1/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	2.60		176.	"	3.34	3.35	"	5	1/2	10	1/8	10	3/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	3.52		324.63	"	3.34	3.35	"	5	3/4	10	1/8	5	1/2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	4.44		515.3	"	3.33	3.37	"	5	1	10	1/8	5	3/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	5.59		818.	"	3.31	3.38	"	5	1 1/4	10	1/8	5	1 1/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"

INSULATION: BLANKETS. L/D = 4 Fluid: Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5	10%	2160.	1	17.7	44.6	8.58	4.90×10^3	9.21
"	"	"	2	21.7	"	6.92	2.45×10^3	"
"	"	"	3	25.6	"	6.41	1.64×10^3	"
20.0	"	"	1		178.2			"
"	"	"	2	33.9	"	8.33	6.17×10^3	"
"	"	"	3		"			"
50.0	"	"	1	32.7	445.6	15.2	2.27×10^4	9.46
"	"	"	2		"			"
"	"	"	3		"			"
100	"	"	1		891.3			"
"	"	"	2		"			"
"	"	"	3		"			"
200	"	"	1	61.6	178.2	26.3	5.73×10^4	9.70
"	"	"	2	107.9	"	17.2	2.86×10^4	"
"	"	"	3	154.2	"	14.1	1.91×10^4	"
500	"	"	1	108.5	4456	44.7	1.06×10^5	9.90
"	"	"	2	193.7	"	27.1	5.28×10^5	"
"	"	"	3	278.9	"	21.2	3.52×10^5	"
1000	"	"	1		8912.7			"
"	"	"	2		"			"
"	"	"	3		"			"
2000	"	"	1	249.3	17825	87.1	2.66×10^5	"
"	"	"	2	464.	"	51.2	1.33×10^5	"
"	"	"	3	678.8	"	39.3	8.86×10^4	"

INSULATION: BLANKETS L/D = 4 Fluid: Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	6.39		1072.	6	3.29	3.40	1	5	1 1/2	10	1/8	5	1 1/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	7.05		1299.	"	3.27	3.42	"	5	2	10	1/8	5	1 1/2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
2			2058.	12	3.32	3.38	"	5	2	10	1/8	5	2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"

INSULATION: BLANKETS L/D = 4 Fluid: Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
3000	10%	2160.	1		26738			9.90
"	"	"	2		"			"
"	"	"	3		"			"
4000	"	"	1	395.45	35650	134.5	4.22×10^5	"
"	"	"	2	736.3	"	77.2	2.11×10^5	"
"	"	"	3	1077.18	"	58.1	1.41×10^5	"
5000	"	"	1	624.8	29297	182.6	6.69×10^5	"
"	"	"	2	1165.	"	103.1	3.34×10^5	"
"	"	"	3	1705.	"	76.5	2.23×10^5	"

INSULATION: CONTINUOUS L/D = 4 Fluid: Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	.76		15.1	6	3.348	3.349	1	10	1/8	10	1/8	10	1/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	1.20		38.0	"	3.34	3.35	"	10	3/8	10	1/8	10	1/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	1.63		69.9	"	3.34	3.35	"	10	1/2	10	1/8	10	1/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	2.06		111	"	3.33	3.36	"	5	3/4	10	1/8	10	1/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	2.60		176	"	3.32	3.38	"	5	1	10	1/8	10	3/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	3.52		324.6	"	3.26	3.42	"	5	1 1/4	10	1/8	5	3/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	4.44		515	"	3.18	3.51	"	5	2	10	1/8	5	1
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	5.59		818	"	3.01	3.66	"	5	2 1/2	10	1/8	5	1 1/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"

INSULATION: CONTINUOUS L/D = 4 Fluid: Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5	10%	2160.	1	3.92	387.7	5.45	6.72×10^{2}	16.4
"	"	"	2	7.68	"	4.69	3.37×10^{3}	"
"	"	"	3	11.45	"	4.47	2.25×10^{2}	"
20	"	"	1		1550			"
"	"	"	2		"			"
"	"	"	3		"			"
50	"	"	1	18.2	3877	12.8	3.11×10^{3}	"
"	"	"	2	35.7	"	9.07	1.56×10^{3}	"
"	"	"	3	53.2	"	7.84	1.04×10^{3}	"
100	"	"	1		7754			"
"	"	"	2	73.	"	12.2	2.37×10^{3}	"
"	"	"	3	102.	"	10.3	1.65×10^{3}	"
200	"	"	1	45.8	15508	26.9	7.84×10^{3}	"
"	"	"	2	89.9	"	17.5	3.92×10^{3}	"
"	"	"	3	133.9	"	14.3	2.61×10^{3}	"
500	"	"	1	84.4	38771	46.1	1.44×10^{4}	"
"	"	"	2	165.6	"	28.6	7.22×10^{3}	"
"	"	"	3	246.7	"	22.8	4.81×10^{3}	"
1000	"	"	1		77542			"
"	"	"	2		"			"
"	"	"	3		"			"
2000	"	"	1	212.7	155084	111.8	3.64×10^{4}	"
"	"	"	2	417.2	"	67.7	1.82×10^{4}	"
"	"	"	3	621.7	"	52.8	1.21×10^{4}	"

INSULATION: CONTINUOUS L/D = 4 Fluid: Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	6.39		1071	6	2.82	3.80	1	5	3	10	1/8	5	2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	7.05		1298	"	2.63	3.94	"	5	3	10	1/8	5	2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
2			2058	12	2.95	3.71	"	5	3 1/2	10	1/8	5	2 1/2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"

INSULATION: CONTINUOUS L/D = 4 Fluid: Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
3000	10%	2160	1		232626			
"	"	"	2		"			
"	"	"	3		"			
4000	"	"	1	337.6	310168	173.9	5.77×10^4	16.4
"	"	"	2	662.2	"	103.9	2.89×10^4	"
"	"	"	3	986.9	"	80.3	1.29×10^4	"
5000	"	"	1	535.1	364810	267.0	9.15×10^4	"
"	"	"	2	1049.7	"	156.	4.58×10^4	"
"	"	"	3	1564.2	"	119.	3.05×10^4	"

INSULATION: CONTINUOUS L/D = 4 Fluid Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	.76		15.1	6	-	-	1	10	1/8	10	1/8	10	1/8
"	"		"	"	-	-	"	"	"	"	"	"	"
"	"		"	"			"	"	"	"	"	"	"
"	1.20		37.97	"	- .001	-	"	10	1/8	10	1/8	10	1/8
"	"		"	"	-	-	"	"	"	"	"	"	"
"	"		"	"	-	-	"	"	"	"	"	"	"
"	1.63		69.9	"	3.347	3.349	"	10	1/4	10	1/8	10	1/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	2.06		111.0	"	3.34	3.35	"	10	3/8	10	1/8	10	1/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	2.60		176.	"	3.34	3.35	"	5	1/2	10	1/8	10	3/8
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	3.52		324.63	"	3.34	3.35	"	5	3/4	10	1/8	5	1/2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	4.44		515.3	"	3.33	3.37	"	5	1	10	1/8	5	3/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	5.59		818.	"	3.31	3.38	"	5	1 1/4	10	1/8	5	1/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"

INSULATION: CONTINUOUS L/D = 4 Fluid Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
5.0	10%	2160.	1	3.92	44.6	7.32	4.9×10^3	14.6
"	"	"	2	7.68	"	6.30	2.45×10^3	"
"	"	"	3	11.45	"	6.00	1.63×10^3	"
20.	"	"	1	9.87	178.2	10.7	1.23×10^4	"
"	"	"	2		"			"
"	"	"	3		"			"
50.	"	"	1		445.6			"
"	"	"	2	35.7	"	10.98	1.14×10^4	"
"	"	"	3		"			"
100.	"	"	1		891.3			"
"	"	"	2		"			"
"	"	"	3	84.4	"	12.4	1.20×10^4	"
200	"	"	1	45.8	1782.	33.7	5.73×10^4	"
"	"	"	2		"			"
"	"	"	3		"			"
500.	"	"	1	84.0	4456.	57.0	1.05×10^5	"
"	"	"	2	165.6	"	33.4	5.28×10^4	"
"	"	"	3	246.7	"	25.5	3.51×10^4	"
1000.	"	"	1		8912.7			"
"	"	"	2	262.8	"	49.4	8.37×10^4	"
"	"	"	3	391.6	"	36.9	5.58×10^4	"
2000	"	"	1	212.7	17825.	135.1	2.66×10^5	"
"	"	"	2	417.2	"	75.7	1.33×10^5	"
"	"	"	3	621.7	"	55.7	8.86×10^4	"

INSULATION: CONTINUOUS L/D = 4 Fluid Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	6.39		1072	6	3.29	3.40	1	5	1 1/2	10	1/8	5	1 1/4
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
"	7.05		1298	"	3.27	3.42	"	5	2	10	1/8	5	1 1/2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
2			2058	"	3.32	3.38	"	5	2	10	1/8	5	2
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"
"			"	"	"	"	"	"	"	"	"	"	"

INSULATION: CONTINUOUS L/D = 4 Fluid Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
3000	10%	2160	1	278.7	26738.	173.9	3.48×10^5	14.6
"	"	"	2		"			"
"	"	"	3		"			"
4000	"	"	1	337.6	35650.	210.2	4.22×10^5	"
"	"	"	2	662.2	"	115.8	2.11×10^5	"
"	"	"	3	986.9	"	83.9	1.41×10^5	"
5000	"	"	1	535.12	29297.	325.0	6.69×10^5	"
"	"	"	2	1049.7	"	175.4	3.34×10^5	"
"	"	"	3	1564.2	"	125.0	2.23×10^5	"

INSULATION: CONTINUOUS L/D = 4 Fluid: Oxygen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	10.2		1298	6	2.63	3.94	1	5	3	5	2 1/2	5	2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
2	5.7	45.8	2058	12	2.95	3.71	"	5	3 1/2	5	2 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"													
"													
"													
"													
"													
"													
"													
"													
"													
"	7.7	61.3	3689	12	2.27	4.15	2	5	3 1/2	5	3	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"

INSULATION: CONTINUOUS L/D = 4 Fluid: Oxygen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
4000	10%	.5	1	337.6	310168	189.5	5.78×10^4	16.4
"	"	"	2	662.2	"	119.5	2.89×10^4	"
"	"	"	3	986.9	"	95.8	1.93×10^4	"
5000	"	"	1	535.1	364810	282.6	9.15×10^4	"
"	"	"	2	1049.7	"	171.6	4.58×10^4	"
"	"	"	3	1564.2	"	134.2	3.05×10^4	"
6000	"	"	1					"
"	"	"	2					"
"	"	"	3					"
8000	"	"	1					"
"	"	"	2					"
"	"	"	3					"
10000	"	"	1					"
"	"	"	2					"
"	"	"	3					"
12000	"	"	1	959.2	875541	480.9	1.64×10^5	"
"	"	"	2	1881.5	"	281.8	8.20×10^4	"
"	"	"	3	2803.8	"	214.6	5.47×10^4	"

INSULATION: CONTINUOUS L/D = 4 Fluid: Hydrogen

Tank Type	Tank Radius	Cylinder Length	Tank Area	No. of Supports	I.D.	O.D.	No. of Inst. Cond.	Fill Pipe Sch.	Fill Pipe Size	Use Pipe Sch.	Use Pipe Size	Vent Pipe Sch.	Vent Pipe Size
1	10.2		1298	6	3.27	3.42	1	5	2	5	1 1/4	5	1 1/2
"	"		"	"	"	"	"	"	"	"	"	"	"
"	"		"	"	"	"	"	"	"	"	"	"	"
2	5.7	45.8	2058	12	3.32	3.38	"	5	2	5	1 1/4	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	6.7	53.6	2815	"	3.30	3.40	2	5	2 1/2	5	1 1/2	5	2 1/2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	7.7	61.3	3689	"	3.28	3.42	"	5	2 1/2	5	2	5	2
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	10.6	85.	7094	"	3.15	3.54	"	5	3	5	3	5	3
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	9.2	73.9	5357	"	3.22	3.47	"	5	3	5	2 1/2	5	2 1/2
"	"	"	"	"	3.15	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"	"	"	"	"

INSULATION: CONTINUOUS L/D = 4 Fluid: Hydrogen

Volume	Ullage	Use Time	Insulation Thickness	Insulation Weight	Loaded Weight	Q Space	Q Ground	Pump Down Time
4000	10%	.5	1	337.6	35650	218.6	4.22×10^5	14.6
"	"	"	2	662.2	"	124.2	2.11×10^5	"
"	"	"	3	986.9	"	92.4	1.41×10^5	"
5000	"	"	1	535.1	29296	333.5	6.69×10^5	"
"	"	"	2	1049.7	"	183.9	3.34×10^5	"
"	"	"	3	1564.2	"	133.4	2.23×10^5	"
8000	"	"	1	732.	46874	455.6	9.15×10^5	"
"	"	"	2	1435.9	"	250.8	4.58×10^5	"
"	"	"	3	2139.7	"	181.8	3.05×10^5	"
12000	"	"	1	959.2	70310	584.9	1.20×10^6	"
"	"	"	2		"			"
"	"	"	3	2803.76	"	226.0	4.00×10^5	"
32000	"	"	1	1844.	187490	1116.	2.30×10^6	"
"	"	"	2	3618.	"	599.7	1.15×10^6	"
"	"	"	3	5391.	"	425.5	7.68×10^5	"
21000	"	"	1	1393.	123041	848.2	1.74×10^6	"
"	"	"	2	2732.	"	458.6	8.70×10^5	"
"	"	"	3	40715	"	327.1	5.80×10^5	"

5.2.1.3 Performance Characteristics

From the foregoing results, some general performance characteristics can be inferred.

Among the short term insulations, shingles/substrate exhibits by far the best ground hold, for both fluids. The approximate ranking for oxygen is shingles/substrate, shingles, fiberglass, in the ratio 1:10:15. For hydrogen ground hold the ranking is shingles/substrate, fiberglass, shingles in the ratio 1:2:7.

In space, the models predict shingles and shingles/substrate to exhibit comparable performance on oxygen tankage while fiberglass performs 10-20 times worse. The ratio here is 1:1:20. Hydrogen tanks in space are better insulated by shingles, followed by shingles/substrate and fiberglass, in the ratio 1:2:20.

Some interesting effects occur in connection with these results. On the ground, no drastic difference is observed between spherical and cylindrical tanks. Shingles alone exhibit poor ground hold characteristics because of the direct lateral conductive path to the tank. In space, both shingle systems show better performance (by a factor of two) on cylindrical tanks. This is an effect of shingle geometry, fewer shingle joints being required on the

cylindrical tank. Fiberglass is relatively insensitive to the difference in spherical and cylindrical geometry. Some comparative results for other L/D ratios are included in the tables for these insulation systems.

Long term insulation systems, blankets and continuously wrapped, perform similarly under ground hold conditions for both hydrogen and oxygen. On hydrogen tankage, there appears to be an unfavorable region for blanket systems in the range of 500 - 1000 ft^3 volumes, due probably to seam geometry, with resulting thermal performance degradation. Other than that, these systems would be rated 1:1 for oxygen under these conditions, with continuously wrapped systems showing 3:1 better than blankets on small hydrogen tankage (<1000 ft^3), and 1:1 in the remainder of the range. Blankets show some definite geometry effects.

In space, the two systems perform about equally well on oxygen tanks. Continuous systems have slightly ($\sim$10%) better thermal performance on intermediate (< 1000 ft^3) tanks, and a definite (25%) advantage on the smallest tanks. Overall, the continuous system should be rated slightly better than blankets, say 1:1.1.

In addition to the blanket geometry effects, both systems exhibit degradation in thermal performance in space, if cylindrical instead of spherical tanks are used. This effect appears to be preponderantly one of surface to volume ratio. A thermal performance summary is shown on the following page.

PERFORMANCE SUMMARY

Approximate Short Term Thermal Performance Ratios

Fiberglass: Shingles/Substrate: Shingles

Oxygen:	Ground Hold	15:1:10
	Space	20:1:1
Hydrogen:	Ground Hold	2:1:7
	Space	20:2:1

Approximate Long Term Thermal Performance Ratios

Blankets: Continuous Wrap

Oxygen:	Ground Hold	1:1
	Space	1:1
Hydrogen:	Ground Hold	1:3 (1000 ft^3)
		1:1 (1000 ft^3)
	Space	1:1:1

For the reader's interest, results displaying the performance of these two systems under different conditions of use have been calculated and included in the tables. The thermal performance of short term systems is too poor to warrant this added effort for those cases.

5.2.1.4 Recommendations

Because of limitations on the duration and scope of this study, it has been impossible to isolate and identify all the effects observed in the calculated results. A detailed study of performance characteristics should be conducted for the shingles/substrate and blanket systems. Additionally, some new methods and materials should be sought for reducing the lateral conductivity of the functional element of these two systems.

5.2.1.5 Conclusions

The mathematical models produced by this study offer a new and better way to investigate external insulation systems. From the results of the study, shingles/substrate systems exhibit best overall short term performance, while blankets offer satisfactory long term thermal performance without many of the difficulties associated with continuous systems. Both systems suffer from lateral conductivity and geometry effects, and further study will be required to minimize these effects on system performance.

5.2.2 Configuration

5.2.2.1 Weight

Weight is a primary consideration for any external insulation system. The tables of the foregoing section show insulation weight as well as total tankage weight, with insulation installed. Following is a brief summary of methods used to calculate insulation weight.

The fiberglass and continuous wrap systems represent the simplest cases. The insulation weight for either of these is:

$$St = (A)RHO(t) + (A)RHOPJ$$

A is the tank area, RHO the insulation density, t the thickness, and RHOPJ the purge jacket density. This calculation does not include attachment weight.

For shingle systems, the same basic formula may be used, while for the shingle/substrate system, a term (A)RHOSUB(tsub) must be added to account for the substrate weight.

For blanket systems, the basic formula is used, except a term 4 NO (WATTACH) is added to account specifically for the attachment device weight. 4 represents the blanket width in feet, hence NO is the number of attachments per linear foot and WATTACH is the weight per attachment.

5.2.2.2 Dimensions

All pertinent system dimensions, including those of tankage, supports, and piping are shown in the appropriate tables of the parametric results.

5.2.3 Technical & Material Specifications

The specification of an external thermal protection system is a complex matter, because such systems have many parts, and the parts have many interrelationships.

System performance may be specified in many ways. The basic system approach should be clearly specified, to insure that minimal thermal performance goals will be met. Minimum acceptable heat leak into the tank when fully loaded, and held on the ground, may be set. However, this may be no guarantee of space thermal performance unless elaborate space simulations are performed.

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A better method of specification is to specify maximum allowable loaded system weight at launch, and required minimum flow rates during the mission lifetime, with perhaps a maximum permissible tank pressure rise. This manner of specification allows the designer maximum freedom within the framework of a specific conceptual approach. It is desirable, if at all possible, to test the system performance under simulated operating conditions because of the uncontrollable variability in cryogenic tankage performance. If such tests are planned, it is important to simulate accurately the tank operating environment, not only with regard to pressure and insulation warm boundary temperature, but also with regard to radiant energy input. There are many space simulation facilities which allow some degree of control over the necessary parameters.

Material specifications are somewhat more straightforward, as one can write the specifications around manufacturer's standard products, as for example Narmco 7343/7193 polyurethane adhesive. The same is true of such items as vacuum/purge jacket laminates. (See the Interim Study Report of this contract for a comprehensive listing of these materials.) The only vendor supplied item over which one has little control, as discussed earlier, is metal coated plastic film. The specifications on this material should be written carefully, so that in the case of delivery of unsatisfactory material, at least a major expense will not be incurred. Although vendors prefer to specify coating thickness by resistivity, this should be avoided if possible,

and the thickness specified by an actual dimensional unit such as Angstroms. If necessary, such thickness can be measured directly by one of several techniques, such as Fizeau interference fringes. In addition, to guard against poor coating practice, oil contamination, etc., the maximum tolerable coating emissivity should also be specified. Discussions must be held with the vendor to determine what feasible limits of emissivity can be met, and what method of determining emissivity is acceptable to both parties. It is advisable to remember to set some limitations on the frequency of coating imperfections such as pinholes, thin spots, etc. Again prior conversations with vendors are the only reasonable way to determine the current state of coating capabilities. Inevitably, one will have to compromise his requirements somewhat.

5.2.4 Summary of Analytic Results

The effort undertaken to calculate the results shown in the previous section was considerable. Some of this work has been described in the Interim Study Report, but the entire effort will be summarized here.

5.2.4.1 Structural Functional Relationships

The structural calculations begin with the sizing of the tank according to volume and materials. Parameters incident to the calculation include, but are not limited to:

		Fluid type (hydrogen or oxygen)
FV	=	Required fluid volume
U	=	Ullage volume per cent
		Tank material; determines RHO, the material density
SD	=	Maximum spherical tank diameter
LD	=	Maximum L/D for cylindrical tank
MACD		Maximum and minimum cylinder diameter
MICD		
P		Maximum tank pressure
UT		Fluid usage time
FPL		Fill pipe length
GHT		Ground hold time
THOT		Environmental temperature

From this information, the tank geometry configuration follows according to the relationships below:

Tank volume:

$$V = (U+1)/FV$$

Spherical tank radius:

$$r = \sqrt[3]{\frac{3V}{4\pi}}$$

Area

$$A = 4\pi r^2$$

For hemispherically headed cylinder tanks: choose r, then the cylinder length is

$$L = \left(V - \frac{4}{3}\pi r^3\right) / \pi r^2$$

If L/D is greater than the specified maximum input, a larger r is chosen and the calculation interated.

Tank wall thickness is calculated for a cylinder by

$$t = \frac{P(D/A)}{2(0.85\ SIG - 0.6P)}$$

where SIG represents the room temperature values for the Ultimate Strength/2 or Yield Strength/1.5 for Inconel X, 304SS, 6061T6 Al, and 6Al-4V Ti. The lower limit of material workability is set at 0.036 in.

For the tank heads

$$t = \frac{P(D/A)}{2(1.7\ SIG - 0.2P)}$$

Spherical heads rather than the more economical flattened (torispherical, etc.) shapes have been used in this study as they were specified as a ground rule in the Contract. Tank heads are sized to withstand evacuation.

Tank weights, empty and loaded, are calculated from:

$$W = \left(\sum_i A_i t_i\right)(1.2)(1.5)\,RHO$$

for oxygen tanks, where the sum is over the tank parts.

1.2 is the allowance for stiffening rings, and 1.5 represents reinforcing for load bearings points.

For hydrogen $W = \left(\sum_i A_i t_i\right)(1.2)\,RHO$

Fluid weight for 0_2 is $WF = FV(70.8)$

for hydrogen $WF = FV(4.418)$

in pounds per cubic foot.

The foregoing values were used to provide design loads for establishing a support system. The support design has been based on the study reported in NASA-37 summarized in the Bibliography/Synposes/Category report. Based on this report, filament-wound fiberglass struts have been selected as the best general purpose supports. Six 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 Fig. 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 Fig. 2. The supports have been designed for a combined acceleration and vibration load of 8.5G downward (tension) and 3.5G upward (compression) using the following equations:

$$DO^2 - DI^2 = \frac{4G(1.5)W}{nF_t \pi \cos\alpha \cos\beta}$$

and

$$DO^4 - DI^4 = \frac{G(1.5W)(64L^2)}{nE\pi \cos\alpha \cos\beta}$$

where

W	=	static load (tank weight, loaded)
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

α and β represent the angles of the support from the vertical, as shown in Fig. 1. Typically α is 10 degrees, and β 45.

These equations have been solved simultaneously for the support diameters using lengths of 1.5 and 3 feet. Fill and vent lines have been sized to cool

and fill the 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.

The flow rate through the fill pipe is given by

$$Q_f = \frac{1}{\rho} \frac{\Delta H \times W}{\Delta h \, \Delta t} \left(\frac{\rho \Delta h \, FV}{\Delta H \times W} + 1 \right)$$

FV = Fluid volume

Δ h = fluid heat of vaporization

W = tank weight

P = liquid density

Δ H = sensible heat removed to cool 1 lb. of tank material from room temperature to cryogenic temperature

Δ t = total time allowed to cool down and fill (1/4 to 1 hour)

The volume of fluid transferred is:

$$V = Q_f / Area_{pipe}$$

and an initial pipe area is assumed. The pressure drop is found from

$$Re = \frac{\rho_l V DIA_{pipe}}{\mu_l} \; ; \; f = f(Re); \; \Delta P = \frac{0.081 \, f \, L \, \rho / \rho_{H_2O} V^2}{12 \, DIA_{pipe}}$$

All dimensions in Ft., Lb, Sec.

and is limited to the value stated above. The calculation is iterated to find the correct pipe size. Once found, the closest standard size is located, and printed by the computer.

The vent pipe size is calculated similarly using saturated gas values, the same Q and 3 to 10 feet of pipe. The velocities are limited to 0.3 speed of sound at saturation temperature.

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 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, with liquid flow assumed.

In addition to the plumbing described above, 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.

The various pipes are summarized in the tables of results. This completes the discussion of the basic tank geometry calculations.

5.2.4.2 Thermal Functional Relationships

The heart of the thermal modeling programs developed for this study resides in two mathematical models described partially in the Interim Study Report. We repeat this description in this section, and present the full solutions in Appendix I.

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 boundaries 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 3 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 three represents that portion of the penetration in contact with the insulation, while region four 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:

$$\frac{K_{r_1}}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_1}{\partial r}\right)+K_{z_1}\frac{\partial^2 T_1}{\partial z^2}=0,\quad r_1\le r\le r_2,\quad 0\le z\le t$$

$$\frac{K_{r_2}}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_2}{\partial r}\right)+K_{z_2}\frac{\partial^2 T_1}{\partial z^2}=0,\quad r_2\le r\le r_3,\quad 0\le z\le t$$

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

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

$$T_1=T_3,\ r=r_1,\ 0\le z\le t;\quad T_1=T_2,\ r=r_2,\ 0\le z\le t$$

$$K_{r_1}\frac{\partial T_1}{\partial r}=K_{r_2}\frac{\partial T_2}{\partial r},\quad r=r_2,\quad 0\le z\le t$$

$$T_2=f_1(z),\ r=r_3,\ 0\le z\le t;\quad T_1=T_2=T_3=0,\ 0\le r\le\infty,\ z=0$$

$$-K_{z_1}\frac{\partial T_1}{\partial z}=H_1(T-T_H),\quad r_1\le r\le r_2,\quad z=t$$

$$-K_{z_2}\frac{\partial T}{\partial z}=H_2(T-T_H),\quad r_2\le r\le r_3,\quad z=t$$

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

The mathematical solution to the problems associated with temperatures one and two above 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 susceptible to Sturm-Liouville analysis producing eigenvalue and orthogonal eigenvector solutions. The solutions are given in detail in Appendix I.

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 multilayer systems, one can take shingle geometry into account, and move a step closer to a real system by breaking the system down into an over-lapped subassembly level as shown in Fig. 4.

