CRYOGENIC STORAGE SYSTEMS DESIGN, FABRICATION AND EVALUATION

FINAL REPORT

CONTRACT: NAS9-5491

VOLUME II
APPENDICES

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Summary of Cryogenic Storage System Evaluation

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Ardeform Pressure Vessel Program

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FOREWARD

In conformance with Phase I of Contract NAS 9-5491, the Instruments & Life Support Division of The Bendix Corporation performed an in-depth evaluation and study of the various aspects that must be considered for a cryogenic storage system. The results of this effort were some 800 pages of text, tables and figures.

This study was conducted to determine the requirements for larger capacity and more refined cryogenic storage systems for space missions of longer duration. Emphasis was placed on cryogenic tankage with outside diameters of 20 inches or larger.

As a result of the data generated during the performance of this study effort, many worthy conclusions can be drawn to assist those engaged in the design and fabrication of cryogenic storage systems. However, due to the voluminousness of this study report, Bendix has designed this publication to serve as a readily accessible reference guide. It represents a condensation of this accumulated data, with emphases being placed on those designs, processes and techniques which were found to be most applicable to cryogenic storage systems of the size under investigation.

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CHAPTER I

MATERIALS, WELDING & PLATING PROCESSES

In the fabrication of a cryogenic storage and supply system, every design facet must be considered for ultimate achievement. Thus, to fully encompass all avenues of investigation this chapter delves into material selection, welding, and plating processes, and highlights those candidates showing the greatest performance in these fields.

MATERIAL SELECTION

The selection of material is of prime importance during the design of the pressure vessel, radiation shields and outer shell. Since each requires different material properties, they are therefore treated separately for a greater indepth analysis.

Pressure Vessel Material

When designing a pressure vessel it is necessary to take the following material properties into consideration:

a. Strength-to-weight ratio
b. Corrosion resistance
c. Formability
d. Weldability
e. Toughness at cryogenic temperatures
f. Creep resistance
g. Plateability
h. Stress-corrosion cracking susceptibility
i. Vacuum integrity.

To date, the most promising candidates for pressure vessel material are Inconel 718, Cryoformed 301 Stainless Steel, Titanium 6AL-4U ELI and Titanium 5AL-2.5V ELI.

Welding of cryoformed 301 SS seriously reduces the strength, while silver brazing reduces its yield strength. The creep strength and stress-corrosion cracking susceptibility of titanium alloys are their most serious drawbacks.

Inconel 718 possesses a good to excellent rating in all properties to be considered for a cryogenic pressure vessel.

Radiation Shield Material

Material properties to be considered for radiation shields are:

a. Formability
b. Stiffness-to-weight ratio
c. Low density
d. Low-vapor pressure up to bake-out temperature
e. Good plateability

Aluminum alloys, magnesium alloys and magnesium-lithium alloys have proven to be the best shield materials, with aluminum being the favored material.

Formability of magnesium at room temperature is relatively poor. Magnesium could prove competitive if techniques are developed for elevated temperature forming of thin walled, large hemispherical parts. Magnesium-lithium alloys also require elevated temperature forming techniques. In addition, poor availability of suitable sheet material and high prices have been limiting factors.

Outer Shell Material

In selecting material for the outer shell, consideration must be given to its:

a. Modulus of elasticity/weight ratio
b. Weldability
c. Brazeability
d. Plateability
e. Vacuum integrity
f. Formability

Stainless steel, aluminum and aluminum honeycomb have proven to be the most logical outer shell material candidates.

Where the inner and outer vessel are of similar analysis, no dissimilar metal joints are required. A transition joint between stainless and aluminum is required if a stainless or high nickel alloy inner and an aluminum outer is used. Aluminum and aluminum honeycomb show a weight advantage, but pose metallurgical bonding problems. While quite expensive, extensive investigation has shown that aluminum honeycomb is attractive for severe weight requirements, and that it can be economically justified.

WELDING PROCESSES

Welding is a process used to join metals by the application of heat. Many welding processes have been developed, concerned with basically (1) the method of generating the necessary heat, (2) the method of adding filler metal, and (3) the method of protecting the molten weld puddle.

Welding is primarily used to join like or similar metals where the joining is required to develop strength and transmit stress. Since the properties of the parent metal can be affected either chemically, metallurgically or physically by the heating of the area to be joined, this influences the selection of a particular welding process.

Welding Comparison

While several welding processes are applicable to the fabrication of cryogenic dewars, the TIG welding process has been used most frequently. However, with the dewar size progressively increasing, the MIG welding process shows advantages in speed, single pass welds of heavier gauge material, and reduction of operator fatigue. Electron beam welding exhibits advantages for very thin sections, joints adjacent to components that are subject to thermal damage, and in cleanliness.

Since there are so many possible joint configurations, no single process can be proclaimed best.

PLATING COMPARISON

Both the standard electroplating baths and the vacuum evaporation process will produce low emissivity coatings suitable for cryogenic liquified gas storage vessels. Each process has its advantages and disadvantages. The primary advantages and limitations of each process are listed below. By referring to the list, the most economical and satisfactory choice between the two processes can be made.

ELECTROPLATING

ADVANTAGES

1. Most plating baths are readily available, up to about 3 feet square tanks, making the process economical up to the tank size available.

2. The process is both well established and well understood, and has proven satisfactory for low emissivity coatings. Pre-cleaning and initial surface requirements have been established.

DISADVANTAGES

1. The liquid necessary for the process must be removed after the plating is complete. Liquid may be trapped in limited accessibility areas.

2. Plating racks can become very heavy and expensive for plating the outer surface of pressure vessels. The buoyancy problem becomes significant as the size gets larger. Filling the vessel with liquid to overcome buoyancy requires husky handling equipment and removal of the liquid for dryness after plating.

3. As the size of article to be plated increases, the facilities that are available become limited. The metal required to merely make up the bath becomes very expensive in the case of those metals such as gold or silver.

VACUUM EVAPORATION

ADVANTAGES

1. Using a suitable low vapor pressure substrate, the surface preparation required to produce a very smooth surface becomes minimal.

2. A very high percentage of the precious metal used for plating actually is deposited on the surface of the article, compared to the large amount of metal remaining in a plating chamber.

3. No post cleaning or drying is required.

4. The capital equipment investment becomes competitive when the size of the article to be plated is large.

5. A very smooth surface can be achieved by the process.

DISADVANTAGES

1. Complex shapes are difficult to plate to a uniform thickness.

2. Substrates suitable for static vacuum systems are considered proprietary.

3. The process requires rather complicated equipment and process control which is not readily available in all areas.

OVERALL COMPARISONS

The final choice of welding technique, plating process, and material will be greatly influenced by the facilities available, previous experience, and cost. The following outline illustrates the type of choices to be made, some factors affecting these choices, and where some freedom still exists in making these choices.

OVERALL SUMMARY

	WELDING PROCESS	PLATING PROCESS	MATERIAL SELECTION
Pressure Vessel			
Size to 30" dia.	TIG	Electroplating	Inconel 718
Above 30" dia.	TIG or MIG	Vacuum Evaporation	Inconel 718
Radiation Shields			
Size to 30" dia.	Not required	Electroplating	Aluminum*
Above 30" dia.	in present design	Vacuum Evaporation	Aluminum*
Vacuum Vessel			
Size to 30" dia.	TIG	Electroplating	Stainless Steel**
Above 30"	TIG or MIG	Vacuum Evaporation	Stainless Steel**

* Where a very critical weight requirement exists, Magnesium or Magnesium-Lithium should be considered.

** Where a very critical weight requirement exists, aluminum or aluminum honeycomb construction should be considered. (Requirements a transition joint, stainless to aluminum).

METALS ANALYSES

The following pages represent a more detailed analyses of those material candidates discussed previously.

Inconel Alloys

Inconel alloys 718 and X-750 are the prime pressure vessel candidates explored during our investigations, and the data supporting their worthiness is based on extensive updating of previously existing data.

Inconel alloy 718 is a high strength weldable alloy containing 52.5% nickel, 19% chromium, 18% iron, 5% niobium, 3% molybdenum, 1% titanium, 0.4% aluminum, and a trace of 4 other elements. This analysis exhibits excellent properties between the range of -423°F. to +1300°F.

Inconel X-750 is an age-hardenable, nickel-chromium alloy, which exhibits excellent cryogenic properties to -423°F. and useful strength up to 1800°F. The material is available in all standard mill products. The alloy contains 70% nickel, 14-17% chromium, and 5-9% iron. It is made age hardenable by 2 1/4 - 2 3/4% titanium and .40-1.00 aluminum with a controlled impurity limit on Mn, Si, S, Cu, C and Cb.

Physical Characteristics of Inconel 718

Inconel 718 is a nickel-chromium alloy developed by the Huntington Alloy Products Division of International Nickel Company. It is a Ni-Cr-Fe-Mo base alloy made age hardenable by a Columbium (Niobium) addition, rather than by aluminum and titanium additions common to Nickel-Chromium alloys developed earlier.

It has a number of unique characteristics that make it a candidate for a cryogenic pressure vessel. These characteristics are:

A. High yield, tensile, creep and rupture strength at temperatures up to 1300°F.

B. Sluggish response to age-hardening which permits annealing and welding without spontaneous hardening during heating and cooling.

C. May be pickled in the age-hardened condition without intergranular attack.

D. Can be welded in either the annealed or age-hardened condition.

E. Exhibits excellent cryogenic properties to -423°F.

F. Responds to combining work hardening with age hardening.

G. Can be machined in either the annealed or age hardened condition.

H. Furnace brazes readily in dry hydrogen, braze-ability is comparable to that of 17-7 PH and is superior to that of alloys containing 2% of aluminum plus titanium.