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 basic physical model as well as its associated mathematical notation are shown schematically in Fig. 4. 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 anisotropy in the x direction has been eliminated because it appears to be a second order effect.

$$\frac{\partial^2 T_1}{\partial X^2} + \frac{K_{y_1}}{K_{X_1}} \frac{\partial^2 T_1}{\partial y^2} = 0, \quad 0 \le X \le L, \quad 0 \le y \le t$$

$$\frac{\partial^2 T_2}{\partial X^2} + \frac{K_{y_2}}{K_{X_2}} \frac{\partial^2 T_2}{\partial y^2} = 0, \quad L_1 \le X \le L_2, \quad 0 \le y \le t$$

$$\frac{\partial^2 T_3}{\partial X^2} + \frac{K_{y_3}}{K_{X_3}} \frac{\partial^2 T_3}{\partial y^2} = 0, \quad L_2 \le X \le L_3, \quad 0 \le y \le t$$

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

$$-k_{y_1} \frac{\partial T_1}{\partial y} = H_5 (T_1 - T_H), \quad 0 \le x \le L_1, \quad y = t$$

$$k_{y_2} \frac{\partial T_2}{\partial y} = H_1 (T_2), \quad L_1 \le x \le L_2, \quad y = 0$$

$$-k_{y_2} \frac{\partial T_2}{\partial y} = H_4 (T_2 - T_H), \quad L_1 \le x \le L_2, \quad y = t$$

$$k_{y_3} \frac{\partial T_3}{\partial y} = H_2 (T_3), \quad L_2 \le x \le L_3, \quad y = 0$$

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

$$k_{x_1} \frac{\partial T_1}{\partial x} = k_{x_2} \frac{\partial T_2}{\partial x}, \quad x = L_1, \quad 0 \le y \le t$$

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

$$k_{x_2} \frac{\partial T_2}{\partial x} = k_{x_3} \frac{\partial T_3}{\partial x}, \quad x = L_2, \quad 0 \le y \le t$$

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

The solution to these equations is derived by separating the variables and solving three Sturm-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 complete solution is shown in Appendix I.

Thermal Performance of Multilayer Shingles on a Substrate

A model was 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 = 0 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:

$$K_{y_1} \frac{\partial T_1}{\partial y} = H_6 (T_1) \quad , \quad 0 \le x \le L_1 \quad , \quad y = 0$$

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

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

5.2.4.3 Heat Transfer Functional Relationships

Once the tank parameters have been calculated, and the penetrations sized, the heat transfer calculations may be begun. The calculation of penetration heat leaks proceeds first, according to the thermal model described in the last section. The results of these calculations are saved, and the system heat transfer calculation starts. The following section describes the methods used for the heat transfer calculations for each system.

Ground Hold Heat Leak

Each of the insulations reported here incorporate some type of purge gas to accommodate ground hold while minimizing condensation and freezing of atmospheric gases. Nitrogen gas is used for purging oxygen tankage while helium is used for hydrogen. Nitrogen has a lower conductivity than helium so it is used in the oxygen case. However, it is not normally suitable for hydrogen tankage because it would freeze at the tank wall.

The trade-off between nitrogen and helium is not as straightforward as it appears on a conductivity basis, because nitrogen neither outgasses from the material nor difuses as rapidly as helium. Therefore, ground hold heat leak gains associated with nitrogen may be partially or totally offset by increased pump down time and attendant heat losses in the early phases of the mission. Since the thermal conductivity of the purged insulations using any gas is several orders of magnitude greater than the evacuated insulation values for each insulation, different ground hold models have not been used for each purging system. One basic model incorporating one dimensional heat flow from the surroundings to the insulation by radiation and atmospheric convection and a series pure conduction in the insulation has been used throughout (convection within the insulation is minimized by the insulating material which breaks up convective patterns).

The approach to calculating this heat leak is summarized as follows: from a heat balance at the insulation outer surface, calculate the surface temperature.

$$\sigma\left(\frac{1}{\frac{1}{\epsilon_S}+\frac{1}{\epsilon_I}}-1\right)\left(T^4-T_H^4\right)+\frac{T}{R}+H\left(T-T_H\right)=0$$

where

ϵ_s = emissivity of surroundings

ϵ_i = emissivity of outer insulation surface

σ = Boltzman constant

T = surface temperature

T_H = surroundings temperature scaled to the tank temperature

R = thermal resistance of insulation

t_i = insulation thickness or a portion therof

H = convective heat transfer coefficient for atmospheric gases

$$\frac{HR}{R} = 0.53(G_r P_r)^{1/4} = \left(0.145 \times 3 \times 10^6 (T_H - T)\left(\frac{3V}{4\pi}\right)^{2/3} \times 0.72\right)^{1/4} \times 0.53$$

for air where

V = tank volume

The insulation resistance is taken from the literature for gas filled insulations, (NBS-100, NBS-56, DDC-19, NBS-85, NASA-30, NBS-118 etc.). Once the surface temperature is known, the heat leak is calculated as follows:

$$Q_{GND} = \frac{A_{surf}}{R} T + \sum_{i=1}^{\text{Number of penetrations}} 2\pi K_{pi} r_i S_i \frac{T_H}{L_i + t_i}$$

where

A_{surf} = insulation surface area

K_{pi} = penetration conductivity

S_i = penetration thickness

r_i = penetration radius

L_i = penetration length outside insulation

t_i = penetration insulation thickness

Heat Transfer During Pump Down

The analysis of heat transfer during pumpdown has been approximated by integrating the thermal conductivity of the insulation as a function of pressure over the pumpdown time. For the purposes of this calculation, the pressure-time relationship has been assumed to be linear for each insulation. The conductivity pressure relationship is from the literature, (i.e., NBS-100, NBS-56, NBS-63, NBS-118, etc.).

The pump down time has been determined from a new two dimensional free-molecular diffusion analysis. Various parameters characterizing the insulations have been selected from the literature (NBS-61, NBS-66, DDC-24, NBS-41, NBS-63, NASA-36, DDC-7, NBS-115, etc.) to model both broad-side and end pumping on the laminar insulations. Blankets and continuous insulations have small perforations in the layers amounting to 1.88% of their surface area to accelerate pumpout (NBS-66, DDC-24, NBS-61, etc.)

The analysis includes the time varying effect of outgassing although the experimental data for this is rather sparse. The actual pressure histories have not been calculated since each of the insulations under consideration have been exposed to and survived typical launch depressurization cycles. This analysis assumes that the free molecular diffusional flow regime is reached at orbital insertion so the continum pumpout has not been analyzed in detail; data reported in the literature (DDC-7, NASA-30, NBS-41, etc.) verifies this procedure.

It is assumed that the purge jacket can be opened at intervals which do not exceed the linear dimension of a shingle or blanket or a maximum of every 4 feet. In all cases the purge jacket is a Mylar-aluminum foil-aluminum foil-Mylar laminate. The values presented here must be assumed to be approximate because of the void of available basic data. The two dimensional pumpdown analysis yields the following result:

$$P = RT\left\{A \sum_m \sum_l \left[\frac{-n}{\lambda_{ml}^2 + Q} e^{Qt} - \frac{\lambda_{ml}^2 n}{Q(Q+\lambda_{ml}^2)} e^{-\lambda_{ml}^2 t} + \frac{n}{Q} e^{-\lambda_{ml}^2 t} - \frac{P_o}{ART} e^{-\lambda_{ml}^2 t} \right] B_{ml} \cos \frac{\gamma_m}{\sqrt{D_1}} \cos \frac{\delta_l}{\sqrt{D_2}} y \right.$$

where

$$\tan \frac{\delta_l d}{\sqrt{D_2}} = \frac{H_2}{\sqrt{D_2}\,\delta_l}, \quad \tan \frac{\gamma_m L}{\sqrt{D_1}} = \frac{H_1}{\gamma_m \sqrt{D_1}}$$

$$\lambda_{ml} = \sqrt{\delta_l^2 + \gamma_m^2}$$

and

$$B_{ml} = \frac{-\left[\sqrt{\frac{D_2}{\delta_l^2}}\sin\left(\sqrt{\frac{\delta_l^2}{D_2}}\,d\right)\sqrt{\frac{D_1}{\gamma_m}}\sin\left(\sqrt{\frac{\gamma_m^2}{D_1}}\,L\right)\right]}{\left(\frac{d}{2}+\frac{1}{4}\sqrt{\frac{D_2}{\delta_l^2}}\sin\left(2\sqrt{\frac{\delta_l^2}{D_2}}\,d\right)\right)\left(\frac{d}{2}+\frac{1}{4}\sqrt{\frac{D_1}{\gamma_m^2}}\sin\left(2\sqrt{\frac{\gamma_m^2}{D_1}}\,L\right)\right)}$$

where

D_1 = diffusion coefficient parallel to the layer

D_2 = diffusion coefficient perpendicular to the layers

d = thickness of insulation

L = 1/2 the spacing between purge back openings or insulation joints or shingle length

H_1 = diffusional conductance at L

H_2 = diffusional conductance at surface of insulation

A and Q are parameters describing outgassing according to

rate = Ae^{-Qt}

R = purge gas constant

T = absolute temperature

n = number of insulation layers/foot

These equations have been solved for the time (T) required to reach a maximum interstitial pressure of 10^{-4} Torr. This result has been used to compute the pumpdown heat leak using the linear pumpdown rate; the result is as follows:

$$\frac{K_g A \Delta T}{1.6t} T_p \left((10^{-4})^{1.6} - 1.0\right) + \sum_i \frac{A_p \Delta T K_{pi}}{L_i}$$

where

t = insulation thickness

A = surface areas

A_p = area of penetration "L"

K_g = effective ground hold insulation conductivity

K_{pi} = penetration conductivity

ΔT = temperature difference

T_p = pumpdown time (hrs.)

L_i = length of penetration

Since the ground hold heat leak is dominated by the purge gas conductivity, the above analysis for heat leak during pumpout only considers the gaseous effects and thus appears the same for each insulation. Notice that the above equation gives a net heat leak per unit pumpdown time which is very close to Q ground/1.6.

Detail insulation characteristics are then included in the Q ground and the pump down time, T_P.

Space Heat Leak

Thermal performance in space is calculated as follows: For fiberglass, the space heat transfer rate is:

$$Q = A_{surf} (K_f) \frac{THOT}{t} + \sum_i Q_{i\,(penetration)}$$

here t is the thickness, and other parameters are as before. For continuous systems, the insulation term above is multiplied by the experimentally determined degradation factors:

$$Perf\,(F_{pc})\,F_{inc}$$

representing perforation, joint and seam degradation. F_{inc} is different for spheres or cylindrical tanks. For blankets and shingles, the situation is more complicated, as we must calculate the insulation geometry which will fit the tank size.

For shingles, the size of the polar shingles is determined by taking the smaller of

$$D_{cap} = \frac{\pi}{6} D_{tank} \quad or \quad 4\ feet$$

the shingle length is the smaller of

$$L_h = \frac{\pi}{12} D_{tank} \quad or \quad 4\ feet$$

the number of shingles is

$$N = 3\ Int \sum \left\{ \left[\left(\frac{\pi}{4} D_t - \frac{\alpha D_t}{6} \right) / L_h \right] - 0.01 \right\} + 1$$

The width follows from

for $L = \frac{\pi}{12} D_t$ $\quad W_i = \frac{\pi D_t}{2} \left\{ \sin\left[\frac{\alpha}{3} + (i-1)\frac{\pi}{18} \right] + \sin\left[\frac{\alpha}{3} + i\frac{\pi}{18} \right] \right\}$

for $L = 4$ $\quad W_i = \frac{\pi D_t}{2} \left\{ \sin\left[\frac{\alpha}{3} + (i-1)\frac{8}{3D_t} \right] + \sin\left[\frac{\alpha}{3} + i\frac{8}{3D_t} \right] \right\}$

For the cylindrical tank

$$L_c = \text{smaller} \begin{cases} 4 \\ L_{cyl} \end{cases} ; \quad W = \pi D_{cyl}$$

$$W_{Head} = 2 \sum_{i=1}^{N} W_i - W_1 - W_2$$

$$W_{cyl} = \pi D_{cyl} \left(\frac{L_{cyl}}{L} \right)$$

The heat transfer is then computed from

$$Q = W_{head}\, Q_{shingle}\left(L_1 = L_{h/3},\ \Delta L_2 = L_{h/3},\ \Delta L_3 = L_{h/3},\ t = t_{/3}\right)$$
$$+ \left(W_{cyl} + f_s\, LS\right) Q_{shingle}\left(L_1 = L_{c/3},\ \Delta L_2 = L_{c/3},\ \Delta L_3 = L_{c/3},\ t = t_{/3}\right)$$
$$+ \frac{\pi}{18} D_c\, K_{y3}\, \frac{T_H}{t} + \sum_i Q_{i\ penetration}$$

where

$$LS = \frac{\pi D}{2} + L_{cyl}$$

Q shingle may be found in Appendix I.

For blankets, the analysis is similar:

Heads: Polar cap $D = \frac{\pi D_t}{6}$ or 4 feet

$$\alpha = \frac{\pi}{6} \text{ or } 4/D_t$$

$$L_h = \text{Smaller}\left\{ \begin{matrix} 4 \\ \frac{\pi}{12} D_t \end{matrix} ;\ N = Int\left[\left(\frac{\pi D_t}{4} - \alpha \frac{D_t}{2}\right)/L_h - 0.01\right] + 1 \right.$$

$$W_i = \text{Smaller}\left\{ \begin{matrix} 4 \\ \frac{\pi}{16} D_t \left\{ \sin\left[\alpha + (i-1)\beta\right] + \sin\left[\alpha + i\beta\right] \right\} \end{matrix} \right.$$

$$LS = \sum_{c=1}^{N} \pi D_t \left[\alpha + (i-1)\beta\right] +$$
$$L \sum^{N} \left\{ Int\left[\frac{\pi D_t}{2} \left\{ \sin\left[\alpha + (i-1)\beta\right] + \sin\left[\alpha + i\beta\right] \right\} / W_i - 0.01 \right] + 1 \right\}$$

$$LS = 2LS$$

Cylinder: $L_c = \begin{cases} \text{Smaller} \\ 4 \\ L_{cyl} \end{cases}$; $W = \begin{cases} \text{Smaller} \\ 4 \\ \frac{\pi}{8} D_t \end{cases}$

$$LS = LS + L_{cyl}\left\{Int\left(\frac{\pi D_t}{W} - 0.01\right) + 1\right\} + \pi D_t\left\{Int\left(\frac{L_{cyl}}{L} - 0.01\right) + 2\right\}$$

$$NO = 2\sum_{i}^{N}\left\{Int\left[\frac{\pi D_t}{2}\left\{\sin[\alpha + (i-1)\beta] + \sin[\alpha + i\beta]\right\}/w_i - 0.01\right] + 1\right\}$$

$$+ \begin{cases} 0 \text{ (sphere)} \\ \left[Int\left(\frac{\pi D_t}{W} - 0.01\right) + 1\right]\left[Int\left(\frac{L_{cyl}}{L} - 0.01\right) + 1\right] \end{cases} + 2$$

Mean widths are then:

$$\overline{W}_{head} = \left[\frac{1}{N}\left(\sum_{i}^{N} w_i\right) + L_h\right]/2 \qquad \overline{W}_{cyl} = \frac{L_c + W}{2}$$

Finally, the heat transfer is

$$Q = f_{p\beta}\, Perf\left(A K_B \frac{T_H}{t}\right) + f_{j\beta} LS + \sum_{i} Q_i \text{ penetrations}$$

Here A is A_{surf} + 4 NO as described earlier. Q penetration may be found in Appendix I.

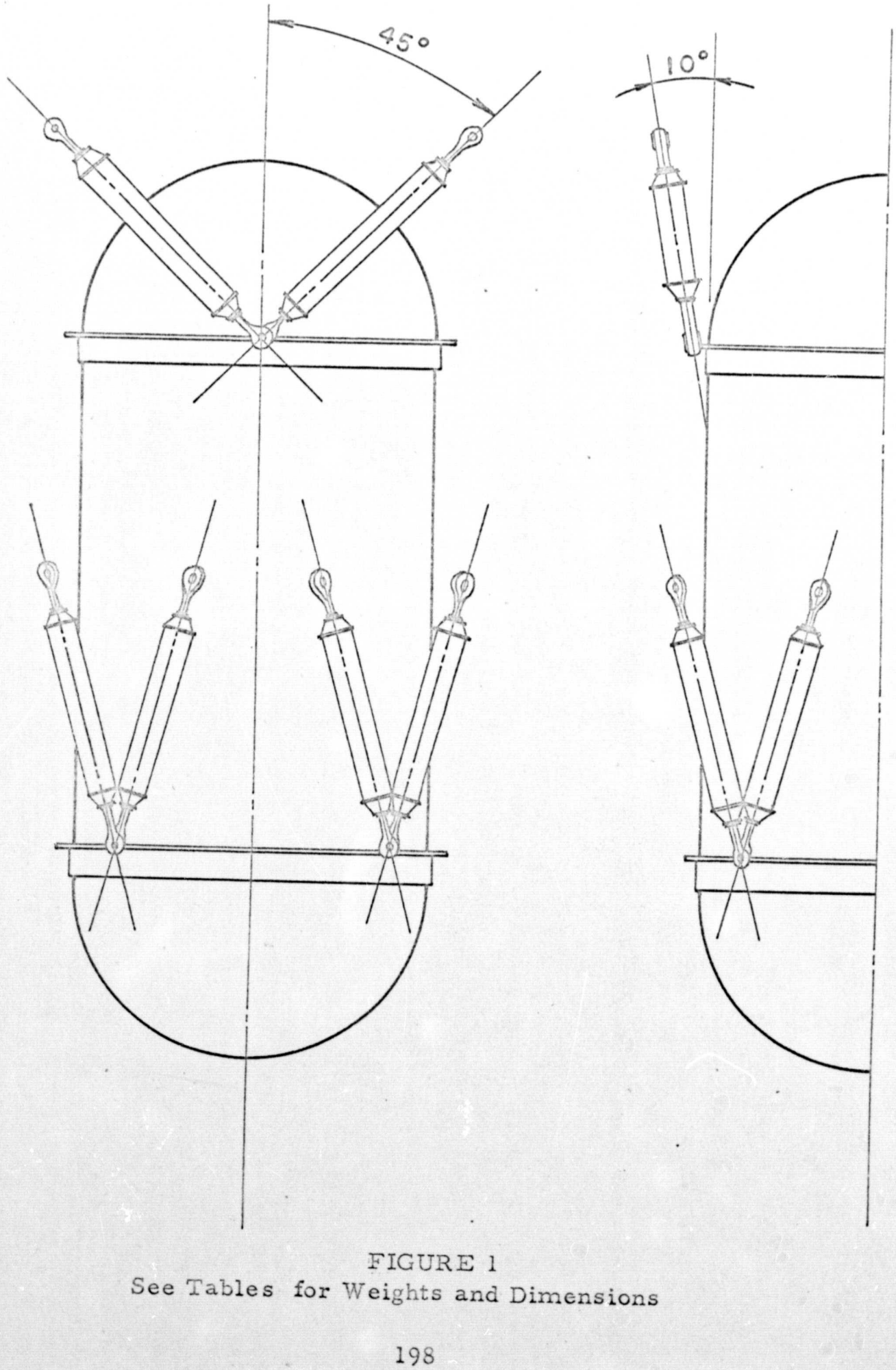


FIGURE 1
See Tables for Weights and Dimensions

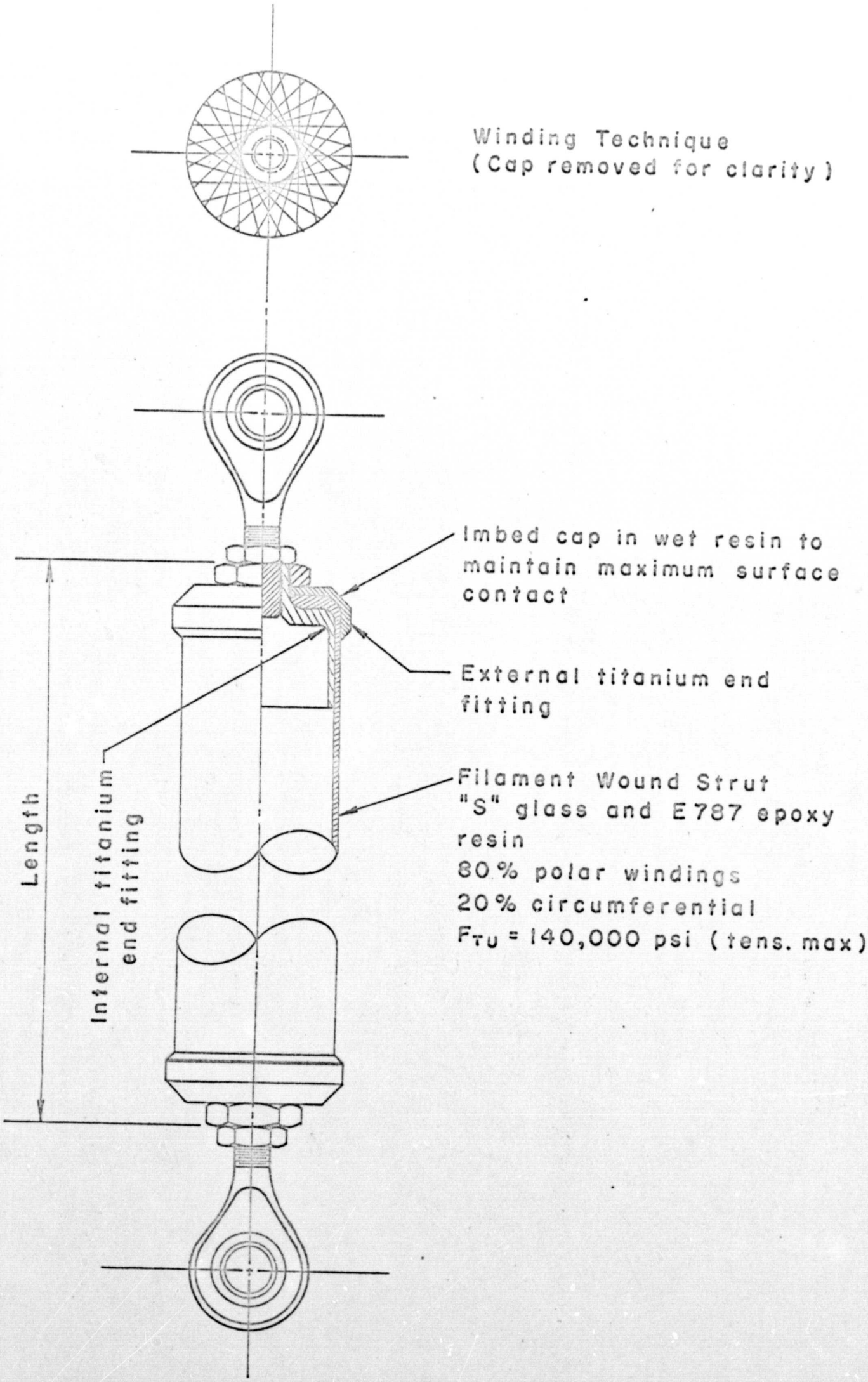

Winding Technique
(Cap removed for clarity)
Imbed cap in wet resin to maintain maximum surface contact
External titanium end fitting
Filament Wound Strut
"S" glass and E787 epoxy resin
80% polar windings
20% circumferential
F_{TU} = 140,000 psi (tens. max)
Length
Internal titanium end fitting