Physical Characteristics of Inconel X-750

Inconel alloy X-750 is an age hardenable nickel-chromium alloy used for its corrosion and oxidation resistance, and high creep rupture strength at temperatures up to 1500°F. The alloy is made age hardenable by the combination of aluminum and titanium with nickel to form gamma prime - the intermetallic compound Ni_3 (AL, Ti).

As a candidate for cyrogenic temperature service, its desirable characteristics are as follows:

A. Retains its toughness to -423°F.

B. Is available in all mill forms.

C. In the mill annealed condition, Inconel alloy X-750 is relatively soft and ductile, hence amenable to deep drawing and spinning, and quite adaptable to stretch forming.

D. Can be welded by resistance and the inert-gas tungsten arc process.

E. Is readily machined as compared to other similar alloys.

F. Responds to combining work hardening with age hardening.

Processing Procedures

Inconel alloys are amendable to various fabrication techniques. However, like other alloys and metals, the processing procedures are governed by the specific physical properties of the material which controls the methods and limits of the various fabrication processes.

Inturgescent Forming

Inconel X-750 was the first inconel material subjected to the Inturgescent Forming Process, and it showed excellent formability. Inconel 718 has now been found to be very amenable to Inturgescent Forming, and with this process Bendix has formed 7 hemispheres 39" x .070" and 4 hemispheres 39" x .175" to date.

Forging

Inconel alloy 718 offers considerable resistance to deformation during hot working. The forces required are somewhat higher than for Inconel X-750. The yield strength at 1800°F is approximately 16,000 PSI.

A forging temperature of 1800-2050°F is recommended for 718. Forging above 2050°F may cause internal bursting or edge cracking and normally a maximum furnace setting of 2050°F is recommended. Direct flame impingement may cause hot spots and must be avoided. Also, build-up of heat during forging, caused by rapid, severe working, must be avoided. In the last operation, the metal should be worked uniformly with a gradually decreasing temperature, finishing with some reduction in the 1800-1850°F range. This hot-cold work will improve the strength of the forging.

All tools and dies should be preheated to about 400-500°F to avoid chilling the forging billet.

Inconel X-750 can be forged without difficulty as long as the recommended forging procedure is followed. Depending upon the end product, forging may be carried out at temperatures from 2200 to 1800°F. Attempts to forge below 1800°F may cause hammer splits in the colder areas. The work should be reheated to 2150°F when its temperature drops below 1900°F.

Other Forming Techniques

Very little data is available on forming of Inconel 718 sheet by spinning, deep drawing, Hydro-forming, bulge forming, or explosive forming.

Machining

Both Inconel 718 and Inconel X-750 are similar to other nickel base alloys, being machinable in either the solution annealed or age hardened condition. Slightly better tool life will be obtained by machining in the solution annealed condition, and a smoother finish will result when machining is performed after age hardening.

Pickling and Descaling

To remove the oxide film after heating operations pickling is required. Inconel alloy X-750 is subject to intergranular attack in certain pickling baths, particularily if the alloy is in the age hardened condition. Time in the bath should be kept to a minimum; the bath temperature should not exceed 125°F. The pickle tank must be properly ventilated as the fumes are toxic. Mechanical removal of scale from sheet material may be accomplished by fine grit and vapor blasting.

Welding

Inconel 718 and X-750 may be welded very satisfactorily using the inert gas tungsten arc process. Welding in either the solutioned or aged condition may be accomplished; however, welding in the aged condition will produce a softened heat affected zone. The weld area must be clean and free of contaminants. Good gas coverage on the face and root surfaces of the weld is necessary to prevent porosity. For severely restrained joints, the low freezing temperature of 718 filler is a serious limitation, and another filler alloy such as Rene' 41 should be considered. Due to its slow response to age hardening, Inconel 718 is not as crack sensitive as other similar nickel-base alloys, and it will not harden during heating and cooling from the welding operation.

Heat Treating

The importance of heat treatment of nickel-base superalloys cannot be over-emphasized. Because of the complex composition of these materials, a wide variance in properties can be achieved in any given alloy by use of different heat treatments. The optimum heat treatment cycle for a given alloy will depend upon the properties desired. Most commercial alloys are offered with a recommended heat treatment that provides an optimum compromise of properties, and Inconels 718 and X-750 are no exceptions.

Systematic investigation of all hardening variables led to the development of two temperature schedules:

(1) Anneal, age at 1325° for 8 hours, furnace cool at the rate of 20°F per hour to 1150°F, air cool.

(2) Anneal, age at 1325°F for 8 hours, furnace cool at the rate of 100°F per hour to 1150°F, hold at 1150°F for 8 hours, air cool.

These two schedules give similar results. A simplified version of this double aging treatment may also be used, which is:

(3) Anneal, age at 1325°F for 8 hours, furnace cool at whatever rate the furnace permits to 1150°F, hold at 1150°F to make the total aging cycle time about 18 hours, air cool.

Optimum tensile properties are obtained by combining work hardening with age hardening.

STAINLESS STEELS

The austenitic, or chromium-nickel (300 series) stainless steels exhibit the necessary corrosion resistance, strength, weldability, cryogenic toughness and formability to become a logical candidate for cryogenic fluid pressure vessels. These desirable properties persist to -423°F, and many vessels have been designed, fabricated, tested, and proven, giving evidence of satisfactory performance of the material for cyrogenic fluid storage and delivery.

300 Series Stainless Steels

In general, the annealed austenitic stainless steels, type 300 series, are suitable for temperatures as low as -423°F. These alloys retain 50-60% of their ductility at -320°F, while the tensile and yield strengths increases about 100% from room temperature to -320°F. Ductility as measured by percent elongation in 2 inch test sections does not indicate brittleness, even though the tensile strength is in the order of 240,000 lb. per sq. inch. The modulus of elasticity is increased when tension testing at low temperatures. Testing to -423°F does reveal a significant decrease in elongation values, but the ratio of notched to unnotched tensile strength remains near unity. The ratio of notched to unnotched tensile strength is a qualitative indication of a material's toughness or resistance to brittle failure.

Metallurgy

The austenitic, or chromium-nickel stainless steels, comprise a group of iron alloys containing from 16 to 26 percent chromiun and from 6 to 22 percent nickel. These steels are noted for high strength as well as for exceptional toughness, ductility and formability. As a class, the austenitic grades exhibit considerably better corrosion-resisting qualities than the martensitic (straight chromium, hardenable) or the ferritic (non-hardenable) grades. The Martensitic and ferritic stainless steels are the 400 series, and their composition varies from 12 to 27% chromium, and from zero to 2 1/2% nickel.

Chemistry

Although classed under the general heading of stainless steels, the austenitic steels form a family of metals quite different than the straight iron-chromium alloys. The addition of large amounts of nickel changes the fundamental crystal structure and with it the entire nature of the metal.

The relative proportion of chromium and nickel exerts a strong influence on the mechanical properties and workability of the steels, and is controlled in types 301, 302, 304, and 305 to produce a distinct series of alloys. In general, stainless steels with a high chromium to nickel ratio (for example, type 301) will harden rapidly when cold worked and are suited for high-strength applications. Whereas an alloy with a high rate of work hardening is desirable for many applications, a slower rate of work hardening is more desirable in alloys for severe drawing and spinning. Type 305 fulfills the need for a stainless with minimum work hardening qualities and maximum ductility. It can be annealed to provide extreme softness.

Physical and Mechanical Properties

A limited number of 300 series stainless steels have shown certain desirable advantages over other 300 series alloys, with respect to ease of fabrication, mechanical properties, weldability, etc.

Stainless type 301 is generally selected for applications where strength, ductility, and good corrosion resistance are essential. This alloy has a high work hardening rate and is supplied in five different tempers which are given in the following table. When cold worked, type 301 can be stress relieved to increase yield strength. The high strength-weight ratio, produced by cold working this steel and other austenitic grades, permits thinner sections to be used while providing comparable strength.

MECHANICAL PROPERTIES OF AUSTENITIC STAINLESS STEELS AT VARIOUS TEMPERS

AISI TYPE	TEMPER	TENSILE STRENGTH[1] (1000 psi)	YIELD STRENGTH[1] (1000 psi)	HARDNESS[2] (Rockwell B)
301	Annealed	75	..	94
	1/4 hard[3]	125	75	..
	1/2 hard[3]	150	110	..
	3/4 hard[3]	175	135	..
	Full hard[3]	185	140	..
302	Annealed	75	..	94
	1/4 hard[3]	125	75	..
304	Annealed	75	..	94
	1/4 hard[3]	125	75	..
304L	Annealed	70	..	94
305	Annealed	70	..	94
321	Annealed	75	..	94

1. Values are minimum. 2. Values are maximum. 3. Available in sheets and strips only.

Stainless type 303 is considered non-weldable because of sulfur or selenium additions to improve machinability.

Type 304 stainless is basically a low carbon (0.08% max.) version of 302.

Type 304L is an even lower carbon (0.03% max.) version of 302. The lower carbon content increases ductility, lowers strength, and allows welding without post-weld annealing.

Type 305 fulfills the need for a stainless with minimum work-hardening qualities and maximum ductility. It can be annealed to provide extreme softness.

Type 321 stainless has been formulated for weldability by virtue of low carbon (0.08 max. %) and by the addition of titanium to form titanium carbides in preference to chromium carbides.