FIGURE 2

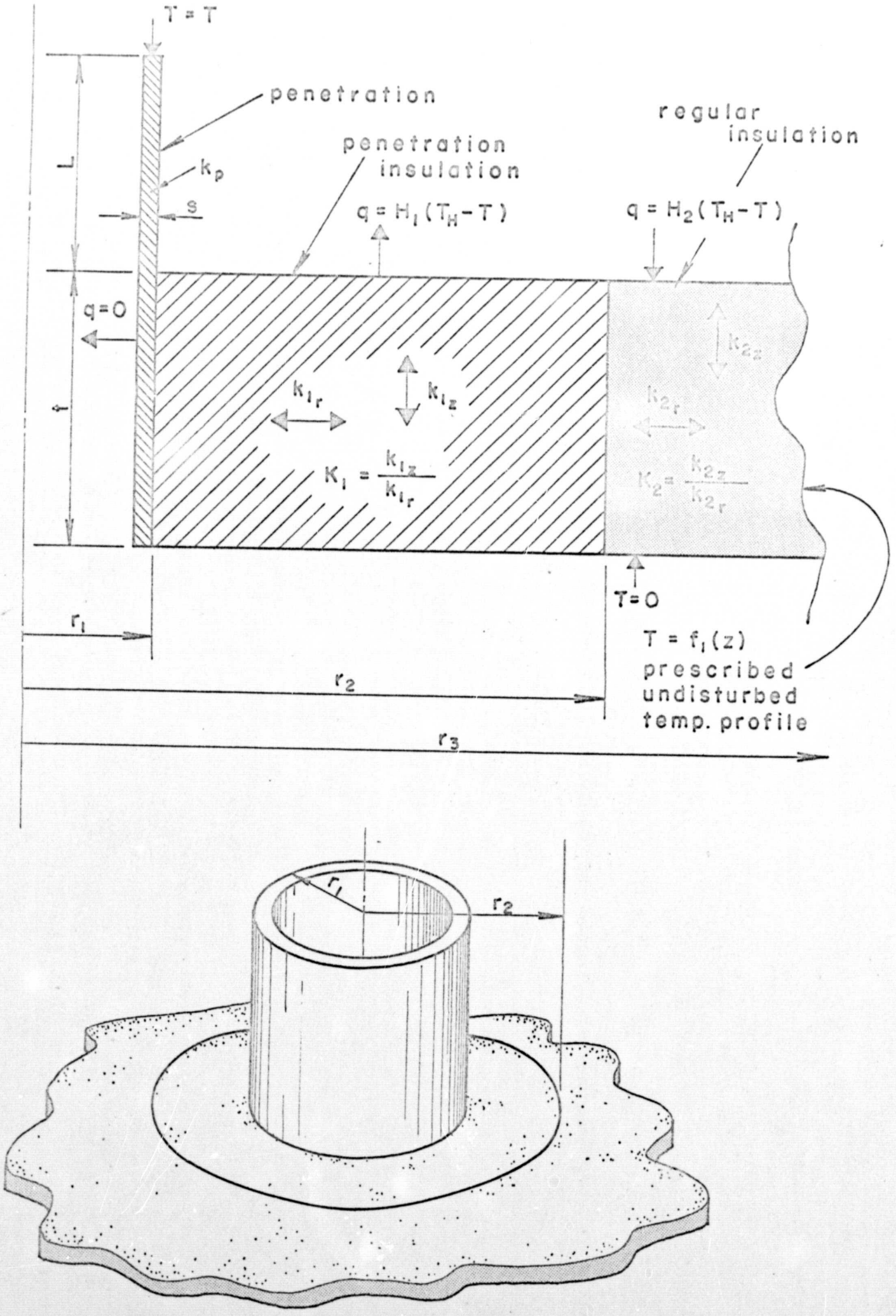
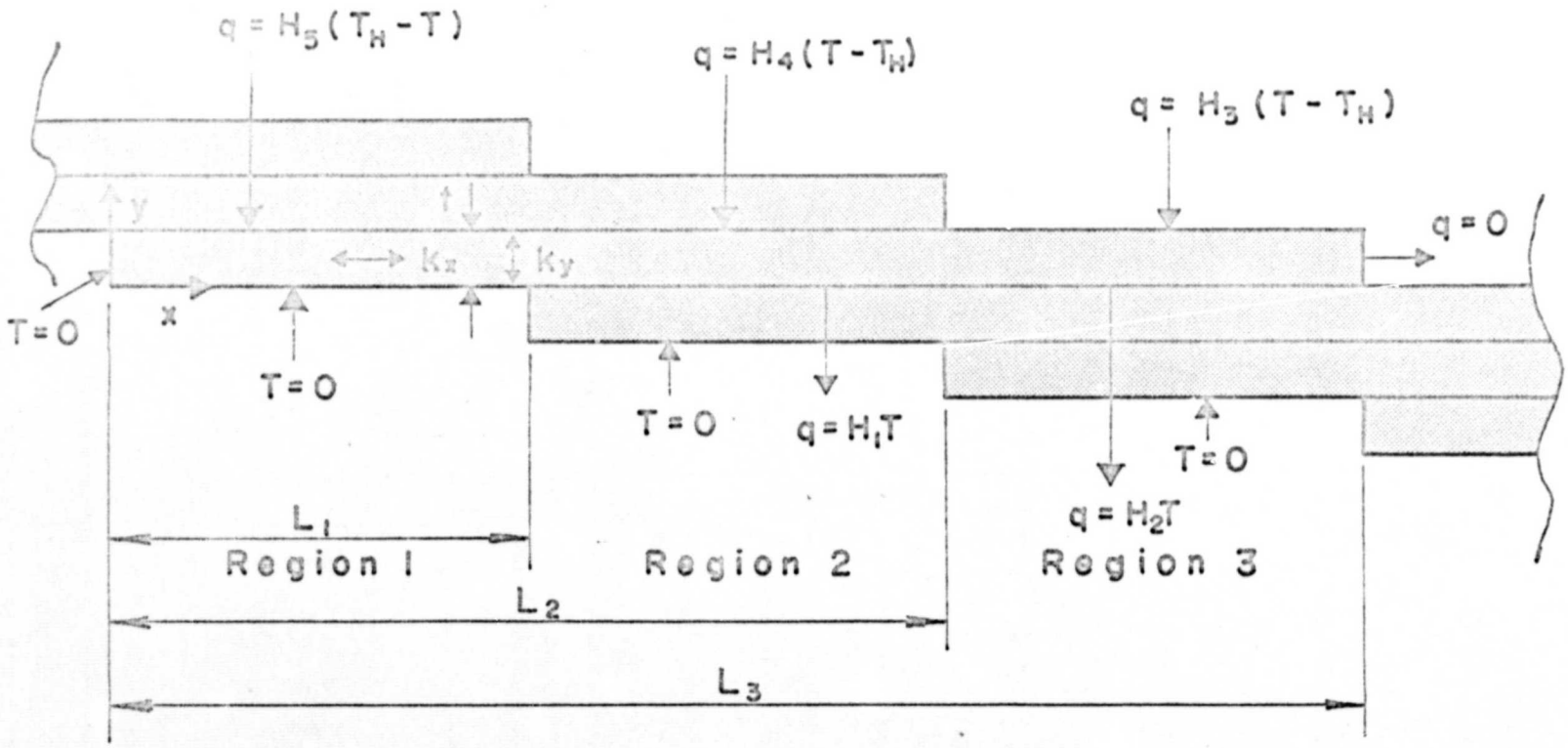

T = T
penetration
penetration insulation
regular insulation
k_p
s
L
$q = H_1(T_H - T)$
$q = H_2(T_H - T)$
q=0
t
k_{1r}
k_{1z}
$K_1 = \frac{k_{1z}}{k_{1r}}$
k_{2z}
k_{2r}
$K_2 = \frac{k_{2z}}{k_{2r}}$
T=0
r_1
r_2
r_3
$T = f_1(z)$
prescribed
undisturbed
temp. profile

FIGURE 3


q = H5 (TH - T)
q = H4 (T - TH)
q = H3 (T - TH)
y
Kx
Ky
x
q = 0
T = 0
T = 0
T = 0
q = H1T
T = 0
q = H2T
L1
Region 1
Region 2
Region 3
L2
L3

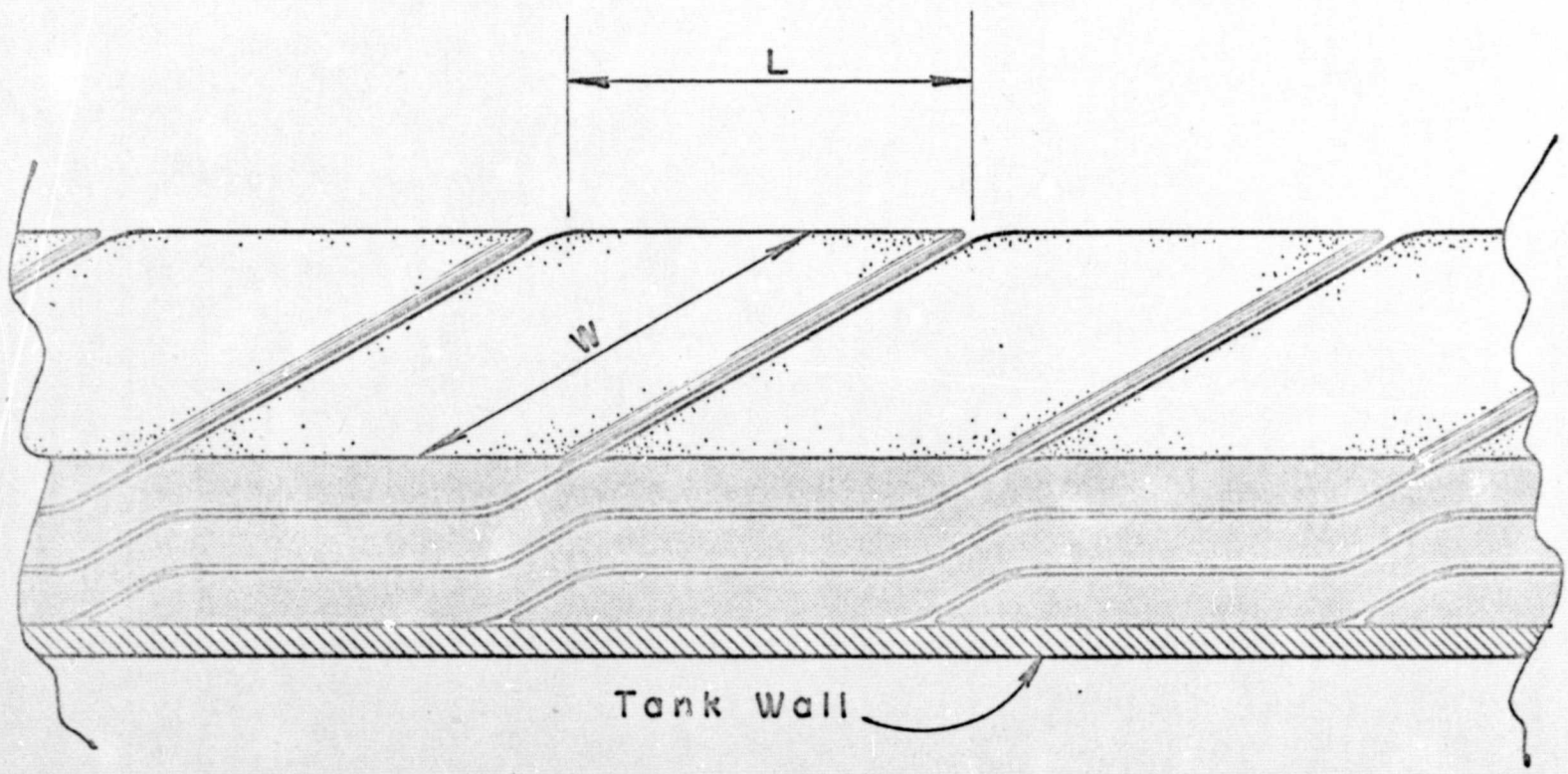

L
W
Tank Wall

FIGURE 4

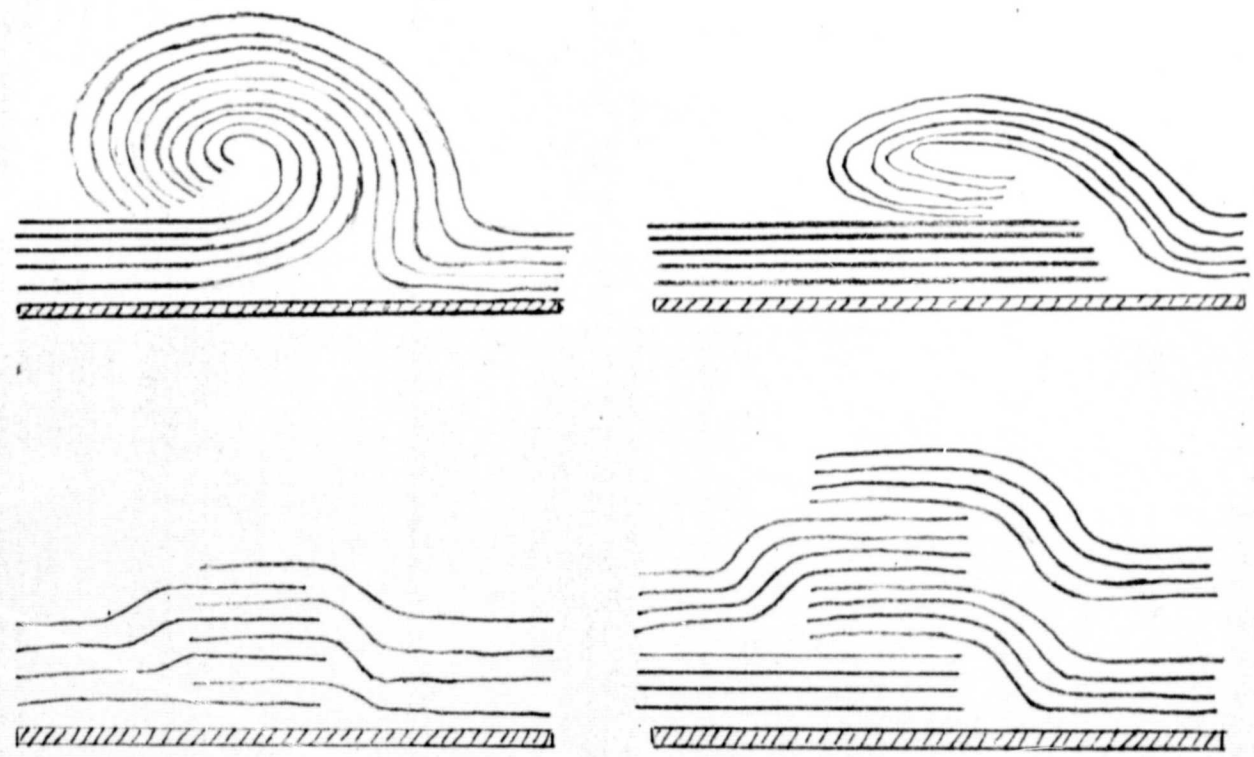


FIGURE 5

Appendix I - Solutions for the Computer Models

Here we present the complete solutions for the penetration and shingle models described earlier:

Penetration Model Summary

The reader is referred to Fig. 3 for explanation of the penetration geometry.

The integrated heat leak through the penetration is:

$$Q = k_{z_1} \int_{r_1}^{r_2} \frac{\partial T_1}{\partial z} 2\pi r\, dr + k_{z_2} \int_{r_2}^{r_3} \frac{\partial T_2}{\partial z} 2\pi r\, dr + k_{ps}\, 2\pi r_1 \left.\frac{\partial T_1}{\partial z}\right|_{\substack{r=r_1 \\ z=0}}$$

Performing the indicated operations, this expression becomes explicitly

$$Q = 2\pi k_{z_1} \sum_n \frac{A_{1n}}{K_1} \left\{ -r_2 K_0(\lambda_{1n} r_2) I_1(\lambda_{1n} r_2) - r_2 I_0(\lambda_{1n} r_2) K_1(\lambda_{1n} r_2) \right.$$

$$\left. + r_1 K_0(\lambda_{1n} r_2) I_1(\lambda_{1n} r_1) + r_1 I_0(\lambda_{1n} r_2) K_1(\lambda_{1n} r_1) \right\}$$

$$+ 2\pi k_{z_1} \sum_n \frac{B_{1n}}{K_1} \left\{ -r_2 K_0(\lambda_{1n} r_1) I_1(\lambda_{1n} r_2) - r_2 I_0(\lambda_{1n} r_1) K_1(\lambda_{1n} r_2) \right.$$

$$\left. + r_1 K_0(\lambda_{1n} r_1) I_1(\lambda_{1n} r_1) + r_1 I_0(\lambda_{1n} r_1) K_1(\lambda_{1n} r_1) \right\}$$

$$+ 2\pi k_{z_1} C_1 \left(\frac{r_2^2}{2} - \frac{r_1^2}{2} \right) + 2\pi k_{z_2} C_2 \left(\frac{r_3^2}{2} - \frac{r_2^2}{2} \right) + 2\pi r_1 k_{ps} C_1 +$$

$$2\pi k_{z_2} \sum_n \frac{A_{2n}}{K_2} \left\{ -r_3 K_0(\lambda_{2n} r_3) I_1(\lambda_{2n} r_3) - r_3 I_0(\lambda_{2n} r_3) K_1(\lambda_{2n} r_3) \right.$$

$$\left. + r_2 K_0(\lambda_{2n} r_3) I_1(\lambda_{2n} r_2) + r_2 I_0(\lambda_{2n} r_3) K_1(\lambda_{2n} r_2) \right\}$$

$$+ 2\pi k_{z_2} \sum_n \frac{B_{2n}}{K_2} \left\{ -r_3 K_0(\lambda_{2n} r_2) I_1(\lambda_{2n} r_3) - r_3 I_0(\lambda_{2n} r_2) K_1(\lambda_{2n} r_3) \right.$$

$$\left. + r_2 K_0(\lambda_{2n} r_2) I_1(\lambda_{2n} r_2) + r_2 I_0(\lambda_{2n} r_2) K_1(\lambda_{2n} r_2) \right\}$$

$$+ 2\pi r_1 k_p S \sum_n \frac{\lambda_{1n}}{K_1} \left\{ A_{1n} \left[-K_0(\lambda_{1n} r_2) I_0(\lambda_{1n} r_1) + I_0(\lambda_{1n} r_2) K_0(\lambda_{1n} r_1) \right] \right\}$$

where (I_0, I_1, K_0, K_1) are Bessel's functions. The small k's represent the thermal conductivities of the geometry, as indicated in Fig. 3, while the K represent ratios of these conductivities. These and remaining constants are shown explicitly below:

$$A_{1n} = N_n + O_n M$$

$$N_n = \left\{ -\frac{k r_1}{S k_p} \left[\frac{L_n}{r_1} \frac{K_1^2}{\lambda_{1n}^2} \left(\frac{t}{2} - \frac{K_1}{4\lambda_{1n}} \sin \frac{2\lambda_{1n} t}{K_1} \right) \right] \right.$$

$$\left. - C_1 \left(\frac{K_1^2}{\lambda_{1n}^2} \sin \frac{\lambda_{1n} t}{K_1} - \frac{K_1 t}{\lambda_{1n}} \cos \frac{\lambda_{1n} t}{K_1} \right) \right\} / R_n$$

$$L_n = D_n \sum_{m=1}^{\infty} E_{m,n} (F_m B_{2m}) + E_{1,n} D_n G (C_1 - C_2) + W_n D_n (C_2 - C_1)$$

$$D_n = \left(\frac{t}{2} - \frac{K}{4\lambda_{1n}} \sin \frac{2\lambda_{1n} t}{K_1}\right)^{-1} \left\{ -K_0(\lambda_{1n} r_1) I_0(\lambda_{1n} r_2) + I_0(\lambda_{1n} r_1) K_0(\lambda_{1n} r_2) \right\}$$

$$E_{m;n} = \left\{ -K_0(\lambda_{2m} r_3)\, I_0(\lambda_{2m} r_2) + I_0(\lambda_{2m} r_3)\, K_0(\lambda_{2m} r_2) \right\} X$$

$$\left\{ \frac{\lambda_{1n}}{K_1} \sin \frac{\lambda_{2m} t}{K_2} \cos \frac{\lambda_{1n} t}{K_1} - \frac{\lambda_{2m}}{K_2} \sin \frac{\lambda_{1n} t}{K_1} \cos \frac{\lambda_{2m} t}{K_2} \right\} /$$

$$\left(\frac{\lambda_{2m}^2}{K_2^2} - \frac{\lambda_{1n}^2}{K_1^2} \right)$$

$$F_m = \left\{ -\frac{k r_2}{r_2} \left[\frac{\lambda_{11}}{K_1} \sin \frac{\lambda_{2m}}{K_2} \cos \frac{\lambda_{11} t}{K_1} - \frac{\lambda_{2m}}{K_2} \sin \frac{\lambda_{11}}{K_1} \cos \frac{\lambda_{2m} t}{K_2} \right] \right\} /$$

$$P_m \left(\frac{\lambda_{2m}^2}{K_2^2} - \frac{\lambda_{11}^2}{K_1^2} \right)$$

$$P_m = k_{r_1} D_1 E_{m,1} \left(\frac{t}{2} - \frac{K_1}{4\lambda_{11}} \sin \frac{2\lambda_{11} t}{K_1} \right) \left(-\lambda_{11} K_0(\lambda_{11}, r_1)\, I_0(\lambda_{11} r_2) \right.$$

$$\left. - \lambda_{11} I_0(\lambda_{11} r_1) K_1(\lambda_{11} r_2) \right) + k_{r_2} \left(\lambda_{2m} K_0(\lambda_{2m} r_3)\, I_1(\lambda_{2m} r_2) \right.$$

$$\left. + \lambda_{2m} K_1(\lambda_{2m} r_2)\, I_0(\lambda_{2m} r_3) \right) X$$

$$\left(\frac{\lambda_{11}}{K_1}\sin\frac{\lambda_{2m}t}{K_2}\cos\frac{\lambda_{11}t}{K_1}-\frac{\lambda_{2m}}{K_2}\sin\frac{\lambda_{11}t}{K_1}\cos\frac{\lambda_{2m}t}{K_2}\right)\Big/$$

$$\left(\frac{\lambda_{2m}^2}{K_2^2}-\frac{\lambda_{11}^2}{K_1^2}\right)$$

$$B_{2,n}=\frac{\int_0^t\left(-\frac{H_2 T_H Z}{k_{z_2}+H_2 t}+f_1(z)\right)\sin\frac{\lambda_{2n}z}{K_2}\,dz}{\left(\frac{t}{2}-\frac{K_2}{4\lambda_{2n}}\sin\frac{2\lambda_{2n}t}{K_2}\right)\left(I_0(\lambda_{2n}r_2)K_0(\lambda_{2n}r_3)-I_0(\lambda_{2n}r_3)K_0(\lambda_{2n}r_2)\right)}$$

f(z) is the undisturbed one dimensional temperature profile far from the penetration, and the H_i are defined in section 5.2.4.2.

$$G=k_{r_1}W_1D_1\left(\frac{t}{2}-\frac{K_1}{4\lambda_{11}}\sin\frac{2\lambda_{11}t}{K_1}\right)\Big/\left(-\lambda_{11}K_0(\lambda_{11}r_1)I_1(\lambda_{11}r_2)\right.$$

$$\left.-\lambda_{11}I_0(\lambda_{11}r_1)K_1(\lambda_{11}r_2)\right)\Big/P_1\;;\quad m=1$$

$$=0\;;\quad m\neq 1$$

$$C_1=H_1T_H/(H_1t+k_{z_1})$$

$$C_2=H_2T_H/(H_2t+k_{z_2})$$

$$W_n=\frac{K_1^2}{\lambda_{1n}^2}\sin\frac{\lambda_{1n}t}{K_1}-\frac{K_1t}{\lambda_{1n}}\cos\frac{\lambda_{1n}t}{K_1}$$

$$O_n = \left\{ \frac{K_1^2}{\lambda_{1n}} \sin \frac{\lambda_{1n} t}{K_1} - \frac{K_1 t}{\lambda_{1n}} \cos \frac{\lambda_{1n} t}{K_1} \right\} / R_n$$

$$R_n = \left[- K_0(\lambda_{1n} r_2) I_0(\lambda_{1n} r_1) + I_0(\lambda_{1n} r_2) K_0(\lambda_{1n} r_1) \right.$$

$$+ \frac{k r_1}{5 k_p} \frac{1}{r_1} \frac{K_1^2}{\lambda_{1n}^2} D_n E_{1,n} H \begin{cases} 1 & n=1 \\ 0 & n \neq 1 \end{cases} + \frac{k r_1}{5 k_p} \frac{K_1^2}{\lambda_{1n}} ($$

$$\left. K_0(\lambda_{1n} r_2) I_1(\lambda_{1n} r_1) + I_0(\lambda_{1n} r_2) K_1(\lambda_{1n} r_1) \right) \Big] X$$

$$\left\{ \frac{t}{2} - \frac{K_1}{4\lambda_{1n}} \sin \frac{2\lambda_{1n} t}{K_1} \right\}$$

$$H = k r_1 \frac{A_{11}}{r_2} \left(\frac{t}{2} - \frac{K_1}{4\lambda_{11}} \sin \frac{2\lambda_{11} t}{K_1} \right) / P_1$$

$$M = \left\{ \frac{k r_1}{5 k_p} \sum_n N_n \frac{K_1^2}{\lambda_{1n}} \left[K_0(\lambda_{1n} r_2) I_1(\lambda_{1n} r_1) + I_0(\lambda_{1n} r_2) K_1(\lambda_{1n} r_1) \right] \right.$$

$$\left[\frac{1}{L} \sin \frac{\lambda_{1n} t}{K_1} + \frac{\lambda_{1n}}{K_1} \cos \frac{\lambda_{1n} t}{K_1} \right] + \frac{k r_1}{5 k_p} \frac{1}{r_1} \sum_n \frac{K_1^2}{\lambda_{1n}^2} ($$

$$\left. L_n + D_n E_{1,n} H N_1 \right) \begin{pmatrix} 1, & n=1 \\ 0, & n \neq 1 \end{pmatrix} \left(\frac{1}{L} \sin \frac{\lambda_{1n} t}{K_1} + \frac{\lambda_{1n}}{K_1} \cos \frac{\lambda_{1n} t}{K_1} \right)$$

$$+ \frac{I_\infty}{L} \Big\} \Big/ \Big\{ - \frac{k r_1}{5 k_p} \sum_n O_n \frac{K_1^2}{\lambda_{1n}} \Big[K_0(\lambda_{1n} r_2)\, I_1(\lambda_{1n} r_1)$$

$$+ I_0(\lambda_{1n} r_2)\, K_1(\lambda_{1n} r_1) \Big] \Big[\frac{1}{L} \sin \frac{\lambda_{1n} t}{K_1} + \frac{\lambda_{1n}}{K_1} \cos \frac{\lambda_{1n} t}{K_1} \Big]$$

$$- \frac{k r_1}{5 k_p} \frac{1}{r_1} \sum_n \frac{K_1^2}{\lambda_{1n}^2} D_n E_{1,n} H O_1 \begin{pmatrix} 1, & n=1 \\ 0, & n \neq 1 \end{pmatrix} \Big($$

$$\frac{1}{L} \sin \frac{\lambda_{1n} t}{K_1} + \frac{\lambda_{1n}}{K_1} \cos \frac{\lambda_{1n} t}{K_1} \Big) + 1 + \frac{t}{L} \Big\}$$

$$B_{1,n} = D_n \sum_{m=1}^{\infty} E_{m,n} A_{2m} + (C_2 - C_1) W_n D_n$$

$$A_{2,m} = F_m B_{2m} + H A_{11} \begin{Bmatrix} 1, & m=1 \\ 0, & m \neq 1 \end{Bmatrix} + G(C_1 - C_2)$$

Temperature profiles in the penetration computed using this result have been checked against published experimental measurements and agree to within 5% with those.

Shingle Model Summary

In the case of multilayer shingles, see Fig. 4, the expression for the integrated heat transfer is

$$Q = \left\{ k_{x_1} \sum_n A_n K_1 \left(\cosh \frac{\lambda_{1n} t}{K_1} - 1 \right) + k_{x_1} \sum_n B_n K_1 \left(1 - \cos \frac{\gamma_{1n} t}{K_1} \right) + k_{y_1} \sum_n A_n \frac{1}{K_1} + k_{y_1} \sum_n B_n \frac{1}{K_1} \left(\cosh \gamma_1 L_1 - 1 \right) \right\} W$$

where W is the shingle width, and the K's are as before. Similarly, also the γ, λ are eigenvalues of the equations.

$$\lambda_{1n} = \frac{(2n-1)\pi}{2L_1} \quad ; \quad \gamma_{1n} = -\frac{H_5 K_1}{k_{y_1}} \tan \frac{\gamma_{1n} t}{K_1} \quad ; \quad K_i = \sqrt{\frac{k_{y_i}}{k_{x_i}}}$$

$$A_n = \frac{2 T_H H_5}{L_1 \lambda_{1n} \left\{ H_5 \sinh \frac{\lambda_{1n} t}{K_1} + \frac{k_{y_1} \lambda_{1n}}{K_1} \cosh \frac{\lambda_{1n} t}{K_1} \right\}}$$

$$B_m = \frac{-k_{x_2} \sum_n E_n \gamma_{2n} \sinh \left(\gamma_{2n} (L_2 - L_1) \right) I8_{n,m}}{k_{x_1} I5_m \gamma_{1m} \cosh \gamma_{1m} L_1}$$

$$E_n = P_n D_n + H \delta_{1,n}$$

$$P_n = \frac{-k_{x_2} \gamma_{2n} \sinh \left(\gamma_{2n} (L_2 - L_1) \right) \cosh \left(\gamma_{31} (L_3 - L_2) \right) - \cosh \left(\gamma_{2n} (L_2 - L_1) \right)}{\gamma_{31} k_{x_3} \sinh \left(\gamma_{31} (L_3 - L_2) \right)}$$

$$D_n = R_n / S_n$$

$$R_n = \left\{ C \frac{K_1}{\gamma_{11}} \left(1 - \cos \frac{\gamma_{11} t}{K_1}\right) \delta_{1,n} + C \left(\frac{K_1^2}{\gamma_{11}^2} \sin \frac{\gamma_{11} t}{K_1} - \frac{K_1 t}{\gamma_{11}} \cos \frac{\gamma_{11} t}{K_1} \right) X \right.$$

$$\left. H_1 k_{y2} \delta_{1,n} - A_n (-1)^{n+1} I6_{n1} + I8_{n1} H \delta_{1,n} \cosh \gamma_{2n} (L_2 - L_1) \right\} /$$

$$(I5_1 \sinh \gamma_{11} L_1) + \frac{\gamma_{2n} k_{x_2} H \delta_{1,n} I8_{n1} \sinh (\gamma_{2n} (L_2 - L_1))}{k_{x_1} I5_1 \gamma_{11} \cosh \gamma_{11} L_1}$$

$$S_n = - \frac{\gamma_{2n} I8_{n1} k_{x_2} P_n \sinh (\gamma_{2n} (L_2 - L_1))}{I5_1 k_{x_1} \gamma_{11} \cosh \gamma_{11} L_1} - \frac{I8_{n1}}{I5_1 \sinh \gamma_{11} L_1}$$

$$- \frac{I8_{n1} P_n \cosh (\gamma_{2n} (L_2 - L_1))}{I5_1 \sinh \gamma_{11} L_1}$$

$$H = \left\{ -\left(\frac{H_1 C}{k_{y2}} - \frac{H_2}{k_{y3}} F \right) I10_1 - (C - F) I9_1 \right\} / I2_{n1}$$

$$C = H_4 T_H / \left(H_1 + \frac{H_4 H_1 t}{k_{y2}} + H_4 \right)$$

$$F = H_3 T_H / \left(H_2 + \frac{H_2 H_3 t}{k_{y3}} + H_3 \right)$$

$$\delta_{1,n} = \begin{cases} 1 & n=1 \\ 0 & n \neq 1 \end{cases}$$

$$I1_m = \frac{H_2^2 K_3^3}{\gamma_{3m}^3 k_{y3}^2} \left\{ \frac{1}{2} \frac{\gamma_{3m} t}{K_3} - \frac{1}{4} \sin \frac{2\gamma_{3m} t}{K_3} \right\} + \frac{H_2 K_3^2}{\gamma_{3m}^2 k_{y3}} \sin^2 \frac{\gamma_{3m} t}{K_3}$$

$$+ \frac{K_3}{\gamma_{3m}} \left\{ \frac{\gamma_{3m} t}{2 K_3} + \frac{1}{4} \sin \frac{2\gamma_{3m} t}{K_3} \right\}$$

$$I2_{nm} = \frac{H_1 H_2 K_2 K_3}{\gamma_{2n} \gamma_{3m} k_{y2} k_{y3}} \left\{ \frac{\sin\left(\frac{\gamma_{2n}}{K_2} - \frac{\gamma_{3m}}{K_3}\right) t}{2\left(\frac{\gamma_{2n}}{K_2} - \frac{\gamma_{3m}}{K_3}\right)} - \frac{\sin\left(\frac{\gamma_{2n}}{K_2} + \frac{\gamma_{3m}}{K_3}\right) t}{2\left(\frac{\gamma_{2n}}{K_2} + \frac{\gamma_{3m}}{K_3}\right)} \right\}$$

$$+ \frac{H_2 K_3}{\gamma_{3m} k_{y3}} \left\{ \frac{\frac{\gamma_{3m}}{K_3}}{\left(\frac{\gamma_{3m}^2}{K_3^2} - \frac{\gamma_{2n}^2}{K_2^2}\right)} - \frac{\cos\left(\frac{\gamma_{3m}}{K_3} - \frac{\gamma_{2n}}{K_2}\right) t}{2\left(\frac{\gamma_{3m}}{K_3} - \frac{\gamma_{2n}}{K_2}\right)} - \frac{\cos\left(\frac{\gamma_{3m}}{K_3} + \frac{\gamma_{2n}}{K_2}\right) t}{2\left(\frac{\gamma_{3m}}{K_3} + \frac{\gamma_{2n}}{K_2}\right)} \right\}$$

$$+ \frac{H_1 K_2}{\gamma_{2n} k_{y2}} \left\{ \frac{\frac{\gamma_{2n}}{K_2}}{\left(\frac{\gamma_{2n}^2}{K_3^2} - \frac{\gamma_{3m}^2}{K_2^2}\right)} - \frac{\cos\left(\frac{\gamma_{2n}}{K_2} - \frac{\gamma_{3m}}{K_3}\right) t}{2\left(\frac{\gamma_{2n}}{K_2} - \frac{\gamma_{3m}}{K_3}\right)} - \frac{\cos\left(\frac{\gamma_{2n}}{K_2} + \frac{\gamma_{3m}}{K_3}\right) t}{2\left(\frac{\gamma_{2n}}{K_2} + \frac{\gamma_{3m}}{K_3}\right)} \right\}$$

$$+ \frac{\sin\left(\frac{\gamma_{2n}}{K_2} - \frac{\gamma_{3m}}{K_3}\right) t}{\left(\frac{\gamma_{2n}}{K_2} - \frac{\gamma_{3m}}{K_3}\right)} + \frac{\sin\left(\frac{\gamma_{2n}}{K_2} + \frac{\gamma_{3m}}{K_3}\right) t}{\left(\frac{\gamma_{2n}}{K_2} + \frac{\gamma_{3m}}{K_3}\right)}$$

$$I5_m = \frac{K_1}{\gamma_{1m}} \left\{ \frac{1}{2} \frac{\gamma_{1m} t}{K_1} - \frac{1}{4} \sin \frac{2\gamma_{1m} t}{K_1} \right\}$$

$$I6_{nm} = \frac{\left\{ -\frac{\gamma_{1m}}{K_1} \sinh \frac{\lambda_{1n} t}{K_1} \cos \frac{\gamma_{1m} t}{K_1} + \frac{\lambda_{1n}}{K_1} \cosh \frac{\lambda_{1n} t}{K_1} \sin \frac{\gamma_{1m} t}{K_1} \right\}}{\frac{\lambda_{1n}^2}{K_1^2} + \frac{\gamma_{1m}^2}{K_1^2}}$$

$$I8_{nm} = \frac{H_1 K_2}{\gamma_{2n} k_{y2}} \left\{ \frac{\sin\left(\frac{\gamma_{2n}}{K_2} - \frac{\gamma_{1m}}{K_1}\right) t}{2\left(\frac{\gamma_{2n}}{K_2} - \frac{\gamma_{1m}}{K_1}\right)} - \frac{\sin\left(\frac{\gamma_{2n}}{K_2} + \frac{\gamma_{1m}}{K_1}\right) t}{2\left(\frac{\gamma_{2n}}{K_2} + \frac{\gamma_{1m}}{K_1}\right)} \right.$$

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

$$I9_m = -\frac{H_2 K_3^2}{k_{y3} \gamma_{3m}^2} \left(\cos \frac{\gamma_{3m} t}{K_3} - 1 \right) + \frac{K_3}{\gamma_{3m}} \sin \frac{\gamma_{3m} t}{K_3}$$

$$I10_m = \frac{K_3^3 H_2}{\gamma_{3m}^3 k_{y3}} \left\{ \sin \frac{\gamma_{3m} t}{K_3} - \frac{\gamma_{3m} t}{K_3} \cos \frac{\gamma_{3m} t}{K_3} \right\}$$

$$+ \frac{K_3^2}{\gamma_{3m}^2} \left\{ \left(\cos \frac{\gamma_{3m} t}{K_3} - 1 \right) + \frac{\gamma_{3m} t}{K_3} \sin \frac{\gamma_{3m} t}{K_3} \right\}$$

Shingles/substrate Model Summary

This solution is similar to the shingle solution, with all coefficient defined as they are in the previous section. The integrated heat transfer is different, and is:

$$Q = \Bigg\{ k_{x_1} \sum_n A_n \sin(\lambda_{1n} L_1) \left(\frac{K_1}{\lambda_{1n}} \left[\cos\left(\frac{\lambda_{1n} t}{K_1} \right) - 1 \right] \right)$$

$$+ k_{x_1} \sum_n B_n \frac{K_1}{\gamma_{1n}} \sinh(\lambda_{1n} L_1) \left(1 - \cos \frac{\gamma_{1n} t}{K_1} \right)$$

$$+ \frac{2H_1}{1.875} \Bigg[c\left(L_2 - \left(\frac{L_2 - L_1}{8} \right) \right) + \sum_n \frac{D_n}{\gamma_{2n}} \left(\sinh \gamma_{2n} \left(\left(\frac{L_2 - L_1}{8} \right) - L_1 \right) \right.$$

$$\left. - \sinh\left(\gamma_{2n} (L_2 - L_1) \right) \right) - \sum_n \frac{E_n}{\gamma_{2n}} \left(- \sinh \gamma_{2n} \left(L_2 - \left(\frac{L_2 - L_1}{8} \right) \right) \right.$$

$$\left. + \sinh\left(\gamma_{2n} (L_2 - L_1) \right) \right\} W$$

Appendix II - Program Listings and Operating Instructions

Below are shown the listings of the tank design/insulation analysis program used with the NOAA time-sharing computer located at NBS Boulder Laboratories. The final version of this program, designed for use on a large batch processing machine (MSC Univac 1108) has superior diagnostics and runs much faster then the version shown. Hence it is recommended that all interested users contact the contract technical monitor if they desire to use the program.

Basically, the function and relationship of the programs shown here have been described earlier in 5.2.4, so only the operation of the program will be described here:

As the program is entered, the computer requests that a mode number specifying the type of run be entered. The entry of this number which is 1 if one wants to design an individual tank, or 5 to automatically generate the tankage of this report, insures that proper linking of programs will occur during execution.

After entry of this parameter, the machine asks for entry of the following parameters, printing some results after each entry. This interactive entry allows the designer to modify his thinking as the design progresses. The results generated are those shown in the tables of section 5.2.1.2. The input variables are:

fluid volume

ullage

tank type (sphere, cylinder)

maximum spherical radius

tank materials

maximum tank pressure

fluid type

support length

cool down time

fill time

fill pipe length

vent pipe length

use pipe length

fill pressure drop

vent pressure drop

use pressure drop

insulation type

insulation thickness

```
*/
AXC      PROGRAM /IN/
      COMMON MODE,VF,UL,V,IT,R,AHS,ACYL
     1,THCYL,THHD,PMX,MAT,DEN,ID,WF,WT
     2,NUM,DIN,DOT,SL
     3,DT,FPL,VPL,UPL,FPSZ,FPTH,
     4VPSZ,VPTH,UPSZ,UPTH,UT,AL1C,AL2C,AL3C,IN,THIN
     5,AL1H,AL2H,AL3H,T,TH,H1,H2,H3,H4,H5,H6,AKY1,AKY2,AKY3,AKX1,AKX2,AKX3
     6,DNIN,DNSB,AK,EGH,WH,WC,Q,TSB,QCH
     1,IN1,IN2,IN3
Ø     FORMAT(F1Ø.5/)
      GO TO(1,99,1593),MODE
      TYPE 1ØØØ
ØØØ   FORMAT($MODE .....=$)
      ACCEPT 6,MODE
3      FORMAT(I1/)
      TYPE 1ØØ1
ØØ1   FORMAT($INSULATION TYPE: CONT. WRAP  =1$/
     1        $                 FIBERGLASS  =2$/
     2        $ EVACUATED       SHINGLES    =3$/
     3        $ NET SPACED:     BLANKETS    =4$/
     4        $ SUPERFLOC:      BLANKETS    =5$/
     5        $ SUBSRATE WITH   SHINGLES    =6$/
     4 $INSULATION=$)
      ACCEPT 6,IN
      TYPE 1ØØ2
ØØ2   FORMAT($INSULATION THICKNESS(IN) =$)
      ACCEPT 1Ø,THIN
      THIN=THIN/12.
593   CONTINUE
K9     EGH=5.9E-3
      IF(ID-1)534,535,534
+34    TH=368.Ø
      GO TO 536
+35    TH=496.
+36    T=THIN
      GO TO (2Ø,21,22,23,24,25),IN
Ø     DNIN=3.Ø
      AK=1.ØE-5
      FC=2.1
      GO TO 3Ø
1     DNIN=1.Ø
      EGH=6.35E-2
      AK=8.35E-4
      GO TO 3Ø
2     DNIN=1.51
      T=THIN/3.
      H1=1.5E-5/T
```

```
      H2=.75E-5/T
222   AKX=2.3E-2
      AKX1=AKX
       AKX2=AKX
      AKX3=AKX
      H3=5. E-3
      H4=1./(1.7E2+3.3E4*T)
      H5=1./(1.7E2+6.6E4*T)
      IF(ID-1)3334,3335,3334
334   TH=368.
      GO TO 3336
335   TH=496.
336   CONTINUE
      AKY1=3.E-5
      AKY2=3.E-5
      AKY3=2.ØE-5
      GO TO 3Ø
3     DNIN=3.Ø
      AK=7.5E-6
      GO TO 3Ø
4     DNIN=Ø.86
      AK=3.ØE-5
      GO TO 3Ø
5     DNIN=1.51
      DSUB=1.Ø
      IF(THIN-1.5/12.)4441,4441,4442
#441   TSB=1./24.
      GO TO 4443
#442   TSB=1./12.
#443    T=(THIN-TSB)/3.
      H1=1./(T*.3333E5+TSB/.ØØØ835)
      H2=1./(T*.6666E5+TSB/.ØØØ835)
      H6=.ØØØ835/TSB
      GO TO 2222
Ø     GO TO(1ØØ,2ØØ,3ØØ,4ØØ,4ØØ,3ØØ),IN
ØØ    WIN=(AHS+ACYL)*DNIN*THIN+(AHS+ACYL)*.Ø1
      CKT=1./(T/AK+1./5.9E-3)
      Q=1.2*2.1*(ACYL+AHS)*CKT*TH
      GO TO 5ØØ
ØØ    WIN=(AHS+ACYL)*DNIN*THIN+(AHS+ACYL)*.Ø1
      FKT=1./(T/AK+1./5.9E-3)
      Q=(ACYL+AHS)*FKT*TH
      GO TO 5ØØ
ØØ    DC=3.141592*R/3.
       ALP=3.141592/3.
      IF(DC-4.)3Ø5,3Ø5,3Ø4
Ø4    ALP=2./R
      DC=4.
```

```
Ø5    SLH=3.141592*R/6.
      IF(SLH-4.)31Ø,31Ø,3Ø9
Ø9    SLH=4.
      INM=3*IFIX((3.141592*R/2.-ALP*R/3.)/SLH-.Ø1)+1
      W=Ø.Ø
      DO 315,I=1,INM
      W=W+3.141592*R*(SIN(ALP/3.+FLOAT(I-1)*8./(6.*R))
     1+SIN(ALP/3.+FLOAT(I)*4./(3.*R)))
      IF(I-2)315,314,315
14    W12=W
15    CONTINUE
      GO TO321
1Ø    INM=3*IFIX((3.141592*R/2.-ALP*R/3.)/SLH-.Ø1)+1
      W=Ø.Ø
      DO 32Ø I=1,INM
      W=W+3.141592*R*(SIN(ALP/3.+FLOAT(I-1)*3.141592/18.)
     1+SIN(ALP/3.+FLOAT(I)*3.141592/18.))
      IF(I-2)32Ø,319,32Ø
19    W12=W
2Ø    CONTINUE
21    SLC=ACYL/(2.*3.141592*R)
       IF(SLC-4.)312,312,311
11     SLC=4.
12    WH=2.*W-W12
      WC=ACYL/SLC
      AL1H=SLH/3.
      AL2H=2.*AL1H
      AL3H=3.*AL1H
      AL1C=SLC/3.
      AL2C=2.*AL1C
      AL3C=3.*AL1C
      Q=.Ø49*.Ø83/THIN+3.14159*DC*AKY3*TH/(18.*THIN)
      WIN=THIN*(ACYL+AHS)*DNIN+(ACYL+AHS)*.Ø1+THIN*DNIN*
     1(ACYL/(2.*3.141592*R)+3.141592*R)/1.2
      IF(IN-6)5ØØ,329,5ØØ
29    WIN=(ACYL+AHS)*(DNIN*THIN+DSUB*TSB+.Ø1)
     1+THIN*DNIN*(ACYL/(2.*3.141592*R)+3.141592*R)/1.2
      GO TO 5ØØ
#ØØ    DC=3.141592*R/3.
       ALP=3.141592/6.
      IF(DC-4.)4Ø2,4Ø2,4Ø1
#Ø1    ALP=2./R
      DC=4.
#Ø2    BLH=3.141592*R/6.
      IF(BLH-4.)43Ø,43Ø,4Ø3
#Ø3    BLH=4.
#3Ø    INM=IFIX((3.141592*R/2.-ALP*R)/BLH-.Ø1)+1
      BET=BLH/R
```

```
      W=4.
      TWH=Ø.Ø
      BLS=Ø.Ø
      BLST=Ø.Ø
       NOB=Ø
      DO 41Ø I=1,INM
      WL=3.141592*R*(SIN(ALP+FLOAT(I-1)*BET)+SIN(ALP+FLOAT(I)*BET))/8.
      IF(W-WL)4Ø7,4Ø8,4Ø8
#Ø8    W=WL
#Ø7    TWH=TWH+W
      BLS=BLS+3.141592*2.*R*(ALP+FLOAT(I-1)*BET)
      BLST=BLST+IFIX(3.141592*R*(SIN(ALP+FLOAT(I-1)*BET)
     1+SIN(ALP+FLOAT(I)*BET))/W-.Ø1)+1
      NOB=NOB+IFIX(3.141592*R*(SIN(ALP+FLOAT(I-1)*BET)+SIN(ALP+FLOAT(I)*BET))
     1/W)+1
      W=4.
#1Ø    CONTINUE
      BLS=BLS+BLH*BLST
      BLS=2.*BLS
      BLC=ACYL/(3.141592*2.*R)
      IF(BLC-4.)431,431,432
#32    BLC=4.
#31    BWC=3.141592*R/4.
      IF(BWC-4.)433,433,434
#34    BWC=4.
#33    ALC=ACYL/(3.141592*R*2.)
      BLS=BLS+ALC*(IFIX(3.141592*R/BWC-.Ø1)+1)+3.141592*2.*R*(IFIX(ALC/BLC
     1-.Ø1)+2)
      IF (IT-1)438,439,438
#38    NOB=2*NOB+(IFIX(3.141592*2.*R/BWC-.Ø1)+1)*( FIX(ALC/BLC-.Ø1)+1)
     1+2
      GO TO 45Ø
#39    NOB=2*NOB+2
#5Ø    WIN=(ACYL+AHS)*(.Ø1+THIN*DNIN*1.Ø5)+4.*FLOAT(NOB)*.1
      TBK=1./(T/AK+1./5.9E-3)
      Q=1.2*(ACYL+AHS)*TBK*TH+.Ø5*.Ø83*BLS/T
      AWH=(TWH/FLOAT(INM)+BLH)/2.
      AWC=(BLC+BWC)/2.
+ØØ    TYPE 2ØØ1,WIN
ØØ1   FORMAT($INSULATION WEIGHT =$,F1Ø.2/)
      TYPE 2ØØ2,Q
ØØ2   FORMAT($PARTIAL Q=$,E14.4/)
      CHAIN (/GD/) .
       END
```

```
*/
AXC      PROGRAM /GD/
      COMMON MODE,VF,UL,V,IT,R,AHS,ACYL
     1,THCYL,THHD,PMX,MAT,DEN,ID,WF,WT
     2,NUM,DIN,DOT,SL
     3,DT,FPL,VPL,UPL,FPSZ,FPTH,
     4VPSZ,VPTH,UPSZ,UPTH,UT,AL1C,AL2C,AL3C,IN,THIN
     5,AL1H,AL2H,AL3H,T,TH,H1,H2,H3,H4,H5,H6,AKY1,AKY2,AKY3,AKX1,AKX2,AKX3
     6,DNIN,DNSB,AK,EGH,WH,WC,Q,TSB,QGH
     7,IN1,IN2,IN3
      GO TO(3,73,73),MODE
      TYPE 999
K99    FORMAT($MODE .....=$)
      ACCEPT 6,MODE
3      FORMAT(I1/)
;3     GO TO(2Ø,3Ø,2Ø,2Ø,2Ø,4Ø),IN
Ø     IF(ID-1)21,22,21
1      GHK=.Ø1ØØ7
       GO TO 5Ø
2      GHK=.Ø546
       GO TO 5Ø
Ø      GHK=.Ø17
+Ø      RGH=T/GHK
      GO TO 55
#Ø     RGH=T/.Ø1ØØ7+TSB/.ØØØ7
+5     TI=.85*TH
      HP=5.57*(V**.166666)
;Ø     IF(TH-TI)69,71,71
39     DLT=-(EGH*TI**4+TI*(1./RGH-HP*(TI-TH)**.25)-EGH*TH**4+HP*(TI-TH)**.25*TH
     1/(4.*EGH*TI**3+1./RGH-HP*(TI-TH)**.25+HP*(TI-TH)**(-.75)
     2*(TI-TH)/4.)
       GO TO 72
;1     DLT=-(EGH*TI**4+TI*(1./RGH+HP*(TH-TI)**.25)-EGH*TH**4-HP*(TH-TI)**.25*TH
     1/(4.*EGH*TI**3+1./RGH+HP*(TH-TI)**.25-HP*(TH-TI)**(-.75)
     2*(TI-TH)/4.)
;2     TI=TI+DLT
      IF((DLT/TI)**2-.ØØØ1)1ØØ,1ØØ,7Ø
ØØ     QGH=(ACYL+AHS)*TI/RGH
       IF(ID-1)1Ø1,1Ø2,1Ø1
Ø1     GHKP=.27
       GO TO 1Ø3
Ø2     GHKP=.23
Ø3     QGHP=Ø.Ø
       DO 12Ø I=1,NUM
       QGHP=QGHP+GHKP*3.141592*DIN*(DOT-DIN)*TH/(2.*(SL+THIN))
2Ø     CONTINUE
       GHKP=6.5
       QGHP=QGHP+GHKP*3.141592*TH*(FPSZ*FPTH/(FPL+THIN)+VPSZ*VPTH/(VPL+THIN)
     1+UPSZ*UPTH/(UPL+THIN)+.5*.Ø32/(R+THIN))
       IF(V-5ØØØ.)125,125,122
22     QGHP=QGHP+.5*.Ø32/(R+THIN)
25     QGH=QGH+QGHP
       TYPE 2ØØØ,(QGHP,QGH)
ØØØ    FORMAT($QPEN(GH)=$,F1Ø.3,$   Q GRD. HOLD=$,F1Ø.3/)
       CHAIN (/PN/)
       END .
```

```
*/
AX←      PROGRAM /PN/
      COMMON MODE,VF,UL,V,IT,R,AHS,ACYL
     1,THCYL,THHD,PMX,MAT,DEN,ID,WF,WT
     2,NUM,DIN,DOT,SL
     3,DT,FPL,VPL,UPL,FPSZ,FPTH,
     4VPSZ,VPTH,UPSZ,UPTH,UT,AL1C,AL2C,AL3C,IN,THIN
     5,AL1H,AL2H,AL3H,T,TH,H1,H2,H3,H4,H5,H6,AKY1,AKY2,AKY3,AKX1,AKX2,AKX3
     6,DNIN,DNSB,AK,EGH,WH,WC,Q,TSB,QGH
     7,IN1,IN2,IN3
      TAN(XXX)=SIN(XXX)/COS(XXX)
      GO TO(3,73,73),MODE
      TYPE 999
K99    FORMAT($MODE ..................=$)
      ACCEPT 6,MODE
3      FORMAT(I1/)
;3     CONTINUE
      GO TO(1Ø,2Ø,3Ø,4Ø,5Ø,3Ø),IN
Ø     PN=1234.567
      PD1=13ØØ.
      PD2=4ØØ.
      PH1=65.
      PH2=5.17E-
      PA=348.*EXP(-14.3)
      PQ=-.ØØ438
      GO TO 1ØØ
Ø     PN=12ØØ.
      PLN=4.
      PD1=5ØØ.
      PD2=5ØØ.
      PH1=5ØØ.
      PH2=5.17E-9
      PA=348.*EXP(-12.)
      PQ=-.ØØ3
      GO TO 1ØØ
Ø     PN=8Ø4.
      SLC=ACYL/(2.*3.141592*R)
      IF(SLC-4.)312,312,311
11    SLC=4.
12    PLN=SLC
      PD1=234ØØ.
      PD2=6.E-5
```

```
      PH1=1.E6
      PH2=5.17E-9
      PA=348.*EXP(-16.862)
      PQ=-.ØØ438
      GO TO 1ØØ
#Ø     PN=6ØØ.
      PD1=1ØØØØ.
      PD2=4ØØ.
      PH1=5ØØ.
      PH2=5.17E-9
      PA=348.*EXP(-16.)
      PQ=-.ØØ438
      GO TO 97
+Ø     PN=396.
      PD1=1ØØØØØ.
      PD2=4ØØ.
      PH1=5ØØØ.
      PH2=5.17E-9
      PA=348.*EXP(-16.862)
      PQ=-.ØØ438
K7     BLC=4.
      BWC=3.141592*R/4.
      IF(BWC-4.)433,433,434
#34    BWC=4.
#33    PLN=.25*(BWC+BLC)
ØØ    PF=1.E-5
      PR=2.22E-3
      PT=15Ø.
      PO=1Ø.
      PA=ACYL+AHS
      PDL=Ø.Ø
      PS=1.
      PD=.Ø1*SQRT(PH2)
5Ø    PDL=PDL+PD
      IF(PS*(PH2/(SQRT(PD2)*PDL)-TAN(PDL/SQRT(PD2))))3ØØ,3ØØ,25Ø
ØØ    PS=PS*(-1.)
      PD=-.5*PD
      IF((TAN(PDL/SQRT(PD2))-PH2/(PDL*SQRT(PD2)))**2-.ØØØØØØ1)35Ø,35Ø,25Ø
·5Ø   PGL=Ø.Ø
      PS=1.
      PD=.Ø1*SQRT(PH1)
51    PGL=PGL+PD
      IF(PS*(PH1/(SQRT(PD1)*PGL)-TAN(PGL/SQRT(PD1))))3Ø1,3Ø1,251
Ø1    PS=PS*(-1.)
      PD=-.5*PD
      IF((TAN(PGL/SQRT(PD1))-PH1/(PGL*SQRT(PD1)))**2-.ØØØØØØ1)351,351,251
51     PLM=SQRT(PDL**2+PGL**2)
      TI=1./PQ*ELOG(PO*1.E-5*(PLM**2+PQ)/(PN*PR*PT*PA))
```

```
      TX=-ELOG(1.E-5)/PLM**2
      IF(TI-TX)85Ø,911,911
C5Ø    TI=TX
K11    PB1=-SQRT(PD1*PD2/(PDL**2*PGL**2))*SIN(THIN*SQRT(PDL**2/PD2))
     1*SIN(PLN*SQRT(PGL**2/PD1))/((THIN/2.+.25*SQRT(PD2/PDL**2)
     2*SIN(2.*THIN*SQRT(PDL**2/PD2)))*(PLN/2.+.25*SQRT(PD1/PGL**2)
     3*SIN(2.*PLN*SQRT(PGL**2/PD1))))
       PFI=PF-(PA*PR*PT/PO)*(-PN*EXP(PQ*TI)/(PLM**2+PQ)
     1-PN*PLM**2*EXP(-PLM**2*TI)/(PQ*(PQ+PLM**2))+PN*EXP(-PLM**2*TI)/PQ
     2-PO*EXP(-PLM**2*TI)/(PA*PR*PT))*PB1
      PFIT=-PA*PR*PT*PB1/PØ*(-PN*PQ*EXP(PQ*TI)/(PLM**2+PQ)
     1+PLM**4*PN*EXP(-PLM**2*TI)/(PQ*(PQ+PLM**2))-PN*PLM**2*EXP(-PLM**2*TI)/PQ
     2+PO*PLM**2*EXP(-PLM**2*TI)/(PA*PR*PT))
      DTI=-PFI/PFIT
      TI=TI+DTI
      IF((DTI/TI)**2-.ØØØ1**2)1ØØØ,911,911
ØØØ   TYPE 2ØØ2,TI
ØØ2   FORMAT($P. D. TIME=$,E14.4/)
K9999 TYPE 999
      ACCEPT 6,MODE
      CHAIN (/IT/)
      END
```

```
*/
AX      PROGRAM /IT/
      COMMON MODE,VF,UL,V,IT,R,AHS,ACYL
     1,THCYL,THHD,PMX,MAT,DEN,ID,WF,WT
     2,NUM,DIN,DOT,SL
     3,DT,FPL,VPL,UPL,FPSZ,FPTH,
     4VPSZ,VPTH,UPSZ,UPTH,UT,AL1C,AL2C,AL3C,IN,THIN
     5,AL1H,AL2H,AL3H,T,TH,H1,H2,H3,H4,H5,H6,AKY1,AKY2,AKY3,AKX1,AKX2,AKX3
     6,DNIN,DNSB,AK,EGH,WH,WC,Q,TSB,QGH
     7,IN1,IN2,IN3
3       FORMAT(I1/)
      IF(MODE-3)3,1Ø,3
      TYPE 999
K99    FORMAT($MODE .....=$)
      ACCEPT 6,MODE
      GO TO(1,1,1Ø5,5,9Ø55),MODE
KØ55   MODE=3
      TYPE 1ØØ1
ØØ1   FORMAT($VF=$)
      ACCEPT 8,VF
```

```
      TYPE 1ØØ2
      ACCEPT 8,UT
ØØ2   FORMAT($UT=$)
      TYPE 1ØØ3
ØØ3   FORMAT($THIN=$)
      ACCEPT 8,THIN
      TYPE 1ØØ4
ØØ4   FORMAT($ID=$)
      ACCEPT 6,ID
      TYPE 1ØØ5
ØØ5   FORMAT($IN=$)
      ACCEPT 6,IN
C      FORMAT(F1Ø.2/)
      CHAIN (/TK/)
+      ID=1
;      UT=.5
      VF=4ØØØ.
      IN1=Ø
      IN2=Ø
      IN3=Ø
      MODE=3
      CHAIN (/TK/)
Ø     IN1=IN1+1
       GO TO(1ØØ,1Ø1,1Ø2,1Ø3,1Ø4,1Ø5,1Ø6,1Ø7,1Ø8),IN1
ØØ     VF=5ØØØ.
       GO TO 11Ø
Ø1     VF=6ØØØ.
       GO TO 11Ø
Ø2     VF=8ØØØ.
       GO TO 11Ø
Ø3     VF=1ØØØØ.
       GO TO 11Ø
Ø4     VF=12ØØØ.
       IF(ID-2)11Ø,199,11Ø
99     IN1=8
       GO TO 11Ø
Ø5     VF=15ØØØ.
       GO TO 11Ø
Ø6     VF=21ØØØ.
       GO TO 11Ø
Ø7     VF=26ØØØ.
       GO TO 11Ø
Ø8     VF=32ØØØ.
       GO TO 11Ø
Ø9     UT=216Ø.
       IN1=Ø
       GO TO 2ØØ
ØØ    IN1=IN1+1
```

```
      GO TO(2Ø1,2Ø2,2Ø3,2Ø4,2Ø5,2Ø6,2Ø7,2Ø8,2Ø9,21Ø,211,212),IN1
Ø1    VF=5.
      GO TO 22Ø
Ø2    VF=2Ø.
      GO TO 22Ø
Ø3    VF=5Ø.
      GO TO 22Ø
Ø4    VF=1ØØ.
      GO TO 22Ø
Ø5    VF=2ØØ.
      GO TO 22Ø
Ø6    VF=5ØØ.
      GO TO 22Ø
Ø7    VF=1ØØØ.
      GO TO 22Ø
Ø8    VF=2ØØØ.
      GO TO 22Ø
Ø9    VF=3ØØØ.
      GO TO 22Ø
1Ø    VF=4ØØØ.
      GO TO 22Ø
11    VF=5ØØØ.
      GO TO 22Ø
12    ID=ID+1
      IF(ID-3)215,3ØØ,215
1Ø    CONTINUE
 SHORT TERM
2Ø    CONTINUE
 LONG TERM
      CHAIN (/TK)
15    GO TO 7
ØØ    CALL EXIT
      END
```

```
*/

C      PRØGRAM /TK/
       COMMON MODE,VF,UL,V,IT,R,AHS,ACYL
      1,THCYL,THHD,PMX,MAT,DEN,ID,WF,WT
      2,NUM,DIN,DOT,SL
      3,DT,FPL,VPL,UPL,FPSZ,FPTH,
      4VPSZ,VPTH,UPSZ,UPTH,UT,AL1C,AL2C,AL3C,IN,THIN
      5,AL1H,AL2H,AL3H,T,TH,H1,H2,H3,H4,H5,H6,AKY1,AKY2,AKY3,AKX1,AKX2,AKX3
      6,DNIN,DNSB,AK,EGH,WH,WC,Q,TSB,QGH
      1,IN1,IN2,IN3
       GO TO(7137,7138,7138),MODE
;137   TYPE 1ØØØ
       ACCEPT 11,MODE
       TYPE 1ØØ1
       ACCEPT 1Ø,VF
       TYPE 1ØØ2
       ACCEPT 1Ø,UL
+       TYPE 1ØØ3
       ACCEPT 11,IT
Ø      FORMAT(F1Ø.5/)
1      FORMAT(I1/)
ØØØ    FORMAT($PROGRAM MODE    ..............=$)
ØØ1    FORMAT($FLUID VOLUME    ..............=$)
ØØ2    FORMAT($ULLAGE (%)        ............=$)
ØØ3    FORMAT($TANK TYPE  :SPHERE      =1$/
     2         $  CYLINDER(HEMI-HEADS) =2$/
     4         $ TANK TYPE       ............=$)
ØØ4    FORMAT($MAX SPHERE DIA. ............=$)
ØØ5    FORMAT($MAXIMUM L/D     ............=$)
ØØ6    FORMAT($MAX. CYLINDER DIA. .........=$)
       GO TC 7139
;138    UL=.1
       IF(V-5ØØØ.)7123,7123,7124
;123    IT=1
       GO TO  7125
;124    IT=2
       ALD=4.
       V=1.1*VF
       R=(V/(3.33333*3.141592))**.333333
       IF(2.*R-33.)29Ø,29Ø,2Ø9
;125     DM=33.Ø
;139    V=(.Ø1*UL+1.ØØ)*VF
       GO TO (1ØØ,2ØØ),IT
ØØ     IF(MODE-3)11Ø1,1Ø11,11Ø1
1Ø1    TYPE 1ØØ4
       ACCEPT 1Ø,DM
Ø11    R=(3.*V/(4.*3.1415921))**.3333333
```

```
      A=4.Ø*3.1415921*R**R
      AHS=A
      ACYL=Ø.Ø
      AREA=A
      IF(R-DM/2.)1Ø5,1Ø5,1Ø2
Ø2    MODE=1
      TYPE 2ØØØ
ØØØ   FORMAT($**********CONFLICT***VOL&DIAMETER**************$/)
      GO TO 5
Ø5    TYPE 2ØØ1,(R,A)
ØØ1   FORMAT($SPHERE      R=$,F1Ø.5,$      A=$,F1Ø.5/)
      GO TO 5ØØ
ØØ    CONTINUE
      TYPE 1ØØ5
      ACCEPT 1Ø,ALD
      TYPE 1ØØ6
      ACCEPT 1Ø,DMX
      RT=(3.*V/(4.*3.1415921))**.33333333
      IF(RT-DMX/2.)2Ø3,2Ø3,2Ø7
Ø3    R=RT*.9Ø
      AL=(V-1.333333*3.1415921*R**3)/(3.1415921*R**2)
      IF(ALD-AL/(2.*R))2Ø4,29Ø,29Ø
Ø4    TYPE 2ØØ2
KØØ2    FORMAT($*******SPHERE INDICATED**********$/)
      GO TO 1ØØ
Ø7    R=DMX/2.
      AL=(V-1.333333*3.1415921*R**3)/(3.1415921*R**2)
      IF(ALD-AL/(2.*R))2Ø9,29Ø,29Ø
Ø9     MODE=1
      TYPE 2ØØ3
ØØ3   FORMAT($*********CONFLICT**L/D&DIAMETER*********$/)
      GO TO 1
9Ø    AHS=4.*3.1415921*R**2
      ACYL=2.*3.1415921*R*AL
      AREA=AHS+ACYL
      TYPE 2ØØ4,(R,AL,AREA,AHS,ACYL)
.ØØ4  FORMAT($RADIUS =$,F1Ø.5/$LENGTH =$,F1Ø.5
     1/$TOTAL AREA =$,F1Ø.5,$ HEADS =$,F1Ø.5,
     2$ CYLINDER =$,F1Ø.5/)
+ØØ    CHAIN (/WL/)
      END
```

```
C      PROGRAM /WL/
       COMMON MODE,VF,UL,V,IT,R,AHS,ACYL
      1,THCYL,THHD,PMX,MAT,DEN,ID,WF,WT
      2,NUM,DIN,DOT,SL
      3,DT,FPL,VPL,UPL,FPSZ,FPTH,
      4VPSZ,VPTH,UPSZ,UPTH,UT,AL1C,AL2C,AL3C,IN,THIN
      5,AL1H,AL2H,AL3H,T,TH,H1,H2,H3,H4,H5,H6,AKY1,AKY2,AKY3,AKX1,AKX2,AKX3
      6,DNIN,DNSB,AK,EGH,WH,WC,Q,TSB,QGH
      7,IN1,IN2,IN3
Ø      FORMAT(F1Ø.5/)
       GO TO(1,1ØØ,1593),MODE
       TYPE 1ØØØ
ØØØ    FORMAT($MODE .....=$)
       ACCEPT 6,MODE
3       FORMAT(T1/)
       TYPE 1ØØ1
ØØ1    FORMAT($TANK MATERIALS:          ICONEL-X .....=1$/
      1$                          3Ø4 SS(5Ø%).....=2$/
      2$                          6Ø61-T6(AL).....=3$/
      3$                          6AL-4V(TI) .....=4$/
      4$MATERIAL=$)
       ACCEPT 6 ,MAT
       TYPE 1ØØ2
ØØ2    FORMAT($MAXIMUM PRESSURE .....=$)
       ACCEPT 1Ø,PM
       TYPE 1ØØ4
ØØ4    FORMAT($FLUID TYPE: H2=1, O2=2$/
      1                    $ .....=$)
       ACCEPT 6,ID
       GO TO 1ØØ
593    MAT=2
       PM=54.7
ØØ     GO TO(1Ø1,1Ø2,1Ø3,1Ø4),MAT
Ø1     SIG=8ØØØØ.
       DEN=123456789.Ø
       EM=123456789.
       GO TO 1Ø5
Ø2     SIG=9ØØØØ.
       DEN=.286
       EM=2.3E7
       GO TO 1Ø5
Ø3     SIG=21ØØØ.
       DEN=.Ø955
       EM=1.E7
       GO TO 1Ø5
Ø4      SIG=7ØØØØ.
        DEN=.164
       EM=1.6E7
```