Formability Properties

There is a 5 to 15% decrease in elongation values of the austenitic steels, depending on the grade, with a 40% cold reduction. It is the slow rate at which the tensile and yield strength curves close as a result of work hardening, and their greater ductility grade to with stand severe deformation during press forming and deep drawing.

Among annealed austenitic grades, type 301 has the highest strength; it work hardens to a higher strength, and retains its ductility at that higher strength, than the other austenitic grades. Thus, survival of 301 extends beyond that of other grades as severity of forming increases.

Weldability

Weldability refers to the suitability of a metal for welding processes and the service performance of the resulting weld. For the stainless steels, weldability concerns not only the customary mechanical properties, but also the chemical features of corrosion.

The welding characteristics of the austenitic stainless steels depend upon physical properties which differ considerably from those of carbon steel in the following respects:

(a) Increased electrical resistance. In the annealed condition, electrical resistance is about 6 times greater, and in the extremely cold worked condition, 12 times greater than that of mild steel.

(b) Greatly reduced thermal conductivity -- about 40 to 50% less than that of carbon steel.

(c) Increased thermal expansion -- about 50% greater than that of carbon steel.

(d) Slightly lower melting point than that of carbon steel.

Austenitic stainless steels can be welded by all of the conventional methods used for plain carbon steel. However when the characteristics of the deposited metal approximate those of the material being welded, the corrosion resistance of the welded joint will be better. The following precautions should be noted:

(e) Any carburization, or increase in carbon, must be carefully avoided or loss in corrosion resistance will result.

(f) Precautions must be taken to prevent any inclusion of foreign material, such as oxides, slag, or dissimilar metal.

(g) The surfaces of all metal to be welded must be clean.

In either arc or gas welding, electrodes or filler rods should have an alloy content slightly higher than that of the parent metal to be welded. Dilution and oxidation of the weld metal cannot always be completely avoided.

Sensitization remains the prime concern in welding the 300 series. Welding produces a temperature band along the weld (heat effected zone) which is within the carbide precipitation range of approximately 700 to 1600°F. Therefore the unstabilized types, such as 301, 302, and 305 require a final anneal for redissolving the chromium carbides, unless the corrosive conditions of service are to be mild.

Most commercial suppliers of welding electrodes and filler rod adjust the composition of their product to compensate for the change in chemistry due to welding. The following table illustrates the electrode selections and heat treatments recommended for satisfactory stainless steel weldments.

RECOMMENDED HEAT TREATMENTS AND ELECTRODES FOR WELDING WROUGHT AUSTENITIC STAINLESS STEELS

AISI TYPE	RECOMMENDED HEAT TREATMENT PREWELD	POSTWELD	RECOMMENDED ELECTRODE
		AUSTENITIC STEELS	
301 302 305 308	(a)	Cool rapidly from between 1950 and 2100 F if corrosion conditions are moderate to severe.	308
304	(a)	Cool rapidly from between 1850 and 2000 F only when corrosion conditions are strong.	308
304L	(a)	Not required for corrosion resistance	308(b) or 347
309(c) 310(c)	(a)	Usually unnecessary because steel is generally in service at high temperatures.	309 310
316	(a)	Cool rapidly from between 1950 and 2100F only when corrosion conditions are severe.	316, 310 (Mo)
316L	(a)	Not required for corrosion resistance.	316L, 310, 310 (Mo), 318
317	(a)	Cool rapidly from between 1950 and 2100 F only when corrosion conditions are severe.	317, 310 310 (Mo)
321, 347	(a)	Not required for corrosion resistance.	347

(a) Unnecessary when the steel is above 60 F. (b) 0.04% C Max. (c) Where corrosion is a factor, 309S are used, and postweld heat treatment is rapid cooling from between 2000 and 2100F.

Brazeability

The brazing of stainless steel is neither difficult nor unusual, but does present some special requirements which must be well understood.

All stainless steels are suitable for brazing, although there are some restrictions to specific alloys. Preventing sensitization in the 300 series is difficult because brazing is done in a temperature range quite similar to that of carbide precipitation. Also, no post anneal can be applied, because the required temperature would approximate or exceed the melting point of the filler alloy. Brazing must be rapid, or it must be restricted to the stabilized or extra low carbon grades.

Passivating

Fabricated stainless steel parts will usually be contaminated with small particles of foreign matter which must be removed to impart full stainless properties. This contamination may originate with machining, blasting, wire brushing, etc. The primary purpose of a passivating treatment is to remove contaminating films, usually iron, and to restore the optimum corrosion resistance of the material.

The most common passivation bath consists of 20% nitric acid (by volume) and 2-3 oz./gallon of sodium dichromate. The bath should be heated to 120-130°F, and a typical immersion time is 30 minutes.

ALUMINUM ALLOYS

Aluminum alloys are particularly noted for their light weight, ease of fabrication, excellent corrosion resistance, and ductility, even at very low (-423°F) temperatures. The density of aluminum is near 0.1 lb. per cubic inch, or about 1/3 the density of steel. The heat treatable aluminum alloys have strength-to-weight ratios exceeding those of many steels and most non-ferrous metals and alloys. Several of the aluminum alloys exhibit excellent weldability, and are compatible with most cryogenic fluids, fuels, and oxidizers, when properly handled.

Alloy Designations

The accepted numerical designations for wrought aluminum and aluminum alloys follow the four digit index system adopted by the Aluminum Association in October 1954, and approved by the American Standards Association in 1957. In this 4 digit system, the first digit identifies the major alloying elements if any. The second digit designates modifications of the original alloy. For example, if the second digit is zero, this indicates that the alloy is the original version as developed, with no new special control on impurities, intergers 1 to 9, assigned consecutively, indicate special control of one or more impurities, and are modifications of the original alloy. The last two digits identify the particular alloy within a major group.

Galvanic Corrosion

Aluminum and its alloys are anodic to most other common metals in a galvanic couple, and as a consequence will be corroded when coupled with a more noble metal in the presence of an electrolyte. Even corrosion products of the more noble metals can be harmful. For example, small quantities of copper dissolved in water will cause corrosion (pitting) of aluminum. Zinc and cadmium are nearly as nodic as aluminum and can usually be safely coupled to aluminum and aluminum alloys, providing the zinc and cadmium coatings are thick enough. Contact with stainless steel or chromium usually causes only slight electrolytic attack of aluminum alloys.

Cryogen Compatability

Aluminum is virtually unaffected, chemically, by liquid and gaseous oxygen, liquid and gaseous nitrogen, and is impermeable to helium and hydrogen. Many vessels for the storage and delivery of the above mentioned materials have proven their compatability with aluminum.

Physical and Mechanical Properties

Certain of the physical and mechanical properties of aluminum are of extreme importance in the fabrication of cryogenic dewars. Only a limited number of aluminum alloys exhibit all of the properties required for the successful fabrication and performance of a cryogenic pressure vessel. Aluminum and its alloys are also useful for radiation shields. Only those alloys which have proven successful for these two applications will be discussed in detail.

Tensile Strength

In the annealed condition, wrought high purity aluminum has a yield strength of 4000 to 5000 psi and an ultimate strength of 10,000 to 13,000 psi. Yield and ultimate strengths range from 11,000 to 22,000 and 12,000 to 27,000 psi respectively, in the strain hardened condition.

The yield strengths of the annealed non-heat treatable alloys range from about 6000 to 23,000 psi, with the ultimate tensile strengths being 2 to 3 times the yield. In the fully strain hardened condition, the yield and tensile strength ranges from 27,000 to 59,000 psi and 29,000 to 63,000 psi respectively.

Annealed heat treatable alloys exhibit approximately the same strength range as the annealed non-heat treatable alloys.

Rigidity

The modulus of elasticity of wrought aluminum and aluminum alloys is 10.0×10^6 to 10.8×10^6 psi in tension and approximately 2% greater in compression.

With a relatively low density, approximately 0.1 lb/in^3, the specific stiffness (ratio of elastic modulus to density) is high. The modulus or rigidity, or shear modulus is in the range of 3.75×10^6 to 4.3×10^6 psi. The rigidity of aluminum alloys is degraded more slowly than strength properties at temperatures to 500°F. The modulus of elasticity is approximately 95%, 90%, and 80% of room temperature values at 300°F, 400°F, and 500°F respectively.

Electrical and Thermal Properties

Aluminum and aluminum alloys are good conductors of both heat and electrical current. The electrical conductivity of EC aluminum is approximately 62% IACS in all tempers. The electrical conductivity of other alloys range from 38 to 55% IACS. In general, the 7000 series are the least conductive.

ALUMINUM PROCESSING PROCEDURES

Formability

Wrought aluminum and its alloys exhibit excellent formability in the annealed (0 temper) and freshly quenched (W temper) conditions and can be fabricated into complex shapes. In the "0" or "W" temper, most alloys begin age hardening immediately at room temperature, and should be formed within 2 hours after heat treatment for best formability. An alternate method is to refrigerate the material at zero °F or lower immediately after quenching to maintain softness. Forming in the "W" temper often eliminates the need for a separate straightening operation after heat treatment, by avoiding distortion caused by solution heat treating and quenching after forming.

The high purity aluminum grades and the non-heat treatable grades possess the best formability. The 3000 series alloys are more formable than other heat treatable alloys.

Machinability

The machinability of aluminum alloys varies widely with alloy and temper. All of the aluminum alloys exhibit machinability superior to steel or titanium. Machining speeds for aluminum alloys must be high, to obtain a low RMS finish, with speeds of 7,000 to 10,000 sfm commonly used.