5⊕

```
Ø5    THMN=SQRT((5.*14.7*1.732*SQRT(1.-.3Ø3**2))/EM)*R*12.Ø
      THHD=PM*R*12./(1.7*SIG-Ø.2*PM)
      IF(THHD-THMN)12Ø,12Ø,12Ø
1Ø    THHD=THMN
2Ø     IF(ACYL)13Ø,13Ø,14Ø
3Ø     THCYL=Ø.Ø
       GO TO 2ØØ
4Ø     THCYL=PM*R*12.Ø/(Ø.85*SIG-Ø.6*PM)
ØØ     GO TO (3ØØ,4ØØ).ID
ØØ     WT=144.Ø*(AHS*THHD+ACYL*THCYL)*1.2*DEN
       WF=VF*4.418
       GO TO 5ØØ
#ØØ     WT=144.Ø*(AHS*THHD+ACYL*THCYL)*1.8*DEN
       WF=VF*7Ø.8
+ØØ     TW=WT+WF
       TYPE 2ØØØ,(THHD,THCYL )
ØØØ   FORMAT($HEAD THICKNESS =$,F1Ø.5/
     1        $WALL THICKNESS =$,F1Ø.5/)
      TYPE 2ØØ1,(WT,WF,TW)
ØØ1   FORMAT($TANK WEIGHT =$,F1Ø.2,$  FLUID WEIGHT =$,F1Ø.2/
     1        $TOTAL WEIGHT =$,F1Ø.2/)
      THHD=THHD/12.
      THCYL=THCYL/12.
      CHAIN (/ST/)
      END
```

```
*/

C       PROGRAM /ST/
        COMMON MODE,WF,UL,V,IT,R,AHS,ACYL
       1,THCYL,THHD,PMX,MAT,DEN,ID,WF,WT
       2,NUM,DIN,DOT,SL
       3,DT,FPL,VPL,UPL,FPSZ,FPTH,
       4VPSZ,VPTH,UPSZ,UPTH,UT,AL1C,AL2C,AL3C,IN,THIN
       5,AL1H,AL2H,AL3H,T,TH,H1,H2,H3,H4,H5,H6,AKY1,AKY2,AKY3,AKX1,AKX2,AKX3
       6,DNIN,DNSB,AK,EGH,WH,WC,Q,TSB,QGH
       7,IN1,IN2,IN3
        GO TO(3,73,1593),MODE
        TYPE 999
K99     FORMAT($MODE .....=$)
        ACCEPT 6,MODE
3       FORMAT(I1/)
        TYPE 1ØØØ
ØØØ     FORMAT($SUPPORT LENGTH (IN).....=$)
        ACCEPT 1Ø,SL
        SL=SL/12.
        GO TO 73
593     SL=3.
;3       G1=8.5
        G2=3.5
        SG=14ØØØØØ.Ø
        E=5.4E6
        ALP=1Ø.Ø
        BET=45.Ø
        IF(THCYL)2ØØ,1ØØ,2ØØ
ØØ      NUM=6
        GO TO 25Ø
ØØ      IF(ACYL/(3.1415921*R**2.)-2.5)1ØØ,22Ø,22Ø
2Ø      NUM=12
5Ø      TW=WF+WT
        ALP=ALP*3.1415921/18Ø.
        BET=BET*3.1415921/18Ø.
        A=6.*G1*TW/(NUM*SG*3.1415921*COS(ALP)*COS(BET))
        B=96.*144.*G2*TW*SL**L/(NUM*E*3.1415921**3
       1*COS(ALP)*COS(BET))
        TYPE 2ØØØ
ØØØ     FORMAT($NUMBER OF STRUTS  =$)
        TYPE 11,NUM
        IF(B/A-A)111,222,222
11      DIN=(((B/A+A)/2.)**2.-B)**.25
        GO TO 333
22      DIN=SQRT(.5*(B/A-A))
33      DOT=SQRT(.5*(B/A+A))
Ø       FORMAT(F1Ø.5/)
1       FORMAT(I2/)
        TYPE 2ØØ1,(DIN,DOT)
ØØ1     FORMAT($STRUT ID= $,F1Ø.5,$  STRUT OD = $,F1Ø.5/)
        DIN=DIN/12.
        DOT=DOT/12.
        CHAIN (/PE/)
        END
```

```
*/

C      PROGRAM /PE/
       COMMON MODE,VF,UL,V,IT,R,AHS,ACYL
      1,THCYL,THHD,PMX,MAT,DEN,ID,WF,WT
      2,NUM,DIN,DOT,SL
      3,DT,FPL,VPL,UPL,FPSZ,FPTH,
      4VPSZ,VPTH,UPSZ,UPTH,UT,AL1C,AL2C,AL3C,IN,THIN
      5,AL1H,AL2H,AL3H,T,TH,H1,H2,H3,H4,H5,H6,AKY1,AKY2,AKY3,AKX1,AKX2,AKX3
      6,DNIN,DNSB,AK,EGH,WH,WC,Q,TSB,QGH
      7,IN1,IN2,IN3
       DIMENSION F(15),DIAN(81),THN(81)
       DO 7393 I=1,8Ø
       IF(I-2)7381,7381,7382
;381   DIAN(I)=.3Ø7
       THN(I)=.Ø49
       GO TO 7393
;382   IF(I-3)16Ø9,16Ø9,1611
6Ø9    DIAN(I)=.41Ø
       THN(I)=.Ø65
       GO TO 7393
611    IF(I-4)7383,7383,7384
;383   DIAN(I)=.545
       THN(I)=.Ø65
       GO TO 7393
;384   IF(I-5)7385,7385,7386
;385   DIAN(I)=.71Ø
      THN(I)=.Ø65
      GO TO 7393
;386   IF(I-7)7387,7387,7388
;387   DIAN(I)=.92
      THN(I)=.Ø65
      GO TO 7393
:388   IF(I-9)7389,7389,739Ø
;389   DIAN(I)=1.185
      THN(I)=.Ø65
      GO TO 7393
;39Ø   IF(I-12)7341,7341,7342
;341    DIAN(I)=1.53
       THN(I)=.Ø65
      GO TO 7393
;342   IF(I-14)7343,7343,7344
.;343  DIAN(I)=1.77
      THN(I)=.Ø65
      GO TO7393
;344   IF(I-17)7345,7345,7346
;345   DIAN(I)=2.245
      THN(I)=.Ø65
```

```
      GO TO 7393
;346   IF(I-21)7347,7347,7348
;347   DIAN(I)=2.7Ø9
      THN(I)=.Ø83
      GO TO 7393
;348   IF(I-26)7349,7349,735Ø
;349   DIAN(I)=3.334
      THN(I)=.Ø83
      GO TO 7393
;35Ø   IF(I-3Ø)7351,7351,7352
;351   DIAN(I)=3.834
      THN(I)=.Ø83
       GO TO 7393
;352   IF(I-34)7353,7353,7354
;353   DIAN(I)=4.334
      THN(I)=.Ø83
      GO TO 7393
;354   IF(I-42)7355,7355,7356
;355   DIAN(I)=5.345
      THN(I)=.1Ø9
      GO TO 7393
;356   IF(I-51)7357,7357,7358
;357   DIAN(I)=6.4Ø7
      THN(I)=.1Ø9
      GO TO 7393
;358   IF(I-67)7359,7359,736Ø
;359   DIAN(I)=8.4Ø7
      THN(I)=.1Ø9
      GO TO 7393
;36Ø   IF(I-86)7361,7361,7393
;361   DIAN(I)=1Ø.842
      THN(I)=.134
;393   CONTINUE
      DIAN(81)=1234.
      THN(81)=12.34
      F(7)=-1.364
      F(8)=-1.5Ø
      F(9)=-1.636
      F(1Ø)=-1.747
      F(11)=-1.851
      F(12)=-1.919
      F(13)=-2.Ø29
      F(14)=-2.Ø72
      F(15)=-2.15
      DO 7 I=1,6
;      F(I)=Ø.Ø
      GO TO(3,73,9876),MODE
      TYPE 999
```

```
K99   FORMAT($MODE .....=$)
      ACCEPT 6,MODE
3      FORMAT(I1/)
      TYPE 1ØØØ
ØØØ   FORMAT($TOTAL COOL DOWN AND FILL TIME ....=$)
      ACCEPT 1Ø,DT
Ø     FORMAT(F1Ø.2/)
ØØ1   FORMAT($FILL  PIPE LENGTH  ........=$)
ØØ2   FORMAT($VENT  PIPE LENGTH  ........=$)
ØØ3   FORMAT($USE   PIPE LENGTH  ........=$)
      TYPE 1ØØ1
      ACCEPT 1Ø,FPL
      TYPE 1ØØ2
      ACCEPT 1Ø,VPL
      TYPE 1ØØ3
      ACCEPT 1Ø,UPL
      TYPE 1ØØ4
ØØ4   FORMAT($FILL  DELTA-PRESSURE ......=$)
      ACCEPT 1Ø,FPDP
      TYPE 1ØØ5
ØØ5   FORMAT($VENT DELTA-PRESSURE ......=$)
      ACCEPT 1Ø,VPDP
      TYPE 1ØØ6
ØØ6   FORMAT($USE   DELTA-PRESSURE .....=$)
      ACCEPT 1Ø,UPDP
      GO TO 73
K876   DT=.5
      IF(V-12ØØØ.)3754,3754,3755
754   DT=.25
755   FPL=2Ø.
      VPL=R
      UPL=R
      FPDP=2Ø.
      VPDP=14.7
      UPDP=14.7
;3     GO TO(2Ø,3Ø),ID
Ø     DH=19Ø.Ø
      SS=115Ø.
      RHO=4.418
      RHOG=.Ø83
      GO TO(21,22,23,24),MAT
1     DSH=123456789.
      GO TO 25
2     DSH=43.Ø
      GO TO 25
3     DSH=75.Ø
      GO TO 25
4     DSH=45.Ø
```

```
5     VCOS=8.85E-6
      VCOST=7.Ø5E-7
      GO TO 4Ø
Ø     DH=91.6
      SS=66Ø.
      RHO=7Ø.8
      RHOG=.273
      GO TO(31,32,33,34),MAT
1     DSH=123456789.
      GO TO 35
2     DSH=39.Ø
      GO TO 35
3     DSH=7Ø.Ø
      GO TO 35
4     DSH=41.Ø
5     VCOS=1.26E-4
      VCOST=4.7E-6
#Ø     DPE=.125
      DQF=DSH*ΠT*(RHO*DH*VF/(ΠSH*ΠT)+1.)/(DH*ΠT*36ØØ.)
+Ø     DPEF=DPE/12.
      FPV=DQF/(3.141592*DPEF**2/4.)
      RE=RHO*FPV*DPEF/VCOS
      REL=.8686*ELOG(RE)
      IRE=IFIX(2.*REL)
      IF(IRE-15)1113,2223,2223
223   FF=.ØØ5
      GO TO 1231
113   FIRE=FLOAT(IRE)
      FE=(2.Ø*REL-FIRE)*(F(IRE)-F(IRE+1))+F(IRE+1)
      FF=1Ø.**FE
231   DP=.Ø81*FF*FPL*RHO*FPV**2/(62.4*DPEF*12.)
      IF(DP-FPDP)6Ø,6Ø,7Ø
;Ø     DPE=DPE+.125
      GO TO 5Ø
3Ø     IP=IFIX(DPE/.12499)
      IF(IP-8Ø)1318,1318,1317
317   IP=81
318   FPSZ=DIAN(IP)
      FPTW=THN(IP)
      TYPE 2ØØØ,(DPE,FPSZ,FPTW)
ØØØ   FORMAT($MINIMUM PIPE SIZE =$,F1Ø.5/
     1$     NOMINAL FILL PIPE SIZE=$,F1Ø.5/
     2$     NOMINAL PIPE THICKNESS =$,F1Ø.5/)
#ØØ    DPE=.125
+ØØ    DPEV=DPE/12.
      VPV=DQF/(3.141592*DPEV**2/4.)
      IF(VPV-.3*SS)5Ø6,5Ø8,5Ø8
+Ø8    DPE=DPE+.125
```

```
      GO TO 5ØØ
+Ø6    CONTINUE
      RE=RHOG*VPV*DPEV/VCOST
      REL=.8686*ELOG(RE)
      IRE=IFIX(2.*REL)
      IF(IRE-15)23Ø8,23Ø7,23Ø7
3Ø7   FF=.ØØ5
      GO TO 23Ø9
3Ø8   FIRE=FLOAT(IRE)
      FE=(2.*REL-FIRE)*(F(IRE)-F(IRE+1))+F(IRE+1)
      FF=1Ø.**FE
K3Ø9   DP=.Ø81*FF*VPL*RHOG*VPV**2/(62.4*12.*DPEV)
      IF(DP-VPDP)6ØØ,6ØØ,7ØØ
;ØØ    DPE=DPE+.125
      GO TO 5ØØ
3ØØ    IP=IFIX(DPE/.12499)
      IF(IP-8Ø)132Ø,132Ø,1319
319   IP=81
32Ø   VPSZ=DIAN(IP)
      VPTW=THN(IP)
      TYPE 3ØØØ,(DPE,VPSZ,VPTW)
ØØØ   FORMAT($MINIMUM VENTPIPE SIZE =$,F1Ø.5/
     1$    NOMINAL VENT PIPE SIZE=$,F1Ø.5/
     2$   VENT PIPE THICKNESS  =$,F1Ø.5/)
#Ø4    DPE=.125
      IF(MODE-3)3998,3999,3998
998   TYPE 4ØØØ
#ØØØ   FORMAT($PERIOD OF TANK USE(HOURS) .....=$)
      ACCEPT 1Ø,UT
999   DQU=VF/(UT*36Ø0.)
+Ø4    DPEU=DPE/12.
      UPV=DQU/(3.141592*DPEU**2/4.)
      RE=RHO*UPV*DPEU/VCOS
      REL=.8686*ELOG(RE)
      IRE=IFIX(2.*REL)
      IF(IRE-15)47Ø3,47Ø4,47Ø4
#7Ø4   FF=.ØØ5
      GO TO 47Ø6
#7Ø3   FIRE=FLOAT(IRE)
      FE=(2.*REL-FIRE)*(F(IRE)-F(IRE+1))+F(IRE+1)
      FF=1Ø.**FE
K#7Ø6  DP=.Ø81*FF*UPL*RHO*UPV**2/(62.4*12.*DPEU)
      IF(DP-UPDP)6Ø4,6Ø4,7Ø4
;Ø4    DPE=DPE+.125
      GO TO 5Ø4
3Ø4    IP=IFIX(DPE/.12499)
      IF(IP-8Ø)1322,1322,1321
321   IP=81
322   UPSZ=DIAN(IP)
      UPTW=THN(IP)
      TYPE 6ØØØ,(DPE,UPSZ,UPTW)
3ØØØ   FORMAT($MINIMUM USE PIPE SIZE =$,F1Ø.5/
     1$    NOMINAL USE  PIPE SIZE=$,F1Ø.5/
     2$  USE PIPE THICKNESS  =$,F1Ø.5/)
       FPSZ=FPSZ/12.
       VPSZ=VPSZ/12.
       UPSZ=UPSZ/12.
       FPTW=FPTW/12.
       VPTW=VPTW/12.
       UPTW=UPTW/12.
       CHAIN (/IN/)
      END
```

```
*/
AX       FUNCTION W(N)
      COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
     1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
      DIMENSION ALAM(2,Ø/5Ø),GAM(2,Ø/5Ø)
      W=(AK1/ALAM(1,N))**2*SIN(ALAM(1,N)*T/AK1)
     1-(AK1*T/ALAM(1,N))*COS(ALAM(1,N)*T/AK1)
      RETURN
      END
      FUNCTION SINH(XX)
      YY=XX
      IF(XX-175.)2Ø,2Ø,1Ø
Ø     XX=175.
Ø     CONTINUE
      SINH= EXPF(XX)-EXPF(-XX))/2.Ø
      XX=YY
      RETURN
      END
      FUNCTION COSH(XX)
      YY=XX
      IF(XX-175.)2Ø,2Ø,1Ø
Ø     XX=175.
Ø     CONTINUE
      COSH=(EXPF(XX)+EXPF(-XX))/2.Ø
      XX=YY
      RETURN
      END
      FUNCTION BJ(NU,X)
      IF(NU)1ØØ,1Ø,1ØØ
Ø     IF(X-3.Ø)2Ø,5Ø,5Ø
Ø     IF(X+3.Ø)5ØØØ,3Ø,3Ø
Ø     BJ=1.-2.2499997*(X/3.Ø)**2+1.2656208*(X/3.)**4
     1-.3163866*(X/3.)**6+.Ø444479*(X/3.)**8
     2-.ØØ39444*(X/3.)**1Ø+.ØØØ21ØØ*(X/3.)**12
      GO TO 1ØØØ
+Ø     CONTINUE
      FO=.79788456-.ØØØØØØ77*(3./X)-.ØØ55274*(3./X)**2
     1-.ØØØØ9512*(3./X)**3+.ØØ137237*(3./X)**4
     2-.ØØØ728Ø5*(3./X)**5+.ØØØ14476*(3./X)**6
      THO=X-.7853981Ø-.Ø4166397*(3./X)
     1-.ØØØØ3954*(3./X)**2+.ØØ262573*(3./X)**3
     2-.ØØØ54125*(3./X)**4-.ØØØ29333*(3./X)**5
     3+.ØØØ13558*(3./X)**6
      BJ=(FO*COSF(THO))/SQRT(X)
      GO TO 1ØØØ
ØØ    IF(NU-1)5Ø1Ø,11Ø,5Ø1Ø
1Ø    IF(X-3.)12Ø,15Ø,15Ø
2Ø    IF(X+3.)5Ø2Ø,13Ø,13Ø
```

```
3Ø    B=.5-.56249985*(X/3.)**2+.21Ø93573*(X/3.)**4
     1-.Ø3954289*(X/3.)**6+.ØØ443319*(X/3.)**8
     2-.ØØØ31761*(X/3.)**1Ø+.ØØØØ11Ø9*(X/3.)**12
      BJ=B**X
      GO TO 1ØØØ
5Ø    CONTINUE
      F1=.79788456+.ØØØØØ156*(3./X)+.Ø1659667*(3./X)**2
     1+.ØØØ1715Ø5*(3./X)**3-.ØØ249511*(3./X)**4
     2+.ØØ113653*(3./X)**5-.ØØØ2ØØ33*(3./X)**6
      TH1=X-2.35619449+.12499612*(3./X)
     1+.ØØØØ565Ø*(3./X)**2-.ØØ637879*(3./X)**3
     2+.ØØØ74348*(3./X)**4+.ØØØ79824*(3./X)**5
     3-.ØØØ29166*(3./X)**6
      BJ=(F1*COSF(TH1))/SQRT(X)
ØØØ   RETURN
+ØØØ   NOOP=7
      GO TO 6ØØØ
+Ø1Ø   NOOP=8
      GO TO 6ØØØ
+Ø2Ø   NOOP=9
3ØØØ  TYPE 666,(NOOP)
366   FORMAT($FAILED NOOP=$,I1)
      CALL EXIT
      END
      FUNCTION BY(NU,X)
      IF(NU)1ØØ,1Ø,1ØØ
Ø     IF(X-3.Ø)2Ø,5Ø,5Ø
Ø     IF(X+Ø.Ø)5ØØØ,3Ø,3Ø
Ø     BY=(2./3.1415926)*ELOGF(X/2.)*BJ(Ø,X)+.36746691
     1+.6Ø559366*(X/3.)**2-.7435Ø384*(X/3.)**4
     2+.253ØØ117*(X/3.)**6-.Ø4261214*(X/3.)**8
     3+.ØØ427916*(X/3.)**1Ø-.ØØØ24846*(X/3.)**12
      GO TO 1ØØØ
+Ø     CONTINUE
      F0=.79788456-.ØØØØØØ77*(3./X)-.ØØ55274*(3./X)**2
     1-.ØØØØ9512*(3./X)**3+.ØØ137237*(3./X)**4
     2-.ØØØ728Ø5*(3./X)**5+.ØØØ14476*(3./X)**6
      TH0=X-.78539816-.Ø4166397*(3./X)
     1-.ØØØØ3954*(3./X)**2+.ØØ262573*(3./X)**3
     2-.ØØØ54125*(3./X)**4-.ØØØ29333*(3./X)**5
     3+.ØØØ13558*(3./X)**6
      BY=(F0*SINF(TH0))/SQRT(X)
      GO TO 1ØØØ
ØØ    IF(NU-1)5Ø1Ø,11Ø,5Ø1Ø
1Ø    IF(X-3.)12Ø,15Ø,15Ø
2Ø    IF(X+3.)5Ø2Ø,13Ø,13Ø
3Ø    B=(2./3.1415926)*X*ELOGF(X/2.)*BJ(1,X)-.6366198
     1+.2212Ø91*(X/3.)**2+2.16827Ø9*(X/3.)**4
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```
     2-1.3164827*(X/3.)**6+.3123951*(X/3.)**8
     3-.ØØ4ØØ976*(X/3.)**1Ø+.ØØ27873*(X/3.)**12
      BY=B/X
      GO TO 1ØØØ
5Ø    CONTINUE
      F1=.79788456+.ØØØØØ156*(3./X)+.Ø1659667*(3./X)**2
     1+.ØØØ171Ø5*(3./X)**3-.ØØ249511*(3./X)**4
     2+.ØØ113653*(3./X)**5-.ØØØ2ØØ33*(3./X)**6
      TH1=X-2.35619449+.12499612*(3./X)
     1+.ØØØØ565Ø*(3./X)**2-.ØØ637879*(3./X)**3
     2+.ØØØ74348*(3./X)**4+.ØØØ79824*(3./X)**5
     3-.ØØØ29166*(3./X)**6
      BY=(F1*SINF(TH1))/SQRT(X)
ØØØ   RETURN
+ØØØ   NOOP=7
      GO TO 6ØØØ
+Ø1Ø   NOOP=8
      GO TO 6ØØØ
+Ø2Ø   NOOP=9
3ØØØ   TYPE 666,(NOOP)
366    FORMAT($FAILED NOOP=$,I1)
      CALL EXIT
K      END
      FUNCTION BI(NU,X)
     CALCULATES THE Ø AND 1 ORDER I BESSEL FUNCTION
     /FOR3/ FILE.....
      YY=X
      IF (NU)1ØØ,1Ø,1ØØ
Ø     IF(X-3.75)2Ø,5Ø,5Ø
Ø     IF(X+3.75)5ØØØ,3Ø,3Ø
Ø     BI=1.+3.5156229*X*X+3.Ø899424*X**4+1.2Ø67492*X**6
     1+.2659732*X**8+.Ø36Ø768*X**1Ø+.ØØ45813*X**12
      GO TO 1ØØØ
+Ø     CONTINUE
      B=.39894228+.Ø1328592/X+.ØØ225319*X**(-2)-.ØØ157565*X**(-3)
     1+.ØØ916281*X**(-4)-.Ø2Ø577Ø6*X**(-5)+.Ø2635537*X**(-6)
     2-.Ø1647633*X**(-7)+.ØØ392377*X**(-8)
      IF(X-175.)691,691,591
+91    CONTINUE
      X=175.
391    BI=B*EXPF(X)/SQRTF(X)
      GO TO 1ØØØ
ØØ    IF(NU-1)5Ø1Ø,11Ø,5Ø1Ø
1Ø    IF(X-3.75)12Ø,15Ø,15Ø
2Ø    IF(X+3.75)5Ø2Ø,13Ø,13Ø
3Ø    B=.5+.8789Ø594*X*X+.51498869*X**4+.15Ø84934*X**6
     1+.Ø2658733*X**8+.ØØ3Ø1532*X**1Ø+.ØØØ32411*X**12
      BI=B*X
```

```
      GO TO 1ØØØ
5Ø    CONTINUE
      B=.39894228-.Ø398ØØ24/X-.ØØ362Ø1*X**(-2)+.ØØ1639Ø1*X**(-3)
     1-.Ø1Ø31555*X**(-4)+.Ø2282967*X**(-5)-.Ø2895312*X**(-6)
     2+.Ø1787654*X**(-7)-.ØØ42ØØ59*X**(-8)
      IF(X-175.)891,891,791
;91    X=175.
C91    CONTINUE
      BI=B*EXPF(X)/SQRTF(X)
ØØØ   X=YY
      RETURN
+ØØØ   NOOP=1
      GO TO 6ØØØ
+Ø1Ø   NOOP=2
      GO TO 6ØØØ
+Ø2Ø   NOOP=3
3ØØØ   TYPE 666,(NOOP)
366    FORMAT($FAILED  NOOP=$,I1)
      CALL EXIT
      END
      FUNCTION BK(NU,X)
     CALCULATES THE Ø AND 1 ORDER K BESSEL FUNCTIONS
     /FOR3/ FILE.........
      IF(NU)1ØØ,1Ø,1ØØ
Ø     IF(X-2.Ø)2Ø,5Ø,5Ø
Ø     IF(X)5ØØØ,5ØØØ,3Ø
Ø     BK=(-ELOGF(X/2.Ø))*BI(Ø,X)-.57721566+.4227842Ø*(X/2.)**2
     1+.23Ø69756*(X/2.)**4+.Ø348859Ø*(X/2.)**6+.ØØ262698*(X/2.)**8
     2+.ØØØ1Ø75Ø*(X/2.)**1Ø+.ØØØØØ74Ø*(X/2.)**12
      GO TO 1ØØØ
+Ø     CONTINUE
      B=1.25331414-.Ø7832358*(2./X)+.Ø2189568*(2./X)**2
     1-.Ø1Ø62446*(2./X)**3+.ØØ587872*(2./X)**4
     2-.ØØ25154Ø*(2./X)**5+.ØØØ532Ø8*(2./X)**6
      IF(X-175.)69Ø2,69Ø2,69Ø1
39Ø1   BK=Ø.Ø
      GO TO 1ØØØ
39Ø2   CONTINUE
      BK=B*EXPF(-X)/SQRTF(X)
      GO TO 1ØØØ
ØØ    IF (NU-1)5Ø1Ø,11Ø,5Ø1Ø
1Ø    IF(X-2.Ø)12Ø,15Ø,15Ø
2Ø    IF(X)5Ø2Ø,5Ø2Ø,13Ø
3Ø    B=X*ELOGF(X/2.)*BI(1,X)+1+.15443144*(X/2.)**2
     1-.67278579*(X/2.)**4-.18156897*(X/2.)**6
     2-.Ø19194Ø2*(X/2.)**8-.ØØ11Ø4Ø4*(X/2.)**1Ø
     3-.ØØØØ4686*(X/2.)**12
      BK=B/X
```

```
      GO TO 1ØØØ
5Ø    CONTINUE
      B=1.25331414+.23498619*(2./X)-.Ø365562Ø*(2./X)**2
     1+.Ø15Ø4268*(2./X)**3-.ØØ78Ø353*(2./X)**4
     2+.ØØ325614*(2./X)**5-.ØØØ68245*(2./X)**6
      IF(X-175)69Ø4,69Ø4,69Ø3
39Ø3   BK=Ø.Ø
      GO TO 1ØØØ
39Ø4   CONTINUE
      BK=B*EXPF(-X)/SQRTF(X)
ØØØ   RETURN
+ØØØ   NOOP=4
      GO TO 6ØØØ
+Ø1Ø   NOOP=5
      GO TO 6ØØØ
+Ø2Ø   NOOP=6
3ØØØ   TYPE 666,(NOOP)
366    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,Ø/5Ø),GAM(2,Ø/5Ø)
      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,Ø/5Ø),GAM(2,Ø/5Ø)
      IF(N-1) 1Ø,2Ø,1Ø
Ø     XXXX=Ø.Ø
      GO TO 3Ø
Ø     XXXX=D(N)*E(1,N)*H
Ø     CONTINUE
      TERR=T-(AK1/(2.*ALAM(1,N)))*SINF(2.*ALAM(1,N)*T/AK1)
      RF=(BI(Ø,ALAM(1,N)*R2)*BK(Ø,ALAM(1,N)*R1)
     1-BI(Ø,ALAM(1,N)*R1)*BK(Ø,ALAM(1,N)*R2)
     2-(AKR1*AK1*AK1/(S*AKP*ALAM(1,N)*ALAM(1,N)))
     3*(-ALAM(1,N)*BI(Ø,ALAM(1,N)*R2)*BK(1,ALAM(1,N)*R1)
     4-ALAM(1,N)*BI(1,ALAM(1,N)*R1)*BK(Ø,ALAM(1,N)*R2)
     5-XXXX/R1))*TERR/2.
      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,Ø/5Ø),GAM(2,Ø/5Ø)
 C2=H2*TH/(H2*T+AKZ2)
 TERR=T-(AK2/(2.*ALAM(2,N)))*SINF(2.*ALAM(2,N)*T/AK2)
 T5=TH*H2/(AKZ2/T+H2)
 B2=((2.ØØ/TERR)*(AK2/ALAM(2,N))**2*(SINF(ALAM(2,N)*T/AK2)-
1(ALAM(2,N)*T/AK2)*COSF(ALAM(2,N)*T/AK2))*(T5/T-C2))
2/((BI(Ø,ALAM(2,N)*R2)*BK(Ø,ALAM(2,N)*R3)
3-BI(Ø,ALAM(2,N)*R3)*BK(Ø,ALAM(2,N)*R2)))
 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,Ø/5Ø),GAM(2,Ø/5Ø)
 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,Ø/5Ø),GAM(2,Ø/5Ø)
 X=T-(AK1/(2.*ALAM(1,1)))*SINF(2.*ALAM(1,1)*T/AK1)
 P=(AKR1*X*D(1)/2.)*(-ALAM(1,1)*BI(Ø,ALAM(1,1)*R1)*BK(1,ALAM(1,1)
1*R2)-ALAM(1,1)*BI(1,ALAM(1,1)*R2)*BK(Ø,ALAM(1,1)*R1))*E(N,1)
2-AKR2*((-ALAM(2,N))*BI(Ø,ALAM(2,N)*R3)*BK(1,ALAM(2,N)*R2)
3-ALAM(2,N)*BI(1,ALAM(2,N)*R2)*BK(Ø,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,Ø/5Ø),GAM(2,Ø/5Ø)
 E=(BI(Ø,ALAM(2,N)*R3)*BK(Ø,ALAM(2,N)*R2)
1-BI(Ø,ALAM(2,N)*R2)*BK(Ø,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,Ø/5Ø),GAM(2,Ø/5Ø)
 TERR=T-(AK1/(2.*ALAM(1,N)))*SINF(2.*ALAM(1,N)*T/AK1)
 D=2./(TERR*(BI(Ø,ALAM(1,N)*R1)*BK(Ø,ALAM(1,N)*R2)
1-BI(Ø,ALAM(1,N)*R2)*BK(Ø,ALAM(1,N)*R1)))
 RETURN
 END
```

```
 FUNCTION AI9(M)
 COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
 DIMENSION AL^M(3,Ø/5Ø),GAM(3,Ø/5Ø)
  AI9=(-H2*AK3*AK3/(AKY3*GAM(3,M)**2))
1*(COS(GAM(3,M)*T/AK3)-1.)+(AK3/GAM(3,M))
2*SIN(GAM(3,M)*T/AK3)
 RETURN
 END
 FUNCTION AI1Ø(M)
 COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
 DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
 AI1Ø=(H2*AK3*AK3*AK3/(AKY3*GAM(3,M)**3))
1*(SIN(GAM(3,M)*T/AK3)-(GAM(3,M)*T/AK3)*COS(GAM(3,M)
2*T/AK3))+(AK3*AK3/GAM(3,M)**2)*(COS(GAM(3,M)*T/AK3)
3-1.+(GAM(3,M)*T/AK3)*SIN(GAM(3,M)*T/AK3))
 RETURN
 END
  FUNCTION TAN(X)
  TAN=SIN(X)/COS(X)
  RETURN
  END
 FUNCTION SINH(XX)
 YY=XX
 IF(XX-175.)2Ø,2Ø,1Ø
Ø XX=175.
Ø CONTINUE
 SINH=(EXPF(XX)-EXPF(-XX))/2.Ø
 XX=YY
 RETURN
 END
 FUNCTION COSH(XX)
 YY=XX
 IF(XX-175.)2Ø,2Ø,1Ø
Ø XX=175.
Ø CONTINUE
 COSH=(EXPF(XX)+EXPF(-XX))/2.Ø
 XX=YY
 RETURN
 END
 FUNCTION AI8(N,M)
 COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
K  DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
 AI8=(H1*AK2/(GAM(2,N)*AKY2))*(SINF((GAM(2,N)/AK2
```

```
     1-GAM(1,M)/AK1)*T)/(2.*(GAM(2,N)/AK2-GAM(1,M)/AK1))
     2-SINF((GAM(2,N)/AK2+GAM(1,M)/AK1)*T)/(2.*(GAM(2,N)/AK2
     3+GAM(1,M)/AK1)))
     4+GAM(1,M)/AK1/((GAM(1,M)/AK1)**2-(GAM(2,N)/AK2)**2)
     5-COS((GAM(1,M)/AK1-GAM(2,N)/AK2)*T)
     6/(2.*(GAM(1,M)/AK1-GAM(2,N)/AK2))
     7-COSF((GAM(1,M)/AK1+GAM(2,N)/AK2)*T)
     8/(2.*(GAM(1,M)/AK1+GAM(2,N)/AK2))
      RETURN
      END
      FUNCTION AI6(N,M)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
K     DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      AI6=((-GAM(1,M)/AK1)*SINH(ALAM(1,N)*T/AK1)*COS(GAM(1,M)*T/AK1)
     1+(ALAM(1,N)/AK1)*COSH(ALAM(1,N)*T/AK1)*SIN(GAM(1,M)*T/AK1))
     2/((ALAM(1,N)/AK1)**2+(GAM(1,M)/AK1)**2)
      RETURN
      END
      FUNCTION AI5(M)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
K     DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      AI5=(AK1/GAM(1,M))*(GAM(1,M)*T/(2.*AK1)
     1-.25*SINF(2.*GAM(1,M)*T/AK1))
      RETURN
      END
      FUNCTION A(N)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
K     DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      A=(2.*H5*TH)
     1/(ALAM(1,N)*AL1*((ALAM(1,N)*AKY1/AK1)*COSH(ALAM(1,N)*T/AK1)
     2+H5*SINH(ALAM(1,N)*T/AK1)))
      RETURN
      END
      FUNCTION D(N)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
      DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      DA=Ø.Ø
      DB=Ø.Ø
      C=H4*TH/(H1+H4*H1*T/AKY2+H4)
      F=H3*TH/(H2+H2*H3*T/AKY3+H3)
      H=(-AI1Ø(1)*(H1*C/AKY2-H2*F/AKY3)-AI9(1)*(C-F))
      IF(N-1)2Ø,1Ø,2Ø
Ø     DA=C*AK1*(1.-COS(GAM(1,1)*T/AK1))/GAM(1,1)
     1+H1*AKY2*C*(AK1*AK1*SIN(GAM(1,1)*T/AK1)/(GAM(1,1)**2)
     2-AK1*T*COS(GAM(1,1)*T/AK1))/GAM(1,1))
     3+AI8(1,1)*H*COSH(GAM(2,1)*(AL2-AL1))/AI2(1,1)
```

```
      DB=AKX2*H*AI8(1,1)*SINH(GAM(2,1)*(AL2-AL1))
     1/(AI2(1,1)*AKX1*AI5(1)*GAM(1,1)*COSH(GAM(1,1)*AL1))
Ø     Q=(DA-A(N)*AI6(N,1)*(-1.**(N+1)))
     1/(AI5(1)*SINH(GAM(1,1)*AL1))+DB
      P=-AKX2*GAM(2,N)*SINH(GAM(2,N)*(AL2-AL1))
     1*COSH(GAM(3,1)*(AL3-AL2))
     2/(GAM(3,1)*AKX3*SINH(GAM(3,1)*(AL3-AL2)))
     3-COSH(GAM(2,N)*(AL2-AL1))
      R=-AI8(N,1)*AKX2*P*SINH(GAM(2,N)*(AL2-AL1))
     1/(AI5(1)*AKX1*GAM(1,1)*COSH(GAM(1,1)*AL1))
     2-AI8(N,1)/(AI5(1)*SINH(GAM(1,1)*AL1))
     3-AI8(N,1)*P*COSH(GAM(2,N)*(AL2-AL1))
     4/(AI5(1)*SINH(GAM(1,1)*AL1))
      D=Q/R
      RETURN
      END
      FUNCTION E(N)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
K       DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      H=Ø.Ø
      IF(N-1)2Ø,1Ø,2Ø
Ø     C=H4*TH/(H1+H1*H4*T/AKY2+H4)
      F=H3*TH/(H2+H2*H3*T/AKY3+H3)
      H=(-AI1Ø(1)*(H1*C/AKY2-H2*F/AKY3)-AI9(1)*(C-F))/AI2(1,1)
Ø     P=-AKX2*GAM(2,N)*SINH(GAM(2,N)*(AL2-AL1))*COSH(GAM(3,1)
     1*(AL3-AL2))
     2/(GAM(3,1)*AKX3*SINH(GAM(3,1)*(AL3-AL2)))
     3-COSH(GAM(2,N)*(AL2-AL1))
      E=P*D(N)+H
      RETURN
      END
      FUNCTION AI1(M)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
K       DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      AI1=(H2**2*AK3**3/(GAM(3,M)**3*AKY3**2))
     1*(GAM(3,M)*T/(2.*AK3)-SINF(2.*GAM(3,M)*T/AK3)/4.)
     2+(H2*AK3**2/(GAM(3,M)**2*AKY3))*(SINF(GAM(3,M)*T/AK3))**2
     3+(AK3/GAM(3,M))*(GAM(3,M)*T/(2.*AK3)+SINF(2.*GAM(3,M)*T/AK3)
     4/4.Ø)
      RETURN
      END
      FUNCTION AI2(N,M)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,T[illegible],T,AK1,AK2,AK3,ALAM,GAM
K       DIMENSION ALAM([illegible].Ø/5Ø).GAM(3.Ø/5Ø)
```

```
 AAA=(H1*H2*AK2*AK3/(GAM(2,N)*GAM(3,M)*AKY2*AKY3))
1*(SINF((GAM(2,N)/AK2-GAM(3,M)/AK3)*T)
2/(2.*(GAM(2,N)/AK2-GAM(3,M)/AK3))
3-SINF((GAM(2,N)/AK2+GAM(3,M)/AK3)*T)
4/(2.*(GAM(2,N)/AK2+GAM(3,M)/AK3)))
 AI2=AAA
5+(H2*AK3/(GAM(3,M)*AKY3))*(GAM(3,M)/AK3
6/((GAM(3,M)/AK3)**2-(GAM(2,N)/AK2)**2)
7-COSF((GAM(3,M)/AK3-GAM(2,N)/AK2)*T)
8/(2.*(GAM(3,M)/AK3-GAM(2,N)/AK2))
9-COSF((GAM(3,M)/AK3+GAM(2,N)/AK2)*T)
1/(2.*(GAM(3,M)/AK3+GAM(2,N)/AK2)))
5+(H1*AK2/(GAM(2,N)*AKY2))*(GAM(2,N)/AK2
6/((GAM(2,N)/AK2)**2-(GAM(3,M)/AK3)**2)
7-COSF((GAM(2,N)/AK2-GAM(3,M)/AK3)*T)
8/(2.*(GAM(2,N)/AK2-GAM(3,M)/AK3))
9-COSF((GAM(2,N)/AK2+GAM(3,M)/AK3)*T)
9/(2.*(GAM(2,N)/AK2+GAM(3,M)/AK3)))
1+SINF((GAM(2,N)/AK2-GAM(3,M)/AK3)*T)
2/(2.*(GAM(2,N)/AK2-GAM(3,M)/AK3))
3+SINF((GAM(2,N)/AK2+GAM(3,M)/AK3)*T)
4/(2.Ø*(GAM(2,N)/AK2+GAM(3,M)/AK3))
 RETURN
 END
```

```
/
AX7     PROGRAM SHINGLES
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
      DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      TYPE 1ØØØØ
      ACCEPT 1Ø,AL1
      TYPE 1ØØØ1
      ACCEPT 1Ø,AL2
      TYPE 1ØØØ2
      ACCEPT 1Ø,AL3
      TYPE 1ØØØ3
      ACCEPT 1Ø,H1
      TYPE 1ØØØ4
      ACCEPT 1Ø,H2
      TYPE 1ØØØ5
      ACCEPT 1Ø,H3
      TYPE 1ØØØ6
      ACCEPT 1Ø,H4
      TYPE 1ØØØ7
      ACCEPT 1Ø,H5
      TYPE 1ØØØ8
      ACCEPT 1Ø,AKY1
      TYPE 1ØØØ9
      ACCEPT 1Ø,AKY2
      TYPE 1ØØ1Ø
      ACCEPT 1Ø,AKY3
      TYPE 1ØØ11
      ACCEPT 1Ø,AKX1
      TYPE 1ØØ12
      ACCEPT 1Ø,AKX2
      TYPE 1ØØ13
      ACCEPT 1Ø,AKX3
      TYPE 1ØØ14
      ACCEPT 1Ø,TH
      TYPE 1ØØ15
      ACCEPT 1Ø,T
      TYPE 1ØØ16
      ACCEPT 11,MEIG1
      TYPE 1ØØ17
      ACCEPT 1Ø,DLEG1
Ø     FORMAT(F1Ø.5/)
1     FORMAT(T2/)
ØØØØ  FORMAT($ AL1=$)
ØØØ1  FORMAT($ AL2=$)
ØØØ2  FORMAT($ AL3=$)
ØØØ3  FORMAT($  H1=$)
ØØØ4  FORMAT($  H2=$)
```

```
ØØØ5 FORMAT($  H3=$)
ØØØ6 FORMAT($  H4=$)
ØØØ7 FORMAT($  H5=$)
ØØØ8 FORMAT($AKY1=$)
ØØØ9 FORMAT($AKY2=$)
ØØ1Ø FORMAT($AKY3=$)
ØØ11 FORMAT($AKX1=$)
ØØ12 FORMAT($AKX2=$)
ØØ13 FORMAT($AKX3=$)
ØØ14 FORMAT($  TH=$)
ØØ15 FORMAT($   T=$)
ØØ16 FORMAT($NO. IN SUM=$)
ØØ17 FORMAT($   DELTA  =$)
     AK1=SQRT(AKY1/AKX1)
     AK2=SQRT(AKY2/AKX2)
     AK3=SQRT(AKY3/AKX3)
     ALAM(1,Ø)=Ø.Ø
     ALAM(2,Ø)=Ø.Ø
     ALAM(3,Ø)=Ø.Ø
     GAM(1,Ø)=Ø.Ø
     GAM(2,Ø)=Ø.Ø
     GAM(3,Ø)=Ø.Ø
     DO 111 I=1,5Ø
11   ALAM(1,I)=3.1415926*(2.*FLOAT(I)-1.)/(2.*AL1)
     I=1
     J=1
     SCALE=AK1/T
     CONTINUE
     UP=3.2*SCALE
     DEL=3.2*SCALE
+     SIGN=-1.Ø
     GAM(I,J)=GAM(I,J-1)+UP
     A=(GAM(I,J)*T)/AK1
     B=(GAM(I,J)*AKY1)/(AK1*H5)
     D1=SINF(A)/COSF(A)+B
     DEL=DEL/2.Ø
     GAM(I,J)=GAM(I,J)-DEL
5    AB=(GAM(I,J)*T)/AK1
     BA=(GAM(I,J)*AKY1)/(AK1*H5)
     D2=SINF(AB)/COSF(AB)+BA
     IF(DLEG1 -D2*D2)2Ø,1ØØ,1ØØ
Ø    IF(D1*D2)3Ø,4Ø,4Ø
Ø    SIGN=-SIGN
     DEL=DEL/2.Ø
     GAM(I,J)=GAM(I,J)+SIGN*DEL
5    D1=D2
     GO TO 15
#Ø    IF(D1)5Ø.6Ø.6Ø
```

```
+Ø     GAM(I,J)=GAM(I,J)+DEL
      GO TO 35
3Ø     GAM(I,J)=GAM(I,J)-DEL
      GO TO 35
ØØ    TYPE 2Ø4,(I,J,GAM(I,J))
Ø4    FORMAT($GAMMA $,I2,2X,I2,4X,E14.4/)
      IF(J-3)1235,1234,1234
234   TEST1=GAM(I,J)-GAM(I,J-1)
      TEST2=GAM(I,J-1)-GAM(I,J-2)
      IF(((TEST1-TEST2)/TEST1)**2-Ø.ØØØ1**2)1236,1236,1235
236   DO 1237,IKI=J,5Ø
237   GAM(I,IKI)=TEST1+GAM(I,IKI-1)
      J=5Ø
235   CONTINUE
      UP=3.2*SCALE
      DEL=GAM(I,J)+UP-(J*3.1415921+1.571)*SCALE
      J=J+1
      IF(J-MEIG1  )5,5,115
15    TYPE 12Ø
2Ø    FORMAT($EIGENVALUE EQUATION 1 COMPLETE$/)
      J=1
      I=2
      HAX=H4
      HBX=H1
      AKYX=AKY2
      AKX=AK2
11     CONTINUE
      SCALE=AKX/T
      GAMT=AKX*SQRT(HAX*HBX)/AKYX
      IF(GAMT*T/AKX-1.57)112Ø,111Ø,111Ø
11Ø   IF(GAMT*T/AKX-3.141593)114Ø,113Ø,113Ø
13Ø   UP=3.14*SCALE
      DEL=1.55*SCALE
      MCASE=3
      GO TO 14ØØ
14Ø   UP=(GAMT-.ØØ1)*T/AKX
      DEL=UP-1.57
      MCASE=2
      GO TO 14ØØ
12Ø   UP=1.57Ø*SCALE
      DEL=1.57*SCALE-GAMT
      MCASE=1
4ØØ   CONTINUE
51    SIGN=-1.Ø
      GAM(I,J)=GAM(I,J-1)+UP
      A=GAM(I,J)*T/AKX
      B=(HAX+HBX)/(GAM(I,J)*AKYX/AKX-HAX*HBX*AKX/(AKYX*GAM(I,J)))
      D1=SIN(A)/COS(A)-B
```

```
      DEL=DEL/2.
      GAM(I,J)=GAM(I,J)-DEL
51    AB=GAM(I,J)*T/AKX
      BA=(HAX+HBX)/(GAM(I,J)*AKYX/AKX-HAX*HBX*AKX/(AKYX*GAM(I,J)))
      D2=SIN(AB)/COS(AB)-BA
      IF(DLEG1-D2*D2)21,101,101
1     IF(D1*D2)31,41,41
1     SIGN=-SIGN
      DEL=DEL/2.0
      GAM(I,J)=GAM(I,J)+SIGN*DEL
6     D1=D2
      GO TO 151
#1     IF(D1)51,61,61
+1     GAM( ,J)=GAM(I,J)+DEL
      GO TO 36
31     GAM(I,J)=GAM(I,J)-DEL
      GO TO 36
01    TYPE 204,(I,J,GAM(I,J))
      IF(J-3)2235,2234,2234
234   IF(GAM(I,J)-GAMT)2235,2235,2238
238   TEST1=GAM(I,J)-GAM(I,J-1)
      TEST2=GAM(I,J-1)-GAM(I,J-2)
      IF(((TEST1-TEST2)/TEST1)**2-.0001)2236,2236,2235