The cold worked condition for non-heat treatable alloys and the fully hardened temper for the heat treatable alloys demonstrates the best machinability. Alloy 2011-T3 and T-8 is the most machinable alloy, while the high silicon (4000) series are the most difficult to machine. Alloys containing more than 5% silicon will not machine to a bright lustrous finish.

Solution Heat Treatment and Aging

Aluminum alloys of the 2000, 6000, and 7000 series may be hardened and strengthened by a two step heat treat operation which has been termed solution heat treatment and aging.

All of the heat treatable alloys will harden somewhat at room temperature, and several of the 2000 series will reach full hardness when held at room temperature for 96 hours, after being properly solution heat treated.

Annealing

Annealing is usually performed by heating at 775 to 825°F for 2 to 3 hours, furnace cooling to 500°F at a rate not to exceed 50°F per hour, followed by air cooling to room temperature. Certain alloys require more elaborate cooling schedules for maximum formability and softness.

Weldability

Aluminum and most aluminum alloys can be welded by many standard commercial processes. The high purity and non-heat treatable, particularly the 5000 series, are most readily welded. Of the heat treatable alloys, the 6000 series are the most weldable. With the exception of a few alloys, such as 2219, 7039, and X7106, the 2000 and 7000 series alloys are the least weldable. The difficulty experienced in welding the high strength, heat treatable alloys, is primarily cracking. Both the base metal and the filler wires used for such alloys have limited ductility during the latter part of the cooling period, and cracking in the weld deposit is likely to occur, especially when restraint is imposed on the joint by either fixturing or joint design.

Gas metal arc (MIG) is currently the most common fusion method for welding aluminum above 0.032 inch thickness. Argon, helium, or argon-helium mixtures are used as shielding gas. The tungsten arc (TIG) process is used for material below 0.032, either TIG or MIG for 0.032 up to 1/4 inch, and MIG is used almost exclusively above 1/4 inch.

The mechanical property changes that result from welding depends on many factors, including alloy composition, temper, joint design and welding technique. Fast welding speeds minimize the size of the heat affected zone, but as a rule, welding degrades the mechanical properties. For the treatable alloys in the 6000 series, 100% joint efficiency can be obtained with proper filler metal selection, and when the welded structure can be solution treated and aged after welding.

For annealed, non-heat treatable alloys, high quality joints wil fail in the base metal, providing the weld bead reinforcement is not removed.

Finishing

In general, the 2000 series (aluminum-copper) alloys are the easiest to electroplate, while the 4000, 5000, and 6000 series, (silicon, magnesium, and magnesium-silicon) alloys are the most difficult.

TITANIUM ALLOYS

Titanium and titanium alloys are noted primarily for their combination of high strength, low density, superior corrosion resistance, and high fatigue strength. Certain alloys have excellent cryogenic properties. Titanium can be produced in the same strength range as steel, but weighs 44% less. An abundance of technical data is now available, making titanium a logical candidate for reliable, weight optimized cryogenic pressure vessels. At the present time however, titanium is not being considered for containing LOX, since the activation energy (impact) for catastrophic reaction is low.

After extensive evaluation on the reactivity of titanium with oxygen, titanium is not recommended for the construction of liquid oxygen tankage. The conclusions of this evaluation are:

a. Titanium's impact sensitivity in LOX is not reduced by polishing, the nature of mating surfaces, weldments, phosphate and anodized coatings or ceramic coatings.

b. Impact sensitivity is essentially independent of the type of titanium alloy.

c. Pickling, passivation, and the presence of abrasives markedly increases reactivity.

d. Deburred edges, the oxide layer formed during heat treating, TFE coatings, and nitriding decrease reactivity, but not sufficiently for acceptance.

e. Electroless or electroplated copper or nickel coatings protect titanium satisfactorily from impact sensitivity in LOX, but LOX or GOX are still subject to detonation upon puncture.

Hydrogen can be absorbed interstitially by titanium if its protective oxide film is removed and the "bare" metal is exposed to hydrogen atmospheres. Hydrogen or disassociated ammonia must never be used as a heat treat atmosphere. The reducing tendency will remove the protective oxide coating and seriously embrittle the material.

It is worthwhile to note that titanium exhibits excellent resistance and compatability with such strong oxidizers and fuels as nitrogen tetroxide and unsymetrical dimethy-hydrazine (UDMH). It is compatible and impermeable with hydrogen, helium, and other low density gases, and is virtually unaffected by liquid nitrogen or gaseous nitrogen below 600°F.

NICKLE AND CHROMIUM-NICKEL MARAGING STEELS

The straight nickel and the chromium-nickel maraging steels develop high strength by a relatively simple, low temperature aging of a low carbon martensitic matrix. The 20% and 25% nickel maraging steels were developed first, followed by 18% nickel maraging steels, and more recently, the 14.5% chromium, 6.5% nickel maraging stainless steel. The straight nickel grades are not corrosion resistant alloys. Their chemical corrosion resistance is slightly better than the low alloy steels. The 14.5 chromium, 6.5% nickel (hereafter referred to as Almar 362) analysis exhibits corrosion resistance approaching the 300 series stainless steels.

The principal advantages of the maraging steels are as follows:

1. High strength.
2. Excellent ductility.
3. Simple heat treatment.
4. No decarburization problem.
5. Good machinability.
6. Low work hardening rate and good formability.
7. Low distortion and dimensional change during aging.
8. Cryogenic strength and toughness.
9. Good weldability.

The annealed structure of the alloys is essentially a carbon-free iron-nickel martensite. Unlike the hard, brittle martensite of conventional low alloy steels, it is soft, readily machined and formed.

PROCESSING PROCEDURES

Hot Working, Cold Working and Forming

The 18% nickel maraging steels may be hot rolled or hot formed (forged) between 1600 and 2300°F. Hot plasticity is best at 2300°F, but temperatures as low as 1500°F may be used if sufficient power is available.

Formation of scale is heavier than for 304 stainless, but lighter than for carbon or low alloy steels. On hot pressing or forging, the scale flakes off readily during initial reduction. Sand blasting is frequently used for removal of surface oxide from finished material. Sodium hydride and other high temperature (above 700°F) descaling treatments should be avoided where partial maraging of the material is detrimental to subsequent operations.

Almar 362 can be readily hot and cold worked by using practices and equipment utilized in processing the conventional austenitic stainless steels.

Forging and hot rolling should be performed using initial hot working temperatures in the range of 2000 to 2250°F. Finishing temperatures may be as low as 1400°F to 1500°F since the material is ductile throughout the temperature range.

Machining

The 18% Ni maraging steels have machinability comparable to SAE 4340 steel of equivalent hardness.

The Almar 362 analysis exhibits machinability superior to the precipitation hardenable stainless steels, but not as good as SAE 303 stainless steel.

Weldability

Both the 18% nickel and the Almar 362 analyses exhibit very good weldability. Pre-heating or post weld annealing is not necessary to prevent cracking nor to restore weld metal ductility and toughness. To achieve high joint efficiency, the weld area need only be aged following welding. In sections up to 1/8" thick, both materials can be readily welded by the inert gas shielded processes. For multiple pass welds, slightly modified welding wire (lower titanium) should be used for more uniform properties and to prevent weld cracking.

The higher titanium content (1.4%) in the 25% and 20% nickel grades makes these grades prone to weld property variations and weld cracking.

Pickling, Cleaning and Finishing

Heating prior to hot working the 18% nickel maraging steels produces a heavier surface oxide or scale and does so more rapidly than on 304 stainless steel, but less than on carbon or low alloy steel.

MAGNESIUM

Magnesium has a density of approximately 1.74 gm/cc, or about two-thirds that of aluminum, and is the lightest of the structural metals. As with most other metals, magnesium is not used in its pure state for stressed applications. Rather, it is alloyed with other metals to obtain the strong, lightweight alloys needed for structural purposes.

Magnesium exhibits many properties that are desirable for aerospace applications, such as weldability, formability, relatively high electrical and thermal conductivity, good dimensional stability, high specific heat, and useful emissivity properties.

Magnesium Alloy Chemistry

Magnesium is primarily furnished in one standard grade, ASTM B 92, containing more than 99.8% Mg. Special grades of primary magnesium are available in which manganese, aluminum, and iron impurities are kept at a maximum of 0.01, 0.002 and 0.003% respectively. These special grades serve chemical and metallurgical applications, such as the preparation of uranium metal.

Aluminum and zinc are relatively soluble in magnesium, but the solubility decreases at low temperatures. Manganese is effective in improving corrosion resistance in alloys that contain zinc and aluminum.

Magnesium demonstrates several rather unique properties which must be considered when producing and fabricating the beta. Molten magnesium is quite reactive, and readily catches fire when exposed to air. It burns with an intensely hot, white flame. Hence molten magnesium must be protected from air with a flux or inert gas.

The hexagonal-close-packed crystal structure of magnesium is unfavorable to plastic deformation because there is only one slip plane at room temperature. Magnesium exhibits much better formability above 210°C, where additional slip planes become active. Unlike other metals, the hot deformation of magnesium must be carried out slowly.

Alloying magnesium with lithium further reduces the density and increases the normally low ductility of alpha HCP (Hexagonal-close-pack) magnesium. Up to 5.7 percent lithium can be dissolved in alpha magnesium. A beta, BCC (body-centered-cubic) phase appears with lithium contents in excess of 5.7 percent. A 100% beta structure is obtained when the lithium content exceeds 10.3 percent. Aluminum, zinc, cadmium, and silver can be added to the magnesium-lithium base to strengthen the material by a precipitation hardening mechanism.