236   DO 2237,IKI=J,50
237   GAM(I,IKI)=TEST1+GAM(I,IKI-1)
      J=50
      GO TO 1500
235   CONTINUE
      IF(MCASE-1)1180,1150,1180
150   UP=3.1416*SCALE
      DEL=GAM(I,J)+UP-J*3.1415926*SCALE
      GO TO 1500
180   IF(MCASE-3)1200,1190,1200
190   IF((GAMT-GAM(I,J))/SCALE-3.14)1194,1192,1192
192   UP=3.140*SCALE
      DEL=GAM(I,J)+UP-(1.58+J*3.142)*SCALE
      GO TO 1500
194   UP=SCALE*(1.57+3.14159*J)-GAM(I,J)
      DEL=UP+GAM(I,J)-GAMT
      MCASE=1
      GO TO 1500
200   MCASE=1
      GO TO 1150
500   CONTINUE
      J=J+1
      IF(J-MEIG1)351,351,215
15    IF(I-2)250,221,250
21    J=1
      I=3
```

```
      HAX=H3
      HBX=H2
      AKYX=AKY3
      AKX=AK3
      GO TO 311
5Ø    TYPE 24Ø
4Ø    FORMAT($EIGENVALUES CALCULATED$/)
      DO 1331,I=1,5Ø
      TQTX=ALAM(1,I)
      TQTY=GAM(1,I)
      TQTZ=GAM(2,I)
       RQT=GAM(3,I)
331   TYPE 13245,(TQTX,TQTY,TQTZ,RQT)
3245  FORMAT(4E14.4/)
      CHAIN (/LNK1Ø/)
      END
```

```
*/

C      PROGRAM SHINGLES
     PART - "2"
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
      DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø),SUM(5Ø),SUM1(5Ø),B(5Ø),G(5Ø)
      TYPE 1ØØØØ
      ACCEPT 11,LIM
      TYPE 1ØØØ1
      ACCEPT 11,LIMF
1     FORMAT(I2/)
ØØØØ  FORMAT($UPPER LIMIT ON SUMS=$)
ØØØ1  FORMAT($UPPER LIMIT ØN FUNC=$)
      DO 1ØØ I=1,LIM
ØØ    SUM(I)=GAM(2,I)*D(I)*SINH(GAM(2,I)*(AL2-AL1))
      ASUM=Ø.Ø
      DO 2ØØ J=1,LIMF
      DO 15Ø I=1,LIM
5Ø    ASUM=ASUM+SUM(I)*AI2(I,J)
      G(J)=(-AKX2*ASUM)
     1/(GAM(3,J)*AI1(J)*AKX3*SINH(GAM(3,J)*(AL3-AL2)))
      TYPE 12,(J,G(J))
2     FORMAT($G$,5X,I2,5X,E14.4/)
ØØ    ASUM=Ø.Ø
      DO 3ØØ I=1,LIM
ØØ    SUM1(I)=GAM(2,I)*E(I)*SINH(GAM(2,I)*(AL2-AL1))
      ASUM=Ø.Ø
      DO 4ØØ J=1,LIMF
      DO 45Ø I=1,LIM
#5Ø    ASUM=ASUM+SUM1(I)*AI8(I,J)
      B(J)=-AKX2*ASUM/(GAM(1,J)*AKX1*COSH(GAM(1,J)*AL1)*AI5(J))
      FKA=B(J)
      FKB=SUM1(J)
      FKC=AI8(J,J)
      FKH=AI8(J,LIM)
      FKI=AI8(LIM,J)
      FKD=ASUM
      FKE=AI5(J)
      FKF=D(J)
      FKG=E(J)
      TYPE 13,(J,FKA,FKB,FKC,FKD,FKE,FKF,FKG,FKH,FKI)
3     FORMAT($B$,5X,I2,5X,9E14.4/)
      ASUM=Ø.Ø
#ØØ    CONTINUE
      TYPE 1ØØØ2
      ACCEPT 1Ø,X
      TYPE 1ØØØ3
```

```
      ACCEPT 1Ø,Y
Ø     FORMAT(F1Ø.5)
ØØØ2  FORMAT($  X=$)
ØØØ3  FORMAT($  Y=$)
      ASUM=Ø.Ø
      BSUM=Ø.Ø
      DO 5ØØ I=1,LIMF
      ASUM=ASUM+A(I)*SIN(X*ALAM(1,I))*SINH(ALAM(1,I)*Y/AK1)
      BSUM=BSUM+B(I)*SINH(X*GAM(1,I))*SIN(GAM(1,I)*Y/AK1)
      T1=ASUM+BSUM
      TYPE 14,(I,ASUM,BSUM,T1)
4     FORMAT($T1$,2X,I2,3(2X,E14.4)/)
+ØØ    CONTINUE
      ASUM=H1*H4*TH*Y/(AKY2*(H1+H1*H4*T/AKY2+H4))
     1+H4*TH/(H1+H1*H4*T/AKY2+H4)
      BSUM=Ø.Ø
      CSUM=Ø.Ø
      DO 6ØØ I=1,LIMF
      BSUM=BSUM+D(I)*COSH(GAM(2,I)*(X-AL1))*((H1*AK2/(GAM(2,I)*AKY2))
     1*SIN(GAM(2,I)*Y/AK2)+COS(GAM(2,I)*Y/AK2))
      CSUM=CSUM+E(I)*COSH(GAM(2,I)*(AL2-X))*((H1*AK2/(GAM(2,I)*AKY2))
     1*SIN(GAM(2,I)*Y/AK2)+COS(GAM(2,I)*Y/AK2))
      T2=ASUM+BSUM+CSUM
      TYPE 15,(I,ASUM,BSUM,CSUM,T2)
5     FORMAT($T2$,2X,I2,4(2X,E14.4)/)
3ØØ    CONTINUE
      ASUM=(1.+H2*Y/AKY3)*(H3*TH/(H2+H2*H3*T/AKY3+H3))
      BSUM=Ø.Ø
      DO 7ØØ I=1,LIMF
      BSUM=BSUM+G(I)*COSH(GAM(3,I)*(AL3-X))*((H2*AK3*SIN
     1(GAM(3,I)*Y/AK3))/(AKY3*GAM(3,I))+COS(GAM(3,I)*Y/AK3))
      T3=ASUM+BSUM
      TYPE 16,(I,ASUM,BSUM,T3)
6     FORMAT($T3$,2X,I2,3(2X,E14.4)/)
;ØØ    CONTINUE
      GO TO 4ØØ
      END
```

```
*/
AX      PROGRAM SHINGLES ON A SUBSTRATE
       COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
      1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
      2,H6
       DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
       TYPE 1ØØØØ
       ACCEPT 1Ø,AL1
       TYPE 1ØØØ1
       ACCEPT 1Ø,AL2
       TYPE 1ØØØ2
       ACCEPT 1Ø,AL3
       TYPE 1ØØØ3
       ACCEPT 1Ø,H1
       TYPE 1ØØØ4
       ACCEPT 1Ø,H2
       TYPE 1ØØØ5
       ACCEPT 1Ø,H3
       TYPE 1ØØØ6
       ACCEPT 1Ø,H4
       TYPE 1ØØØ7
       ACCEPT 1Ø,H5
       TYPE 1ØØ2Ø
       ACCEPT 1Ø,H6
       TYPE 1ØØØ8
       ACCEPT 1Ø,AKY1
       TYPE 1ØØØ9
       ACCEPT 1Ø,AKY2
       TYPE 1ØØ1Ø
       ACCEPT 1Ø,AKY3
       TYPE 1ØØ11
       ACCEPT 1Ø,AKX1
       TYPE 1ØØ12
       ACCEPT 1Ø,AKX2
       TYPE 1ØØ13
       ACCEPT 1Ø,AKX3
       TYPE 1ØØ14
       ACCEPT 1Ø,TH
       TYPE 1ØØ15
       ACCEPT 1Ø,T
       TYPE 1ØØ16
       ACCEPT 11,MEIG1
       TYPE 1ØØ17
       ACCEPT 1Ø,DLEG1
1Ø     FORMAT(F1Ø.5/)
11     FORMAT(I2/)
1ØØØØ FORMAT($ AL1=$)
1ØØØ1 FORMAT($ AL2=$)
```

```
1ØØØ2 FORMAT($ AL3=$)
1ØØØ3 FORMAT($  H1=$)
1ØØØ4 FORMAT($  H2=$)
1ØØØ5 FORMAT($  H3=$)
1ØØØ6 FORMAT($  H4=$)
1ØØØ7 FORMAT($  H5=$)
1ØØ2Ø FORMAT($  H6=$)
1ØØØ8 FORMAT($AKY1=$)
1ØØØ9 FORMAT($AKY2=$)
1ØØ1Ø FORMAT($AKY3=$)
1ØØ11 FORMAT($AKX1=$)
1ØØ12 FORMAT($AKX2=$)
1ØØ13 FORMAT($AKX3=$)
1ØØ14 FORMAT($  TH=$)
1ØØ15 FORMAT($   T=$)
1ØØ16 FORMAT($NO. IN SUM=$)
1ØØ17 FORMAT($   DELTA  =$)
      AK1=SQRT(AKY1/AKX1)
      AK2=SQRT(AKY2/AKX2)
      AK3=SQRT(AKY3/AKX3)
      ALAM(1,Ø)=Ø.Ø
      ALAM(2,Ø)=Ø.Ø
      ALAM(3,Ø)=Ø.Ø
      GAM(1,Ø)=Ø.Ø
      GAM(2,Ø)=Ø.Ø
      GAM(3,Ø)=Ø.Ø
      I=1
      J=1
1     CONTINUE
      UP=3.141592/(2.*AL1)
      DEL=UP/2.Ø
5     SIGN=-1.Ø
      ALAM(I,J)=ALAM(I,J-1)+UP
      A=ALAM(I,J)*AL1
      B=H6/(AKX1*ALAM(I,J))
      D1=A-B
      DEL=DEL/2.Ø
      ALAM(I,J)=ALAM(I,J)-DEL
15    AB=ALAM(I,J)*AL1
      BA=H6/(AKX1*ALAM(I,J))
      D2=AB-BA
      IF(DLEG1 -D2*D2)2Ø,1ØØ,1ØØ
2Ø    IF(D1*D2)3Ø,4Ø,4Ø
3Ø    SIGN=-SIGN
      DEL=DEL/2.Ø
      ALAM(I,J)=ALAM(I,J)+SIGN*DEL
35    D1=D2
      GO TO 15
```

```
4Ø      IF(D1)5Ø,6Ø,6Ø
5Ø      ALAM(I,J)=ALAM(I,J)+DEL
        GO TO 35
6Ø      ALAM(I,J)=ALAM(I,J)-DEL
        GO TO 35
1ØØ     TYPE 2Ø4,(I,J,ALAM(I,J))
2Ø4     FORMAT($ALAM  $,I2,2X,I2,4X,E14.4/)
        IF(J-3)1235,1234,1234
1234    TEST1=ALAM(I,J)-ALAM(I,J-1)
        TEST2=ALAM(I,J-1)-ALAM(I,J-2)
        IF(((TEST1-TEST2)/TEST1)**2-Ø.ØØØ1**2)1236,1236,1235
1236    DO 1237,IKI=J,5Ø
        ALAM(I,IKI)=TEST1+ALAM(I,IKI-1)
1237    J=5Ø
1235    CONTINUE
        UP=3.141592/(2.*AL1)
        DEL=UP/2.
        J=J+1
        IF(J-MEIG1   )5,5,115
115     TYPE 12Ø
12Ø     FORMAT($EIGENVALUE EQUATION 1 COMPLETE$/)
        J=1
        I=1
        HAX=H5
        HBX=H6
        AKYX=AKY1
        AKX=AK1
311      CONTINUE
        SCALE=AKX/T
        GAMT=AKX*SQRT(HAX*HBX)/AKYX
        IF(GAMT*T/AKX-1.57)112Ø,111Ø,111Ø
111Ø    IF(GAMT*T/AKX-3.141593)114Ø,113Ø,113Ø
113Ø    UP=3.14*SCALE
        DEL=1.55*SCALE
        MCASE=3
        GO TO 14ØØ
114Ø    UP=(GAMT-.ØØ1)*T/AKX
        DEL=UP-1.57
        MCASE=2
        GO TO 14ØØ
112Ø    UP=1.57Ø*SCALE
        DEL=1.57*SCALE-GAMT
        MCASE=1
14ØØ    CONTINUE
351     SIGN=-1.Ø
        GAM(I,J)=GAM(I,J-1)+UP
        A=GAM(I,J)*T/AKX
        B=(HAX+HBX)/(GAM(I,J)*AKYX/AKX-HAX*HBX*AKX/(AKYX*GAM(I,J)))
```

```
      D1=SIN(A)/COS(A)-B
      DEL=DEL/2.
      GAM(I,J)=GAM(I,J)-DEL
151   AB=GAM(I,J)*T/AKX
      BA=(HAX+HBX)/(GAM(I,J)*AKYX/AKX-HAX*HBX*AKX/(AKYX*GAM(I,J)))
      D2=SIN(AB)/COS(AB)-BA
      IF(DLEG1-D2*D2)21,1Ø1,1Ø1
21    IF(D1*D2)31,41,41
31    SIGN=-SIGN
      DEL=DEL/2.Ø
      GAM(I,J)=GAM(I,J)+SIGN*DEL
36    D1=D2
      GO TO 151
41    IF(D1)51,61,61
51    GAM(I,J)=GAM(I,J)+DEL
      GO TO 36
61    GAM(I,J)=GAM(I,J)-DEL
      GO TO 36
1Ø1   TYPE 2Ø4,(I,J,GAM(I,J))
      IF(J-3)2235,2234,2234
2234  IF(GAM(I,J)-GAMT)2235,2235,2238
2238  TEST1=GAM(I,J)-GAM(I,J-1)
      TEST2=GAM(I,J-1)-GAM(I,J-2)
      IF(((TEST1-TEST2)/TEST1)**2-.ØØØ1)2236,2236,2235
2236  DO 2237,IKI=J,5Ø
      GAM(I,IKI)=TEST1+GAM(I,IKI-1)
2237  J=5Ø
2235  CONTINUE
      IF(MCASE-1)118Ø,115Ø,118Ø
115Ø  UP=3.1416*SCALE
      DEL=GAM(I,J)+UP-J*3.1415926*SCALE
      GO TO 15ØØ
118Ø  IF(MCASE-3)12ØØ,119Ø,12ØØ
119Ø  IF((GAMT-GAM(I,J))/SCALE-3.14)1194,1192,1192
1192  UP=3.14Ø*SCALE
      DEL=GAM(I,J)+UP-(1.58+J*3.142)*SCALE
      GO TO 15ØØ
1194  UP=SCALE*(1.57+3.14159*J)-GAM(I,J)
      DEL=UP+GAM(I,J)-GAMT
      MCASE=1
      GO TO 15ØØ
12ØØ  MCASE=1
      GO TO 115Ø
15ØØ  CONTINUE
      J=J+1
      IF(J-MEIG1)351,351,215
215   GO TO (22Ø,221,25Ø),I
22Ø   J=1
```

```
          I=2
          HAX=H4
          HBX=H1
          AKYX=AKY2
          AKX=AK2
          GO TO 311
221       J=1
          I=3
          HAX=H3
          HBX=H2
          AKYX=AKY3
          AKX=AK3
          GO TO 311
25Ø       TYPE 24Ø
24Ø       FORMAT($EIGENVALUES CALCULATED$/)
          CHAIN (/L1/)
          END
```

```
C      PROGRAM SHINGLES ON A SUBSTRATE
C      PART - "2"
       COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
      1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
       DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø),SUM(5Ø),SUM1(5Ø),B(5Ø),G(5Ø)
       TYPE 1ØØØØ
       ACCEPT 11,LIM
       TYPE 1ØØØ1
       ACCEPT 11,LIMF
11     FORMAT(I2/)
1ØØØØ  FORMAT($UPPER LIMIT ON SUMS=$)
1ØØØ1  FORMAT($UPPER LIMIT ØN FUNC=$)
       DO 1ØØ,I=1,LIM
1ØØ    SUM(I)=GAM(2,I)*D(I)*SINH(GAM(2,I)*(AL2-AL1))
       ASUM=Ø.Ø
       DO 2ØØ,J=1,LIMF
       DO 15Ø,I=1,LIM
15Ø    ASUM=ASUM+SUM(I)*AI2(I,J)
       G(J)=(-AKX2*ASUM)
      1/(GAM(3,J)*AI1(J)*AKX3*SINH(GAM(3,J)*(AL3-AL2)))
       TYPE 12,(J,G(J))
12     FORMAT($G$,5X,I2,5X,E14.4/)
2ØØ    ASUM=Ø.Ø
       DO 3ØØ,I=1,LIM
3ØØ    SUM1(I)=GAM(2,I)*E(I)*SINH(GAM(2,I)*(AL2-AL1))
       ASUM=Ø.Ø
       DO 4ØØ,J=1,LIMF
       DO 45Ø,I=1,LIM
45Ø    ASUM=ASUM+SUM1(I)*AI6(I,J)
       B(J)=AKX2*ASUM/(AI5(J)*(H6*COSH(GAM(1,J)*AL1)
      1+AKX1*GAM(1,J)*SINH(GAM(1,J)*AL1)))
       TYPE 13,(J,B(J))
13     FORMAT($B$,5X,I2,5X,E14.4/)
4ØØ    ASUM=Ø.Ø
       TYPE 1ØØØ2
       ACCEPT 1Ø,X
       TYPE 1ØØØ3
       ACCEPT 1Ø,Y
1Ø     FORMAT(F1Ø.5)
1ØØØ2  FORMAT($  X=$)
1ØØØ3  FORMAT($  Y=$)
       ASUM=Ø.Ø
       BSUM=Ø.Ø
       DO 5ØØ,I=1,LIMF
       ASUM=ASUM+A(I)*((H6/(AKX1*ALAM(1,I)))*SIN(ALAM(1,I)*X)
      1+COS(ALAM(1,I)*X))*((H6*AK1/(AKY1*ALAM(1,I)))
      2*SINH(ALAM(1,I)*Y/AK1)+COSH(ALAM(1,I)*Y/AK1))
       BSUM=BSUM+B(I)*((H6*AK1/(AKY1*GAM(1,I)))
```

```
     1*SIN(GAM(1,I)*Y/AK1)+COS(GAM(1,I)*Y/AK1))
     2*((H6/(AKX1*GAM(1,I)))*SINH(GAM(1,I)*X)
     3+COSH(GAM(1,I)*X))
      T1=ASUM+BSUM
      TYPE 14,(I,ASUM,BSUM,T1)
14    FORMAT($T1$,2X,I2,3(2X,E14.4)/)
5ØØ   CONTINUE
      ASUM=H1*H4*TH*Y/(AKY2*(H1+H1*H4*T/AKY2+H4))
     1+H4*TH/(H1+H1*H4*T/AKY2+H4)
      BSUM=Ø.Ø
      CSUM=Ø.Ø
      DO 6ØØ,I=1,LIMF
      ASUM=ASUM
      BSUM=BSUM+D(I)*COSH(GAM(2,I)*(X-AL1))*((H1*AK2/(GAM(2,I)*AKY2))
     1*SIN(GAM(2,I)*Y/AK2)+COS(GAM(2,I)*Y/AK2))
      CSUM=CSUM+D(I)*COSH(GAM(2,I)*(AL2-X))*((H1*AK2/(GAM(2,I)*AKY2))
     1*SIN(GAM(2,I)*Y/AK2)+COS(GAM(2,I)*Y/AK2))
      T2=ASUM+BSUM+CSUM
      TYPE 15,(I,ASUM,BSUM,CSUM,T2)
15    FORMAT($T2$,2X,I2,4(2X,E14.4)/)
6ØØ   CONTINUE
      ASUM=(1.+H2*Y/AKY3)*(H3*TH/(H2+H2*H3*T/AKY3+H3))
      BSUM=Ø.Ø
      DO 7ØØ,I=1,LIMF
      BSUM=BSUM+G(I)*COSH(GAM(3,I)*(AL3-X))*((H2*AK3*SIN
     1(GAM(3,I)*Y/AK3))/(AKY3*GAM(3,I))+COS(GAM(3,I)*Y/AK3))
      T3=ASUM+BSUM
      TYPE 16,(I,ASUM,BSUM,T3)
16    FORMAT($T3$,2X,I2,3(2X,E14.4)/)
7ØØ   CONTINUE
      GO TO 4ØØ
      END
```

```
*/

      FUNCTION AI7(N,M)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
      DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      AX=H6**2*AK1**2*(-GAM(1,M)*SINH(ALAM(1,N)*T/AK1)
     1*COS(GAM(1,M)*T/AK1)/AK1+ALAM(1,N)*COSH(ALAM(1,N)*T/AK1
     2)*SIN(GAM(1,M)*T/AK1)/AK1)/(AKY1**2*ALAM(1,N)
     3*GAM(1,M)*((GAM(1,M)/AK1)**2+(ALAM(1,N)/AK1)**2))
```

```
 BX=H6*AK1*(-GAM(1,M)*COSH(ALAM(1,N)*T/AK1)
1*COS(GAM(1,M)*T/AK1)/AK1+ALAM(1,N)*SINH(ALAM(1,N)*T/AK1)
2*SIN(GAM(1,M)*T/AK1)/AK1+GAM(1,M)/AK1)
3/(GAM(1,M)*AKY1)
 BY=H6*AK1*(ALAM(1,N)*COSH(ALAM(1,N)*T/AK1)
1*COS(GAM(1,M)*T/AK1)/AK1+GAM(1,M)*SINH(ALAM(1,N)*T/AK1)
2*SIN(GAM(1,M)*T/AK1)/AK1-ALAM(1,N)/AK1)
3/(ALAM(1,N)*AKY1)
 AY=(ALAM(1,N)*SINH(ALAM(1,N)*T/AK1)*COS(GAM(1,M)*T/AK1)
1+GAM(1,M)*COSH(ALAM(1,N)*T/AK1)*SIN(GAM(1,M)*T/AK1))
2/AK1
 AI7=AX+(BX+BY+AY)/((GAM(1,M)/AK1)**(ALAM(1,N
1)/AK1)**2)
 RETURN
 END
 FUNCTION AI9(M)
 COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
 DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
  AI9=(-H6*AK1*AK1/(AKY1*GAM(1,M)**2))
1*(COS(GAM(1,M)*T/AK1)-1.)+(AK1/GAM(1,M))
2*SIN(GAM(1,M)*T/AK1)
 RETURN
 END
 FUNCTION AI1Ø(M)
 COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
 DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
 AI1Ø=(H6*AK1*AK1*AK1/(AKY1*GAM(1,M)**3))
1*(SIN(GAM(1,M)*T/AK1)-(GAM(1,M)*T/AK1)*COS(GAM(1,M)
2*T/AK1))+(AK1*AK1/GAM(1,M)**2)*(COS(GAM(1,M)*T/AK1)
3-1.+(GAM(1,M)*T/AK1)*SIN(GAM(1,M)*T/AK1))
 RETURN
 END
  FUNCTION TAN(X)
  TAN=SIN(X)/COS(X)
  RETURN
  END
 FUNCTION SINH(XX)
 YY=XX
 IF(XX-175.)2Ø,2Ø,1Ø
1Ø  XX=175.
2Ø  CONTINUE
 SINH=(EXPF(XX)-EXPF(-XX))/2.Ø
 XX=YY
 RETURN
 END
```

```
      FUNCTION AI5(M)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM

      DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      AI5=(H6*H6*AK1/(AKY1**2*GAM(1,M)**3))*(GAM(1,M)*T/(2.*AK1)
     1-.25*SINF(2.*GAM(1,M)*T/AK1))
     2+H6*AK1*AK1*SIN(GAM(1,M)*T/AK1)**2/(AKY1*GAM(1,M)**2)
     3+(AK1/GAM(1,M))*(GAM(1,M)*T/(2.*AK3)+.25*SIN(2.*GAM(1,M)
     4*T/AK1))
      RETURN
      END
      FUNCTION A(N)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM

      DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      B=H5*TH*(H6*(1.-COS(ALAM(1,N)*AL1))/(AKX1*ALAM(1,N)**2)
     1+SIN(ALAM(1,N)*AL1)/ALAM(1,N))
      C=(SINH(ALAM(1,N)*T/AK1)*(H5*H6*AK1/(AKY1*ALAM(1,N))
     1+AKY1*ALAM(1,N))+COSH(ALAM(1,N)*T/AK1)*(H5+H6*AK1))
     2*(H6**2*(.5*ALAM(1,N)*AL1-.25*SIN(2.*ALAM(1,N)*AL1))
     5/(AKX1**2*ALAM(1,N)**3)
     3+H6*SIN(ALAM(1,N)*AL1)**2/(AKX1*ALAM(1,N)**2)
     4+(ALAM(1,N)*AL1*.5+.25*SIN(2.*ALAM(1,N)*AL1))/ALAM(1,N))
      A=B/C
      RETURN
      END
      FUNCTION D(N)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM
      DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      DA=Ø.Ø
      DB=Ø.Ø
      C=H4*TH/(H1+H4*H1*T/AKY2+H4)
      F=H3*TH/(H2+H2*H3*T/AKY3+H3)
      H=(-AI1Ø(1)*(H1*C/AKY2-H2*F/AKY3)-AI9(1)*(C-F))
      IF(N-1 )Ø,1Ø,2Ø
1Ø    D      T1Ø(1)/AKY2+C*AI9(1)+H*AI6(N,1)*COSH(GAM(2,N,
     1*(
```

```
      FUNCTION COSH(XX)
      YY=XX
      IF(XX-175.)2Ø,2Ø,1Ø
1Ø    XX=175.
2Ø    CONTINUE
      COSH=(EXPF(XX)+EXPF(-XX))/2.Ø
      XX=YY
      RETURN
      END
      FUNCTION AI8(N,M)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM

      DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      AI8=(H1*AK2/(ALAM(2,N)*AKY2))*(SINF((GAM(2,N)/AK2
     1-GAM(1,M)/AK1)*T)/(2.*(GAM(2,N)/AK2-GAM(1,M)/AK1))
     2-SINF((GAM(2,N)/AK2+GAM(1,M)/AK1)*T)/(2.*(GAM(2,N)/AK2
     3+GAM(1,M)/AK1)))
     4+GAM(1,M)/AK1/((GAM(1,M)/AK1)**2-(GAM(2,N)/AK2)**2)
     5-COS((GAM(1,M)/AK1-GAM(2,N)/AK2)*T)
     6/(2.*(GAM(1,M)/AK1-GAM(2,N)/AK2))
     7-COSF((GAM(1,M)/AK1+GAM(2,N)/AK2)*T)
     8/(2.*(GAM(1,M)/AK1+GAM(2,N)/AK2))
      RETURN
      END
      FUNCTION AI6(N,M)
      COMMON AL1,AL2,AL3,H1,H2,H3,H4,H5,AKY1,AKY2,AKY3,
     1AKX1,AKX2,AKX3,TH,T,AK1,AK2,AK3,ALAM,GAM

      DIMENSION ALAM(3,Ø/5Ø),GAM(3,Ø/5Ø)
      AIX=(H6*H1*AK1*AK2/(GAM(2,N)*GAM(1,M)*AKY1*AKY2))
     1*(SIN((GAM(2,N)/AK2-GAM(1,M)/AK1)*T)/(2.*GAM(2,N)/AK2
     2-2.*GAM(1,M)/AK1)-SIN((GAM(2,N)/AK2+GAM(1,M)/AK1)*T)
     3/(2.*GAM(1,M)/AK1+2.*GAM(2,N)/AK2))
      AI6=AIX
     4+(H6*AK1/(AKY1*GAM(1,N)))*(GAM(1,M)
     5/((GAM(1,M)/AK1)**2-(GAM(2,N)/AK2)**2)
     6-COS((GAM(1,M)/AK1-GAM(2,N)/AK2)*T)/(2.*GAM(1,M)/AK1
     7-2.*GAM(2,N)/AK2)-COS((GAM(1,M)/AK1+GAM(2,N)/AK2)*T)
     8/(2.*GAM(1,M)/AK1+GAM(2,N)*2./AK2))
     9+(H1*AK2/(GAM(2,N)*AKY2))*(GAM(2,N)
     1/((GAM(2,N)/AK2)**2-(GAM(1,M)/AK1)**2)
     2-COS((GAM(2,N)/AK2-GAM(1,M)/AK1)*T)/(2.*GAM(2,N)/AK2
     3-2.*GAM(1,M)/AK1)-COS((GAM(2,N)/AK2+GAM(1,M)/AK1)*T)
     4/(2.*GAM(2,N)/AK2+2.*GAM(1,M)/AK1))
     5+SIN((GAM(2,N)/AK2-GAM(1,M)/AK1)*T)/(2.*GAM(2,N)/AK2
     6-2.*GAM(1,M)/AK1)+SIN((GAM(2,N)/AK2+GAM(1,M)/AK1)*T)
     7/(2.*GAM(2,N)/AK2+2.*GAM(1,M)/AK1)
      RETURN
      END
```

```
C      PROGRAM  "PAP"
      PENETRATION ANALYSIS PROGRAM
       COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
      1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
       DIMENSION ALAM(2,Ø/5Ø),GAM(2,Ø/5Ø),SUM(Ø/5Ø) ALL(Ø/5Ø),ANN(Ø/5Ø),
      1B1(Ø/5Ø),A2(Ø/5Ø),SUM1(Ø/5Ø),SUM2(Ø/5Ø),A1(Ø/5Ø)
       TYPE 1ØØØ1
       ACCEPT 1Ø, T
       TYPE 1ØØØ2
       ACCEPT 1Ø,R1
       TYPE 1ØØØ3
       ACCEPT 1Ø,R2
       TYPE 1ØØØ4
       ACCEPT 1Ø,R3
       TYPE 1ØØØ5
       ACCEPT 1Ø,S
       TYPE 1ØØØ7
       ACCEPT 1Ø,AKP
       TYPE 1ØØØ8
       ACCEPT 1Ø,AKR1
       TYPE 1ØØØ9
       ACCEPT 1Ø,AKZ1
       TYPE 1ØØ1Ø
       ACCEPT 1Ø,AKR2
       TYPE 1ØØ11
       ACCEPT 1Ø,AKZ2
       TYPE 1ØØ13
       ACCEPT 1Ø,H1
       TYPE 1ØØ14
       ACCEPT 1Ø,H2
       TYPE 1ØØ15
       ACCEPT 1Ø,TH
       TYPE 1ØØ16
       ACCEPT 1Ø,DLEG1
       TYPE 1ØØ17
       ACCEPT 11,MEIG1
       TYPE 1ØØ18
       ACCEPT 1Ø,DLEG2
       TYPE 1ØØ19
       ACCEPT 11,MEIG2
Ø      FORMAT(F1Ø.5/)
1      FORMAT(I2/)
ØØØ1 FORMAT($          T=$)
ØØØ2 FORMAT($         R1=$)
ØØØ3 FORMAT($         R2=$)
ØØØ4 FORMAT($         R3=$)
ØØØ5 FORMAT($          S=$)
ØØØ7:XSØØØ8 FORMAT($       AKR1=$)
```

```
ØØØ9 FORMAT($       AKZ1=$)
ØØ1Ø FORMAT($       AKR2=$)
ØØ11 FORMAT($       AKZ2=$)
ØØ13 FORMAT($         H1=$)
ØØ14 FORMAT($         H2=$)
ØØ15 FORMAT($         TH=$)
ØØ16 FORMAT($DELTA EIG1=$)
ØØ17 FORMAT($MAXNUMEIG1=$)
ØØ18 FORMAT($DELTA EIG2=$)
ØØ19 FORMAT($MAXNUMEIG2=$)
     AK1=SQRT(AKZ1/AKR1)
     AK2=SQRT(AKZ2/AKR2)
    EIGENVALUES "1"
     J=1
     ALAM(1,Ø)=Ø.Ø
     ALAM(2,Ø)=Ø.Ø
     SCALE=AK1/T
     AKX=AK1
     AKZX=AKZ1
     I=1
     HX=H1
     CONTINUE
     UP=3.2*SCALE
     DEL=3.2*SCALE
+     SIGN=-1.Ø
     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.Ø
     ALAM(I,J)=ALAM(I,J)-DEL
5    AB=(ALAM(I,J)*T)/AKX
     BA=(ALAM(I,J)*AKZX)/(AKX*HX)
     D2=SINF(AB)/COSF(AB)+BA
     IF(DLEG1 -D2*D2)2Ø,1ØØ,1ØØ
Ø    IF(D1*D2)3Ø,4Ø,4Ø
Ø    SIGN=-SIGN
     DEL=DEL/2.Ø
     ALAM(I,J)=ALAM(I,J)+SIGN*DEL
5    D1=D2
     GO TO 15
#Ø    IF(D1)5Ø,6Ø,6Ø
+Ø    ALAM(I,J)=ALAM(I,J)+DEL
     GO TO 35
3Ø    ALAM(I,J)=ALAM(I,J)-DEL
     GO TO 35
ØØ   IF(I*J-1)2Ø3,1Ø3,2Ø3
Ø3   TYPE 2Ø4
```

```
Ø4    FORMAT($           LAMBDA(I,J)            $/)
Ø3    CONTINUE
      IF(J-3)1235,1234,1234
234   TEST1=ALAM(I,J)-ALAM(I,J-1)
      TEST2=ALAM(I,J-1)-ALAM(I,J-2)
      IF(((TEST1-TEST2)/TEST1)**2-Ø.ØØØ1**2)1236,1236,1235
236   DO 1237,IKI=J,5Ø
      ALAM(I,IKI)=TEST1+ALAM(I,IKI-1)
237   J=5Ø
235   CONTINUE
      UP=3.2*SCALE
      DEL=ALAM(I,J)+UP-(J*3.1415921+1.571)*SCALE
      J=J+1
      IF(J-MEIG1   )5,5,11Ø
1Ø    I=I+1
      J=1
      AKX=AK2
      AKZX=AKZ2
      HX=H2
      SCALE=AK2/T
      DEL=3.2*SCALE
      IF(I-2)1,1,115
15    TYPE 12Ø
2Ø    FORMAT($EIGENVALUE EQUATION 1 COMPLETE$/)
     EIGENVALUE - 2
      GAM(1,Ø)=Ø.Ø
      GAM(2,Ø)=Ø.Ø
      SIGN=1.Ø
      III=1
      R1X=R1
      R2X=R2
1     IF (R1X-R2X) 51,51,41
#1     TA=3./(R1X-R2X)
      GO TO 61
+1     TA=3./(R2X-R1X)
31     DEL=TA/5.
      I=1
;Ø     GAM(III,I)=GAM(III,I-1)+TA/2
      D1=BJ(Ø,GAM(III,I)*R1X)*BY(Ø,GAM(III,I)*R2X)
     1-BJ(Ø,GAM(III,I)*R2X)*BY(Ø,GAM(III,I)*R1X)
CØ     GAM(III,I)=GAM(III,I)+DEL*SIGN
      D2=BJ(Ø,GAM(III,I)*R1X)*BY(Ø,GAM(III,I)*R2X)
     1-BJ(Ø,GAM(III,I)*R2X)*BY(Ø,GAM(III,I)*R1X)
      IF(D1*D2)9Ø,9Ø,1Ø1
KØ     IF(D2*D2-DLEG2   )2ØØ,2ØØ,95
K5     SIGN=-SIGN
      DEL=DEL/2.
      D1=D2
```

```
      GO TO 8Ø
Ø1    D1=D2
      GO TO 8Ø
ØØ    I=I+1
      JJ=I-1
      IF(JJ*III-1)2Ø1,198,2Ø1
98    TYPE 199
99    FORMAT($           GAMMA(NU,X)           $/)
Ø1    CONTINUE
      IF(JJ-3)2235,2234,2234
234   TESTA=GAM(III,JJ)-GAM(III,JJ-1)
      TESTB=GAM(III,JJ-1)-GAM(III,JJ-2)
      IF(((TESTA-TESTB)/TESTA)**2-.ØØØ1**2)2236,2236,2235
236   DO 2237,IIKI=JJ,5Ø
      GAM(III,IIKI)=GAM(III,IIKI-1)+TESTA
      I=5Ø
237   JJ=5Ø
235   CONTINUE
      SIGN=1.
      DEL=TA/5.
      IF(I-MEIG2  )7Ø,7Ø,1ØØØ
ØØØ   IF(III-1)1Ø27,1Ø13,1Ø27
Ø13   III=2
      R1X=R2
      R2X=R3
      GO TO 31
Ø27   CONTINUE
      TYPE 14ØØ
4ØØ   FORMAT($EIGENVALUE EQUATION 2 COMPLETE$/)
      CHAIN (/LINK1/)
      END
```

```
*/
AXO      PROGRAM  "PAP"
     PART  -----  "2"
     PENETRATION ANALYSIS PROGRAM
      COMMON T,R1,R2,R3,ALAM,GAM,AK1,AK2,
     1AKP,S,H1,H2,TH,H,AKR1,AKR2,AKZ1,AKZ2
      DIMENSION ALAM(2,Ø/5Ø),GAM(2,Ø/5Ø),SUM(Ø/5Ø),ALL(Ø/5Ø),ANN(Ø/5Ø),
     1B1(Ø/5Ø),A2(Ø/5Ø),A1(Ø/5Ø)
      TYPE 1ØØØ6
      ACCEPT 1Ø,AL
      TYPE 1ØØ2Ø
      ACCEPT 11,MNL
      MNLP=MNL
      MNN=MNL
      MNNP=MNL
      MM=MNL
      MMA=MNL
      MMP=MNL
      MNA2=MNL
      MNB1=MNL
      MNB1P=MNL
      MT1=MNL
      MT2=MNL
Ø     FORMAT(F1Ø.5/)
1     FORMAT(I2/)
ØØØ6  FORMAT($          AL=$)
ØØ2Ø  FORMAT($MAX    SUM =$)
ØØ33  FORMAT($           R=$)
ØØ34  FORMAT($           Z=$)
      C1=H1*TH/(H1*T+AKZ1)
      C2=H2*TH/(H2*T+AKZ2)
      G=AKR1*W(1)*D(1)*(T/2.-(AK1/(4.*ALAM(1,1)))
     1*SIN(2.*T*ALAM(1,1)/AK1))*(-ALAM(1,1)*BK(Ø,ALAM(1,1)*R1)
     2*BI(1,ALAM(1,1)*R2)-ALAM(1,1)*BI(Ø,ALAM(1,1)*R1)
     3*BK(1,ALAM(1,1)*R2))/P(1)
      TERR=T-(AK1/(ALAM(1,1)*2.))*SINF(2.*ALAM(1,1)*T/AK1)
      H=AKR1*TERR/(2.*R2*P(1))
      SUM(Ø)=Ø.Ø
      DO 32Ø IK=1,MNLP
      SUM(IK)=(F(IK)*B2(IK))
2Ø    CONTINUE
      DO 31Ø IJ=1,MNL
      SUMA=Ø.Ø
      DO 313 IK=1,MNLP
13    SUMA=SUMA+E(IK,IJ)*SUM(IK)
      ALL(IJ)=D(IJ)*SUMA+E(1,IJ)*D(IJ)*G*(C1-C2)+W(IJ)*D(IJ)
     1*(C2-C1)
1Ø    CONTINUE
```

```
15    FORMAT(1ØX,I2,5X,E14.4/)
      DO 41Ø IJ=1,MNN
      TERR=T-(AK1/(ALAM(1,IJ)*2.))*SINF(2.*ALAM(1,IJ)*T/AK1)
      ANN(IJ)=((-AKR1*AK1*AK1*ALL(IJ)/ALAM(1,IJ)**2)*(TERR/2.)
     1/(S*AKP*R1)
     2+C1*((AK1**2/ALAM(1,IJ)**2)*SIN(ALAM(1,IJ)*T/AK1)
     3-AK1*T*COS(ALAM(1,IJ)*T/AK1)/ALAM(1,IJ))*(-AKR1/(S*AKP)))/RF(IJ)
#1Ø    CONTINUE
      ID=69
      ASUM=Ø.Ø
      ASUM1=Ø.Ø
      ASUM2=Ø.Ø
      DO 61Ø IJ=1,MM
      TERM=Ø.Ø
      IF(IJ-1)6Ø3,6Ø7,6Ø3
3Ø7    TERM=D(1)*E(1,1)*H
3Ø3    CONTINUE
      ASUM=ASUM+(AK1/ALAM(1,IJ))**2
     1*(-ALL(IJ)/R1+ANN(IJ)*(ALAM(1,IJ)*(-BI(Ø,(ALAM(1,IJ)*R2)))
     2*BK(1,(ALAM(1,IJ)*R1))-ALAM(1,IJ)*BI(1,(ALAM(1,IJ)*R1))
     3*BK(Ø,(ALAM(1,IJ)*R2)))*((SINF(ALAM(1,IJ)*T/AK1)/(AL))+
     4(ALAM(1,IJ)/AK1)*COSF(ALAM(1,IJ)*T/AK1))
     5-TERM*ANN(1)/R1)
31Ø    CONTINUE
      ASUM1=-TH/AL
      DO 63Ø IL=1,MMP
      TERM=Ø.Ø
      IF (IL-1)623,625,623
325    TERM=D(1)*O(1)*E(1,1)*H
323    CONTINUE
      ASUM2=ASUM2+(AK1/ALAM(1,IL))**2*(-TERM/R1
     1+O(IL)*(-ALAM(1,IL)*BI(Ø,(ALAM(1,IL)*R2))*BK(1,(ALAM(1,IL)*R1))
     2-ALAM(1,IL)*BI(1,(ALAM(1,IL)*R1))*BK(Ø,(ALAM(1,IL)*R2))))
     3*((1./(AL))*SINF(ALAM(1,IL)*T/AK1)+(ALAM(1,IL)/AK1)
     4*COSF(ALAM(1,IL)*T/AK1))
33Ø    CONTINUE
      AM=(AKR1*ASUM/(S*AKP)+ASUM1)/(-1.-T/AL-AKR1*ASUM2/(S*AKP))
      TYPE 637
337    FORMAT($FUNCTION M CALCULATED$/)
      DO 71Ø IIJ=1,MNL
      A1(IIJ)=ANN(IIJ)+O(IIJ)*AM
;1Ø    CONTINUE
      TYPE 712
;12    FORMAT($ FUNCTION A1(N) DEFINED$/)
      DO 451 IL=1,MNA2
      A2(IL)=SUM(IL)
#51    CONTINUE
      A2(1)=A2(1)+H*A1(1)+G*(C1-C2)
```

```
      TYPE 452
#52    FORMAT($FUNCTION A2(N) DEFINED$/)
      ASUM=Ø.Ø
      DO 51Ø IJ=1,MNB1
      B1(IJ)=ALL(IJ)+D(IJ)*E(1,IJ)*H*A1(1)
      ASUM=Ø.Ø
+Ø9    CONTINUE
+1Ø    CONTINUE
2123  CONTINUE
      TYPE 1ØØ33
      ACCEPT 1Ø,R
      TYPE 1ØØ34
      ACCEPT 1Ø,Z
      IF(R-123.456)9Ø1,9Ø3,9Ø1
KØ1    IF(R-R2)8Ø7,8Ø7,837
CØ7    ASUM=Ø.Ø
      ASUM1=Ø.Ø
      ASUM2=Ø.Ø
      DO 73Ø I=1,MT1
      ASUM=ASUM+A1(I)*(-BI(Ø,(ALAM(1,I)*R))*BK(Ø,(ALAM(1,I)*R2))
     1+BI(Ø,(ALAM(1,I)*R2))*BK(Ø,(ALAM(1,I)*R)))
     2*SINF(ALAM(1,I)*Z/AK1)
      ASUM1=ASUM1+B1(I)*(-BI(Ø,(ALAM(1,I)*R))*BK(Ø,(ALAM(1,I)*R1))
     4+BI(Ø,(ALAM(1,I)*R1))*BK(Ø,(ALAM(1,I)*R)))
     5*SINF(ALAM(1,I)*Z/AK1)
      ASUM2=C1*Z
;3Ø    CONTINUE
      T1=ASUM+ASUM1+ASUM2
      TYPE 736,T1
;36    FORMAT($......T1=$,F1Ø.5/)
C17    IF(R-R2)827,837,837
C37    ASUM=Ø.Ø
      DO 74Ø I=1,MT2
      ASUM =ASUM+A2(I)*(-BI(Ø,(ALAM(2,I)*R))*BK(Ø,(ALAM(2,I)*R3))
     1+BI(Ø,(ALAM(2,I)*R3))*BK(Ø,(ALAM(2,I)*R)))
     2*SINF(ALAM(2,I)*Z/AK2)
     3+B2(I)*(-BI(Ø,(ALAM(2,I)*R))*BK(Ø,(ALAM(2,I)*R2))
     4+BI(Ø,(ALAM(2,I)*R2))*BK(Ø,(ALAM(2,I)*R)))
     5*SINF(ALAM(2,I)*Z/AK2)
;4Ø    CONTINUE
      T2=ASUM+C2*Z
      TYPE 744,T2
C27    GO TO 12123
;44    FORMAT($.......T2=$,F1Ø.5/)
KØ3    CONTINUE
      ASUM=Ø.Ø
      ASUM1=Ø.Ø
      ASUM2=Ø.Ø
```

```
 ASUM3=Ø.Ø
 ASUM4=Ø.Ø
 DO 913 N=1,MNL
 ASUM=ASUM+(A1(N)/AK1)*(-R2*BK(Ø,(ALAM(1,N)*R2))*BI(1,
1(ALAM(1,N)*R2))-R2*BI(Ø,(ALAM(1,N)*R2))*BK(1,(ALAM(1,N)
2*R2))+R1*BK(Ø,(ALAM(1,N)*R2))*BI(1,(ALAM(1,N)*R1))
3+R1*BI(Ø,(ALAM(1,N)*R2))*BK(1,(ALAM(1,N)*R1)))
 ASUM1=ASUM1+(B1(N)/AK1)*(-R2*BK(Ø,(ALAM(1,N)*R1))
1*BI(1,(ALAM(1,N)*R2))
2-R2*BI(Ø,(ALAM(1,N)*R1))*BK(1,(ALAM(1,N)*R2))
3+R1*BK(Ø,(ALAM(1,N)*R1))*BI(1,(ALAM(1,N)*R1))
4+R1*BI(Ø,(ALAM(1,N)*R1))*BK(1,(ALAM(1,N)*R1)))
 ASUM2=ASUM2+(A2(N)/AK2)*(-R3*BK(Ø,(ALAM(2,N)*R3))
1*BI(1,(ALAM(2,N)*R3))
2-R3*BI(Ø,(ALAM(2,N)*R3))*BK(1,(ALAM(2,N)*R3))
3+R2*BK(Ø,(ALAM(2,N)*R3))*BI(1,(ALAM(2,N)*R2))
4+R2*BI(Ø,(ALAM(2,N)*R3))*BK(1,(ALAM(2,N)*R2)))
 ASUM3=ASUM3+(B2(N)/AK2)*(-R3*BK(Ø,(ALAM(2,N)*R2))
1*BI(1,(ALAM(2,N)*R3))
2-R3*BI(Ø,(ALAM(2,N)*R2))*BK(1,(ALAM(2,N)*R3))
3+R2*BK(Ø,(ALAM(2,N)*R2))*BI(1,(ALAM(2,N)*R2))
4+R2*BI(Ø,(ALAM(2,N)*R2))*BK(1,(ALAM(2,N)*R2)))
 ASUM4=ASUM4+(ALAM(1,N)/AK1)*(-BK(Ø,(ALAM(1,N)*R2))
1*BI(Ø,(ALAM(1,N)*R1))
2+BI(Ø,(ALAM(1,N)*R2))*BK(Ø,(ALAM(1,N)*R1)))*A1(N)
K13   CONTINUE
 Q1=6.2831842*AKZ1*(ASUM+ASUM1+C1*(R2**2-R1**2)/2.)
 Q2=6.2831842*AKZ2*(ASUM2+ASUM3+C2*(R3**2-R2**2)/2.)
 QP=6.2831842*R1*AKP*S*(ASUM4+C1)
 Q=Q1+Q2+QP
 V1=Q1*T/(AKZ1*(R2**2-R1**2)*TH)
 V2=Q2*T/(AKZ2*(R3**2-R2**2)*TH)
 V3=QP*T/(AKP*R1*S*TH)
 TYPE 937,(Q,Q1,Q2,QP,V1,V2,V3)
K37   FORMAT(7(E14.4,5X/))
 END
```