There is very little data available on the effect of low pressures on Magnesium-lithium alloys at cryogenic temperatures. However, the existing data suggest that no weight loss occurs at these temperatures. Extensive use of these alloys by Lockheed and IBM in space vehicles also suggests that the alloys are not adversely affected by low pressures and low temperatures.

Tensile Properties

Magnesium, in common with other nonferrous metals but in contrast to mild steel, exhibits no definite yield point. Instead, the metal tends to yield gradually when stressed above the proportional limit. In accordance with ASTM procedure, the yield strength of magnesium alloys is defined as the stress at which the stress strain curves deviate 0.02% from the modulus line.

Fatigue

The good fatigue properties of magnesium are a valuable asset when the metal is designed into moving or vibrating members. High cycles at low stress show magnesium at its best. Precision design based on laboratory fatigue tests is no more feasible for magnesium than for other metals. Considerable scatter is to be expected in fatigue test data for magnesium.

Machinability

Magnesium and its alloys can be machined at extremely high speeds using greater depth of cut and higher rate of feed than can be used in machining other structural metals. There are no significant differences in machinability among the magnesium alloys. Therefore, a specific magnesium alloy would rarely, if ever, be selected in place of another magnesium alloy only because of difference in machinability.

An outstanding machining characteristic of magnesium alloys allows these materials to acquire an extremely fine finish. Surface smoothness readings of 3 to 5 micro-inches have been reported for machined magnesium and are produced at both high and low speeds, with and without a collant.

Formability of Magnesium

Both room and elevated temperature properties of magnesium alloys are important in forming. In fact, properties of the metal at elevated temperatures are of prime importance because most forming of magnesium is done hot. The properties important in forming are tensile strength, tensile yield strength, elongation, compressive yield strength, shear strength, and bend radius.

Weldability

Most magnesium alloys and forms are readily welded by arc and electric resistance methods. The amount of heat required for melting magnesium is comparatively low. The relatively high values for thermal conductivity and expansion co-efficients of magnesium alloys can result in distortion during welding unless this is considered in tooling and jigging. Protection against oxidation is necessary during the fusion welding of magnesium. An inert gas is used to shield the molten metal during arc welding, while a flux serves the same purpose when gas welding or brazing. Such protection is not needed for electric resistance welding techniques.

Design Considerations

The combination of light weight, strength, and stiffness to thickness permits light weight yet rigid structures of magnesium.

In single-shell structures using curved or flat panels, material choice is based on maximum bending strength, stiffness and buckling strength at minimum weight. Magnesiúm panels offer a very competitive solution.

Many aerospace applications require finishes for thermal control. Finishes of this type have been readily applied to magnesium surfaces. Magnesium may be anodized, electroplated, vapor plated or chemically treated. Details of processing are readily available for specific requirements.

BERYLLIUM

Beryllium, atomic no. 4, has approximately the same density as magnesium, but an elastic modulus of 40 x 10^6, 1.4 times the modulus of steel. Beryllium's melting point is 232°F, with useful strength characteristics to 1100°F. Typical tensile strengths of hot pressed blocks range from 35,000 to 55,000 PSI. Yield strengths (2 percent offset) range from 27,000 to 42,000 PSI. Thermal conductivity and heat capacity are both high.

Beryllium's modulus to density ratio suggests its value for aerospace applications, but careful processing is required to avoid brittleness. The material tends to be notch sensitive, is difficult to form, and machining requires special practice. The joining techniques are still being investigated for further improvement. Typical notch impact strength is less than 1 ft.-lb. under certain conditions. Research is aimed at reducing grain size, improving purity, and lowering strain rates to increase strength and elongation properties. Beryllium is beginning to take its place as an established material of aerospace construction, but with few exceptions is utilized only in applications involving compression loading.

Beryllium Metallurgy

The following table compares beryllium with several other competitive aerospace metals with respect to density and Young's modulus.

WHERE BERYLLIUM STANDS AMONG SELECTED AEROSPACE METALS

	Density (Lb/In^3)	Young's Modulus (Million PSI)	E/D x 10^{-8}
Beryllium	0.067	44.0	6.5
Magnesium (A-763)	0.0628	6.5	1.02
Aluminum (7075-T6)	0.0975	10.4	1.05
Titanium (Ti-$8M_n$)	0.163	16.5	1.01
Structural Steel (4340)	0.282	30.0	1.03
High Alloy Steel (AM355)	0.282	25.7	0.91

Note that beryllium has approximately 6.5 times the modulus to density ratio of the other materials being compared. Most aerospace applications utilizing beryllium have required a high molulus to density ratio, low specific weight, nuclear or X-ray characteristics, or a combination of one or more of the above plus the thermal characteristics of beryllium.

Physical and Mechanical Properties

A great deal of effort has been expended on the development and evaluation of beryllium alloys. Except for possibly dispersed BeO in beryllium metal, no alloy yet approaches commerial status.

Conclusions

1. Methods of producing pure beryllium are still under research and development.

2. Beryllium is most usefull where a high stiffness to weight ratio is required.

3. The mechanical properties are somewhat unpredictable and are very anisotropic.

4. The brittleness of beryllium is still being investigated.

5. The high cost of beryllium will be reduced only after volume production techniques are improved and utilized.

6. The cryogenic properties are unknown at the present time.

WELDING PROCESSES

There are six basic welding processes which lend themselves to cryogenic tankage fabrication. These six processes are:

(1) Inert gas shielded processes.

(2) Electron Beam Welding.

(3) A. C. Resistance Welding.

(4) Electron Beam Welding.

(5) Friction Welding.

(6) High Frequency Resistance Welding.

Since each process technique varies as befits its descriptive title, each process will be discussed briefly to highlight those variances.

Inert Gas Shielded Processes

A very important group of welding processes are those which shield the arc from the atmosphere with a chemically inert gas such as helium or argon or helium/argon mixtures. In the original version of the inert-gas-shielded process (inert-gas-arc, for short), the arc is established between the base metal and a single tungsten electrode while the inert gas flows around the weld area to prevent oxidation. Since this process uses a tungsten electrode it is also called "TIG" (tungsten arc, inert gas) welding. Filler metal may or may not be added to produce the weld joint.

In a variation of the process, the tungsten electrode (termed "nonconsumable electrode") is replaced with a metal electrode ("consumable"). The somewhat cumbersome name of the latter process is "inert gas-metal-arc", the process is usually abbreviated to "MIG" welding (Metal arc Inert Gas). It employs a special "welding gun" that feeds the electrode wire to the work automatically.

Tungsten Arc Inert Gas (TIG)

Some outstanding features of the TIG process are listed below:

(1) Produces high quality welds in both ferrous and non-ferrous metals.

(2) Requires little or no post weld cleaning.

(3) Arc and weld pool are visible to operator.

(4) Metal does not transfer through the arc.

(5) Welding is possible in all positions.

Shielding Gases

Argon, helium and argon/helium mixtures are the commonly used inert gases for TIG welding. The amount of gas required is proportional to the size of the weld joint, and is measured in cubic feet per hour. Usage volume typically runs 15 to 50 C.F.H. Argon is the most common choice, because it affords better control of the weld pool and arc, is more easily ionized and maintains a smooth arc at lower current values. It also affords better visibility in the arc, and is less expensive than helium. There is little difference in soundness of welds whether argon or helium is employed. Helium exhibits a higher electrical resistance in the arc, raising the arc temperature at a given current, with deeper penetration as a result. Because of the higher electrical resistance, a smooth arc is obtainable only at rather high current values (above approximately 60 amperes.) A combination of argon and helium is useful to obtain deeper penetration at lower current values. Straight helium is useful for welding materials with a very low alloy addition and high thermal conductivity, such as copper and copper alloys.

TIG Torch Design

TIG torches are available which are air cooled (up to approximately 150 amps) or water cooled. The cooling is required to prevent damage to the o-ring seal between the torch and gas cup, and to prevent melting the tungsten electrode. Flow of the inert gas out of the cup is maintained during welding, and a post flow of gas after the arc is extinguished, to prevent oxidation of the tungsten while it is hot, and to protect the weld puddle.

Metallic Arc Inert Gas (MIG)

One of the fundamental differences between TIG and MIG welding is that the electrode in MIG welding is consumed in the process, and supplies the filler metal. The primary advantages of MIG welding are as follows:

(1) More economical than TIG (faster).

(2) Requires a minimum of post weld clean-up or spatter removal.

(3) Welds metals which had been difficult with other processes.

(4) Arc is visible.

(5) Useful in all positions.

(6) Yields greater penetration and strength in some materials (aluminum).

(7) Provides long welds with no stops, reduces operator fatigue.

MIG Welding Guns

The manually controlled welding gun with its cable assembly is the tool with which the operator makes his weld. Its primary purpose is to deliver the electrode wire and gas from the wire feeder, and the welding current from the power source to the arc area. In general, most small wire guns are not water cooled; the electrode wire and the shielding gas aid in cooling. Water cooling is required when heavy duty cycles and higher currents are used. The cable assembly directs the electrode from the wire feeder through the contact tube. The contact tube carries the welding current to the electrode and must maintain intimate contact with the moving electrode.

MIG Shielding Gases

In addition to the conventional Argon, Helium, or Argon/Helium Mixtures, MIG has successfully utilized other gases on certain metals. Carbon Dioxide has been used on mild steel simulating the gas generated by lime-type coated electrodes. It has been found that carbon dioxide and carbon monixide constitute 80% to 90% of the gases generated by this type coating. The use of CO_2 for MIG welding mild steel makes this process more economically competitive with stick electrode, by eliminating the rather expensive inert gases. CO_2 produces a deep penetration pattern. Bead contour is good with no tendency towards undercutting. The chief drawback of CO_2 is the tendency for the arc to be rather violent, resulting in more weld spatter.

Argon plus 1, 2, or 5% oxygen improves penetration over straight argon. It also improves bead contour and eliminates the tendency to undercut at the edge of the weld that is obtained with pure argon when welding steel.

Hot Wire Welding

Hot wire welding is a modification of TIG and MIG, using a tungsten electrode to provide the majority of the welding current, a separate wire feeder to provide the filler, and a additional power source to heat the filler wire by I^2R heating. Conventionally, the electrode is fed into the arc in the cold state. By employing the hot wire principle, the electrode is heated and then deposited behind the tungsten arc. The speed of TIG hot wire welding becomes two to three times faster than that of TIG cold wire welding. The quality level is equal to, or better, than TIG welding with cold wire addition. The process exhibits good penetration control, and appears to show promise for surfacing. Because the deposition rate and arc energy, or heat input, are governed by separate power sources, it is possible to control the penetration into the base metal without impairing bond strength. This is particularly useful in cladding or surfacing operations since dilution of the base metal is decreased and changes in the chemistry of the deposited metal are minimized.

The Hot Wire process is quite new, equipment has become available only very recently, and will require further watching and evaluation.

Electron Beam Welding

Electron beam joining is a vacuum process for the fusion joining of materials. It utilizes the heat that is dissipated when a highly collimated beam of electrons impinges in a material. This beam can be either self- or work-accelerated. The basic components of an electron beam welder consists of a vacuum chamber, vacuum pumping system, a source of a collimated electron beam (gun), and a device for manipulating the workpiece.

Physical and Mechanical Metallurgy of Electron Beam Welding

Electron Beam welding offers the following prime advantages:

(1) Welding is accomplished in a vacuum atmosphere.

(2) Welding is accomplished with low energy input.

(3) Welding with great variation in nugget geometry.

For reasons (1) and (2), electron beam welding is especially attractive for joining refractory metals where reaction with an atmosphere and grain growth are serious problems.

Electron beam welding results in very little distortion, and very close tolerances after welding. Welding of finish machined parts is a proven design concept. The very high energy density, but low total energy input, allows welding very close to components that would be damaged by more conventional techniques.

Many refinements of electron beam welding have been developed in the past few years, and even more sophisticated advances are anticipated in the future. Advances in terms of beam controls, optics, welding of thermally shock-sensitive materials, micromodules, and unusual brazed joints are anticipated.

A. C. Resistance Welding

In this process, the surfaces to be joined are heated to the plastic condition by the passage of a high amperage localized electric current accompanied by controlled mechanical pressure to bring the parts into complete union. To produce the required high current at low voltage, alternating current has been found most convenient, since by the use of suitable transformers, almost any desired combination of current and voltage can be obtained. Only in special instances is direct current used for this purpose.

Resistance welding is limited to those shapes and sizes which lend themselves to the mechanical requirements of the process. The suitable joint designs are very limited, and the necessary equipment is rather large with a high current requirement as compared to other processes.

Ultrasonic Welding

Ultrasonic welding was discovered accidentally in 1950 while investigating the addition of ultrasonics when spot welding. It was found that a weld was produced when the electrode of the spot welder was ultrasonically excited, even though the welding current was not on. Studies revealed that the weld was achieved when the vibrations from the electrodes were induced into the specimens being joined. Since that time, extensive work has been done to determine the feasibility of welding several metal combinations and configurations.

Studies so far have given only limited information about the possible uses of ultrasonic welding. Butt, seam, and spot welds can be made in thin-gage sheets of moderately ductile materials, such as mild steel, iron, aluminum, copper and gold. Thin sheets of plastic can be joined by ultrasonic welding.

Currently, one aluminum producing company is using ultrasonic welding techniques (high-speed seam welding) to join aluminum foil. This welding method is being used because thinner gages can be welded than with other welding methods, and surface preparation is not critical. Ultrasonic welding is being used also in the manufacture of transistors because of the high purity desired in transistor material.

The advantages of ultrasonic welding are:

(1) Very thin-gage materials can be welded.

(2) Surface preparation is not critical.

(3) Minimum surface deformation results.

(4) No contamination from gases and arcs arise.

(5) Thin sections can be welded to thick sections.

(6) Dissimilar metals can be joined.

(7) There is minimum melted or heat-affected zone.

The disadvantages of ultransonic welding are:

(1) Heavy-gage material is not weldable.

(2) Materials being welded tend to weld to the coupling and anvil.

(3) Equipment life is short because of fatigue.

(4) Very ductile materials will yield under ultrasonic strain without sliding.

(5) Hard materials will fatigue under the stresses necessary for welding.

<u>Friction Welding</u>

The friction welding of metals, a process that has been developed in the Soviet Union, is a variation of pressure welding. It differs from conventional pressure welding by the method of generating the welding heat. The heat is developed at the welding surfaces by the friction of the two surfaces rubbing together.

Welding usually is accomplished by rotating one piece under pressure against the other piece, which is held stationery. After sufficient heat for welding has been generated because of friction, rotation is stopped and the clamping force between the two pieces is increased thereby welding the two pieces together. Welds of this type may be made on a conventional drill press or milling machine. However, the axial loads on the spindles of these machines become quite high during friction welding, and damage to the bearings may result. It is preferred to use machines especially designed for friction welding.

The advantages of friction welding include its simplicity and power requirements. For a high-production application, friction welding is easily automated. Surface cleanliness presents no problem, as most surface impurities and oxides are broken up, dispersed, or thrown off during the friction heating process.

A variety of materials have been welded successfully by the friction method. Some of these are mild and low-alloy high-strength steels, cast iron, aluminum and brass. Dissimilar metals or alloys also may be welded together, such as copper to brass, brass to steel, and aluminum to aluminum-magnesium alloys. This process has been applied generally to the joining of small pieces, pieces of bar stock, tubing, etc. It may also be used to weld pipe or tubing to flat surfaces. Large fixed objects, such as gas pipelines, may be friction welded successfully by rotating a short section between the two fixed ends and welding all three pieces together in one operation.

<u>High Frequency Resistance Welding</u>

High-frequency resistance welding has been developed into a useful tool for a rather limited number of applications, primarily for the high-speed production of tubing. Very high welding speeds can be obtained with the process; for example, 100 to 500 feet per minute in 0.081 and 0.010 inch thicknesses, respectively, in aluminum and steel. Weldments have been made for many materials, including copper, brass, stainless steel, zirconium, nickel, silver, and Inconel. Dissimilar metal combinations can be welded. The thickness range of the process to date is from 0.004 to 0.125 inches. The best use of the process is in applications where continuous runs can be made, but short pieces can also be made, if necessary. One disadvantage, especially for welding short pieces, is that the beginning and ending of each joint is unwelded for several inches.

PLATING PROCESSES

Plating involves the deposition of a film or coating of metal on the surface of either a metal or non-metal part. This coating may have a variety of functional purposes.

Surface plating of cryogenic tankage pressure vessels, outer shells and discrete-radiation shields has two distinct functions. First, the surfaces must have a very low emissivity to limit radiation heat transfer. Secondly, since the surfaces subject to plating are exposed to a static vacuum environment, they must not be porous or in any way subject to appreciable outgassing.

While there have been many processes developed for particular applications, electroplating and vapor plating have received broad application due to their diversity.

Electroplating

Electroplating involves the production of metallic coatings on either metallic or non-metallic parts by an electro-chemical process. The metal coating, which is deposited on the part being plated, is produced by passing an electric current through an ionic solution causing a separation of metal at one of the electrodes.

Electrical Characteristics of Solutions

An electrolytic solution is capable of conducting an electric current. Two conducting electrodes are placed in the solution. These electrodes are then connected to the poles of a battery, power supply or other suitable EMF source. The electrode connected to the positive pole is termed the anode while the other, the cathode, is connected to the negative pole. When the EMF is applied to the electrodes, a current will flow through the electrolyte, the magnitude of which depends upon the EMF, the type and strength of the solution.

Due to the potential difference between the two electrodes, the ions are displaced in the solution. The positive ions move in the direction of positive current, from anode to cathode while the anions move in the opposite direction. The ions migrate to the electrodes where they are discharged in some form. The discharge may be in the form of the evolution of a gas or the deposition of a coating of material.

This latter case is the basic practice used in the electroplating process.

Electroplating is best considered as an art since its success is heavily dependent upon experience and facilities rather than on theoretical data. Thus, electroplating varies from one facility to another and from one metal to another.

Aluminum alloys are considered as the most difficult to plate. Among the other metals presently considered as quite difficult to plate are magnesium, beryllium and titanium. The majority of irons and steels, including stainless steels, are considered easy to plate. These materials are among the first to be plated and the procedures are well advanced.

Vapor Phase Deposition

The term vapor phase deposition covers several different processes for the production of metallic coatings, such as:

(1) The evaporation and condensation of metals under vacuum conditions.

(2) Cathodic sputtering under vacuum where the coating material is liberated from the cathode plate by the high energy impingement of positive ions. The liberated particles of the coating material strike the work to be coated with relatively higher energy compared to that involved in the evaporation process.

(3) Chemical vapor deposition process in which the vapor of a metallic chemical compound is allowed to strike a hot work piece, disassociating into the metal element and other fragments of the molecule. Many of the compounds are metal halides or organo-metallic compounds such as carbonyls.

(4) Vapor phase replacement in which an actual replacement of atoms of the workpiece by other metal atoms takes place, combined with diffusion of the replacing atoms into the workpiece and diffusion to the surface of the atoms of the workpiece being replaced.

The vacuum-evaporation process has been found to be the most suitable process for producing low emission coatings on the surfaces of cryogenic tankage. One of the major criteria for successfully using the vacuum-evaporation process is that the part to be plated must have a smooth surface. This can be accomplished through the use of either an epoxy or polyimide varnish which is allowed to level out to a high gloss surface. These coatings must be processed at a maximum temperature and for a sufficient period of time to remove the volatiles.

Equipment large enough to handle both hemispheres and complete spheres coated on either the convex or concave surface is available on custom order.

In contrast to the problems encountered in electro-plating, there is no problem of immersing a large hollow sphere in a liquid bath. There is also no problem of rinsing off the parts to eliminate the deposit of chemicals on the dried parts since the parts are ready for assembly immediately after the evaporation is completed. The cost of the equipment is less than that required for electroplating and the cost of operation should be comparable. Tooling and handling fixtures should not be too different from the handling equipment required for electroplating. The masking problem is quite simple and should be inexpensive.

CHAPTER II

SHELL FABRICATION PROCESSES

There are three distinct parts in a cryogenic storage system which are fabricated from one of the numerous forming processes available. However, since the material selection is usually different for the pressure vessel, discrete radiation shields, and outer shell, the forming process must necessarily be compatible with the type of material to be used.

Within this chapter, a description of the process, the available facilities and size capabilities will be presented. Also, this chapter will investigate such facets as the control of overall dimensions, wall thickness, costs involved, surface finish obtained, and the capability of the process to adhere to schedules.

Chronologically, the fabrication processes shown in the column at left will be discussed:

a. Arde-Form
b. Hydroform
c. Forging
d. Spinning
e. Inturgescent Forming
f. Machining and Milling
g. Chemical Milling
h. Electroforming
i. Explosive Forming
j. Magnetic Forming
k. Electrohydraulic

ARDE-FORMING

Arde-Form, or cryoform is a cryogenic stretch forming process for fabrication of ultra light weight (flight weight) pressure vessels. The technique is based on the ability of stainless steels to work harden at cryogenic temperatures to very high strength levels.

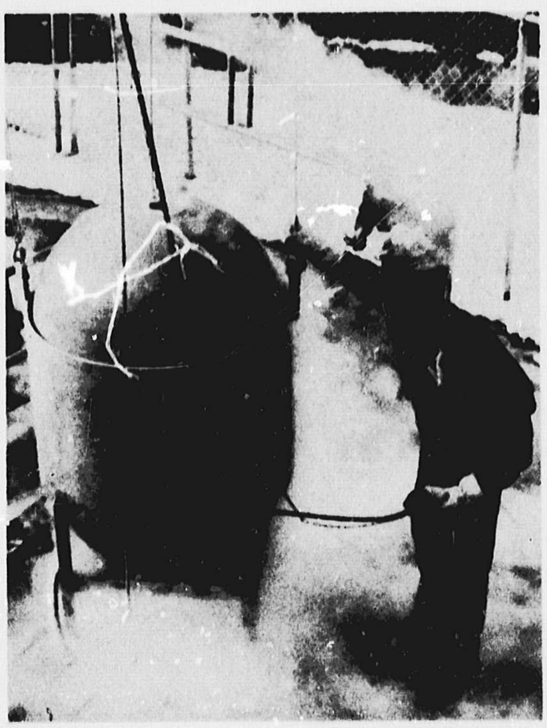
Description of Process

The Arde-Form process consists of fabricating an undersized vessel (preform) from work-hardenable material while the material is still in an annealed condition. In this condition the material is readily welded, machined and formed into the pre-determined preform shape. After the undersized vessel is fabricated, the entire vessel is strengthened by stretching cyrogenically in liquid nitrogen (-320°F) to the final size required.

The first step in Ardeforming is the fabrication of an undersized vessel called the preform. The preform is a predetermined composite geometry fabricated by welding together specific geometrical details of annealed stainless steel. These pre-assembly sections are made by drawing, rolling, spinning, or other common fabricating techniques. For a spherical vessel, the preform consists of a rolled and welded cylinder, two truncated cones of rolled and welded sheet stock, and two flat discs for end enclosures. All details are assembled by welding and a pressurizing boss is incorporated in one of the discs. Cryogenic expansion of the preform now takes place in an outdoor pit. This stainless steel forming tank is designed to hold the preform and the liquid nitrogen bath used to cool the vessel. The forming tank is filled with liquid nitrogen to a level well above the level of the preform to ensure effective cooling of the vessel. The preform is now partially filled with liquid nitrogen and sealed off except for a pressurizing line which leads to a supply of compressed nitrogen gas. After the preform cools to liquid nitrogen temperature (-320°F), the pressurizing line is opened and the preform is stretched preform to an approximate 7% strain by the nitrogen gas. At this point, the vessel will be an approximate sphere. The unit is then removed from the stretching tank, annealed and again cryogenically prestrained to approximately 7% strain. This cycle of cryogenic stretching and annealing is repeated to achieve the desired final diameter and strength characteristics. Any scale caused by annealing is removed by a closely controlled pickling operation.

Available Facilities

The trade name Ardeform was given to this cryoforming process by the company which has proprietary control of the fabricating process, namely Arde, Inc., Paramus, New Jersey. They have two facilities for the design and fabrication of these light weight, high strength pressure vessels. The main office, located in Paramus, New Jersey, is the administrative center and also houses the engineering and research facilities. An area which is devoted entirely to the fabrication of Ardeformed pressure vessels is located in Mahwah, New Jersey.



PRESSURE VESSEL BEING RAISED FROM N_2 TNAK

The cryogenic stretch-forming facility consists of a large liquid nitrogen forming tank, 10 feet in diameter by 20 feet deep, a high pressure cryogenic pumping system capable of 20,000 psi with appropriate controls and valves and a reserve 25,000 gal. liquid nitrogen low pressure storage system. The facility, remotely operated from a control room through a system of control valves, is instrumented with pressure and temperature sensors as well as the necessary safety devices.

Size and Shape Capabilities

The Ardeform process is amenable to many sizes and shapes of pressure vessels. As applied to cryogenic pressure vessels, the various shapes, spherical, and cylindrical with paraboloidal ends and cylindrical with hemispherical ends can be readily formed by this process. The process does not appear to have a size or shape limitation, but is affected by such factors as the weld length capabilities of the welding machine, dimensions of the heat treating furnace, forming tank size and general handling.

Vessels other than the spherical vessel have similar factors governing size as spherical vessels, but in addition, are limited in size by tolerance limitations upon thickness and overall dimensions. A technique employing a restraining die during stretching has been used to alleviate this problem but increases the cost of fabrication by a considerable amount.

Dimensional Control

One of the biggest problems associated with the Ardeforming technique has been the attainment of pressure vessels within the tolerance limits desired. Since the method is a "free-form" deformation technique, there are no physical restraints used to form the required geometry. The resultant pressure vessel sizing depends upon closely controlled fabrication of the preform so that it corresponds to the design preform. Each pressure vessel configuration requires considerable study prior to finalization of the preform design such that with the correct internal pressurization the desired final shape will be achieved. On initial preform design units prior to finalization, a tolerance of ± 1% of mean target diameter was attained. With experience being gained, a normal tolerance of ± .10 in. is considered to be attainable on large diameter spheres.

An alternate means of improving dimensional control would be to utilize a completely closed die for the final sizing operation. The use of such equipment would assure dimensional integrity, however, it is felt that costs associated with tooling of this nature could more profitably be utilized in perfecting the "free-form" technique. The "free-form" technique permits rapid size changes while maintaining a minimum tooling cost. Also, utilizing a heavy forming die would result in evaporation of considerable liquid nitrogen in the cool-down procedure, with associated increased cost.

Thickness tolerances attainable are a function of sheet metal tolerances; additional variation due to preform operations on sheet, and possible variable thinout imposed on material of varying thickness during the cryogenic stretch forming operation. The latter leads to a possible implication that some thin material is actually stressed above the design stress level. It has been found that this condition is not applicable for a spherical vessel. Measurements taken prior to cryogenic stretching and after three anneal and stretch cycles showed little additional thinout on a dimensional basis. A general acceptance standard for material thickness of preform components made by spinning, deep drawing, hydroforming or other common methods is ± 5%. Vessels have been successfully built with good dimensional, weight, and strength characteristics from these preform components.

Surface Finish

In Ardeforming, the resultant surface finish is attributed to preform material surface finish, control during heat treating and general handling techniques.

Being a process which employs the use of sheet material for preform details, Ardeforming has an advantage concerning surface finish since sheet material can be procured with a finish of 4-6 RMS. However, this surface finish is not maintained during cryogenic pressurization. This forming operation, stretching the material, causes the finish to be increased in RMS from 10-16. A light polishing is now required to reduce the surface back to 8 RMS. This stretching effect upon finish, however, is not the only factor affecting the finish. Annealing operations performed during the forming procedure also contribute to surface finish degradation.

During the annealing operation a black scale tends to form on the outer vessel surface. Arde uses a pickling procedure to remove this scale from the outer surface. Pickling not only removes any scale but also results in a further increased RMS surface finish. Since the pickling process cannot be used to clean the inner surface of the vessel, a full Argon purge is maintained in the vessel during heat treat to minimize scale formation. Even with this procedure a slight scale develops on the inner surface. A sloshing technique, employing an oil base solution containing small grit is used to remove this scale. This technique removes the scale but does not remove the black color on the inside surface.

Process Time

The two main factors controlling processing time are the prior experience in a particular pressure vessel fabrication and the availability of material. Due to the tight limitations on material composition, the procurement period for material can be extensive. If these two factors are favorable, the processing time for Ardeform is competitive with other fabrication techniques.

The fabrication plan is broken down into three major phases; namely, procurement and development, assembly, and stretching. On the average, these phases require 4, 3 and 2 months respectively.

Advantages - Disadvantages

In summary, it can be stated that the Ardeforming technique is in itself a relatively simple means of obtaining a pressure vessel. As with all forming methods, however, there are advantages and disadvantages which govern the practicability of a method. Listed below are such characteristics pertaining to the Ardeforming technique and resulting vessels.

ADVANTAGES

LIGHT WEIGHT VESSELS: The Ardeforming technique is geared toward fabrication of light weight pressure vessels since the limitation upon the minimum wall thickness is determined solely by the ability to handle ultra-thin-walled vessels.

HIGH STRENGTH: The high strength characteristics of thin wall vessels at cryogenic temperatures as well as at room temperature can be realized.

CREEP STRENGTH: Ardeformed vessels exhibit no measurable creep or distortion under high pressure.

VESSEL RELIABILITY: The amount of stretch during forming is usually 12 to 14% for cylindrical vessels and 7 to 8% for spherical vessels. Any material flaws, even those undetectable by x-ray would result in a burst vessel. Thus, the process itself is a proof test which guarantees vessel reliability.

STRESS CONCENTRATION: Stretching the preform reduces stress concentrations from fabrication so that the entire unit is approximately the same strength level.

SIZE VERSATILITY: The cryoform process is economically adaptable to nearly any size and shape pressure vessel. It is uniquely adaptable to the fabrication operation of certain (spherical, cylindrical) large light weight vessel shapes.

WELD INTEGRITY: Stretching the weld offers clear advantage in assuming high weld efficiency and weld integrity.

COST: Pressure vessels formed by the Ardeforming technique seem to be competitive based on a 10-20 unit order of vessels, because of nonrecurring costs.

DISADVANTAGES

VESSEL SURFACE FINISH: Presently considerable polishing is required to reduce the surface back to an 8 RMS finish desired for low emissivity. Internal surface of vessel is black from the heat treating process.

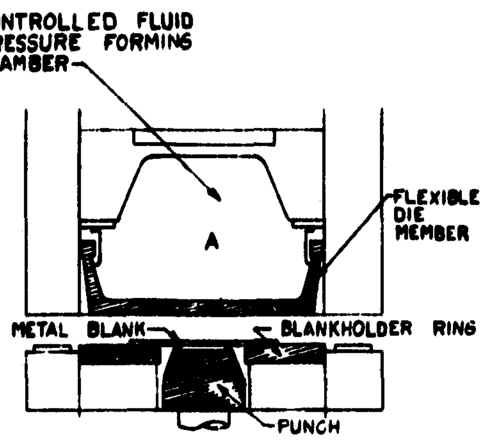
DIMENSIONAL CONTROL: Dimensional control is a problem area that exists, but is steadly being overcom by various techniques, some of which are quite costly. At present a normal tolerance of ± 0.10 in. on diameter is considered attainable on large diameter spheres and ± 5% on wall thickness variation.

STUDY DESIGN TIME: Time is considerably long, accounting for approximately one-half the total processing time. Design study time is very dependent upon previous experience with a typical size and shape vessel.

MATERIAL COMPOSITION: Strength of cryoformed vessels requires that the material exhibit large strain hardening. The transformation characteristics of 301 Stainless Steel require very tight control of the chemical composition.

PROCESSING TIME: Current estimates of processing time, approximately 9 months, seem reasonable for vessel fabrication, but previous processing time exceeded schedules by a factor of four.

HYDROFORM MACHINE OPERATING CYCLE SEQUENCE



FORMING CHAMBER RAISED
METAL BLANK ON BLANKHOLDER RING

HYDROFORMING

Hydroforming is a method of deep drawing metal under accurately controlled fluid pressure, using a punch formed to the desired shape of the final product and a flexible universal female diaphragm. Basically, the process can be described as pressure forming metal against a punch with a flexible die.

Description of Process

The basic components of the machine are the forming chamber which contains the pressurized fluid, the female flexible diaphragm that seals the fluid within the forming chamber, and the lower portion of the machine which consists of the blankholder ring and the male punch. The metal blank to be drawn is placed on the blankholder ring. A schematic of the machine setup is shown at left.

During the forming process, the punch, mounted in the bed of the machine, is moved upward by a hydraulic ram. Upon entry of the punch into the forming chamber, the pressure of the fluid in the chamber is further increased by the displacement of the punch and metal being formed. Simultaneously, with the punch movement, positive pressure is exerted on all points of the flexible diaphragm and transmitted to metal blank causing an even flow or distribution of metal that literally wraps itself around the punch. The finished part is formed to the exact geometry of the punch.

Through the instantaneous control of the hydraulic pressure, it is possible to start a forming cycle, release the pressure, raise the forming chamber, and inspect the partially formed blank at any time during the operation. The pressure cycle may then be started again and the drawing operation completed without affecting the condition of the part.

Available Facilities

The hydroform technique of drawing metal to desired shape and sizes is principally associated with the Cincinnati Milling Machine Company, Cincinnati, Ohio, since the company is the developer of the process and manufacturer of production hydroforming machines. The present hydroforming machines vary in size from 8" to 40". These machine size designations are not the maximum size finished part capacities of the machines, but are the maximum metal blank size capabilities of 8 and 40 inch diameters, respectively, or any diagonal which falls inside these diameters. The maximum finished part size is governed by the punch diameter and draw depth, which for the above machines are 6" diameter, 5" draw and 24" diameter, 16" draw respectively. At present, however, no 40" machines have been built, but only exist on the drawing board.

There are approximately 34 companies who have Cincinnati Hydroforming Machines and use them for drawing operations. Listed below are a few of the companies that possess the larger hydroform machines.

COMPANY	MACHINE SIZE
Areo Trades Corp. Mineola, New York	12", 19", 32"
Contour Forming, Inc. Newark, Ohio	8", 12", 19", 32"
Jones Metal Products Co. West Lafayette, Ohio	25", 32"
Chrysler Corp, Jet Engine Div. Warren, Michigan	(2) 32"

Shape and Size Capabilities

Since the forming operation depends upon the ability of the metal to be stretched and bent in such a manner as to conform to the geometry of the punch, one possible limitation upon the shape and size of the finished part would appear to be the material properties of the metal. It has been found that, in most metals and shapes drawn, the percent stretch does not exceed the limits that would cause metal tearing. There are however, metals such as the stainless steels where workhardening necessitates an anneal during the drawing operation. All in all, the material properties have not limited the shape and size of hydroformed parts using the current size machines.

For the current application of large diameter hemispheres and cylindrical shells with hemispherical ends, the limiting factor for part size seems to be the existing machines. The 26" punch diameter and 14" draw depth limits of this machine limit hydroforming of thin walled hemispheres to an approximate 26" diameter size range. When shells of heavier wall are considered, the overall size limitations are reduced. The hydroforming technique is thus oriented toward forming thin-walled parts.

Dimensional Control

The hydroforming process is capable of producing parts with minimal dimensional variation in overall part size and wall thickness. However, quality control must be adhered to during the draw to prevent such common flaws as wall wrinkles, flange wrinkles and puckers from occuring.

The following table shows examples of hydroforming results for various metals.

MATERIAL	REQUIRED O.R. (in.)	PART O.R. (in.)	REQUIRED THICKNESS (in.)	PART THICKNESS (in.)
304-L Stainless Steel	11.280	11.291	0.030	0.030
Aluminum 6061-0	10.565	10.572	0.020	0.020
Inconel 718	9.853	9.850	0.030	0.030
304-L Stainless Steel	5.435	5.434	0.035	0.034

The maximum radius variation between the required dimension and the finished part size is 0.1%. The only thickness variation, based on nominal dimensions, shown in the latter example, is 2.86%. Variation along the shell wall from girth to apex is approximately 10% of the nominal. These few examples thus do show the ability of this drawing technique to produce quality parts of different size and from various metals.

Surface Finish

Even though hydroforming is basically a drawing process, it does not produce the "draw marks" or "shock lines" typical of a conventional draw process. The areas, where surface finish would normally be subjected to degradation, include the male punch, the female die (flexible diaphragm) and the hold down ring. However, in hydroforming these areas do not mar the part surface.

Even though the process mechanics are such that no surface finish degradation occurs, the surface is roughened by the fact that the metal is stretched. The surface finish is increased approximately 2-6 RMS just due to this stretching. Also, heat treating is required for the stainless steels at some time during the drawing cycle. As a result of this operation, a cleaning process, normally pickling is required to remove the black scale, with a resultant further increase in RMS. Though the parts are subjected to these degrading factors, the good surface finish is still obtained since the initial metal blank is from sheet material which can be procured with a surface finish of 4-6 RMS.

Process Time

The processing time for hydroforming is comparatively short because the primary factors such as lead time, setup and drawing time are considerably less than for other drawing processes.

The lead time for tooling is greatly reduced since only one tool or punch is required, and for most jobs the punch can be turned on a lathe in a few hours. The simplicity of the one punch and universal diaphragm arrangement make tool changes very easy and fast. Required tool changes are also reduced since a number of different gage blanks can be formed with the same tool.

Finally, normally only one drawing cycle is required for most parts, and even if more than one draw is needed for some of the more work hardenable materials no tooling changes are necessary.

Normally, delivery of hydroformed parts can be accomplished in a matter of days.

Advantages - Disadvantages

Hydroforming possesses many features desirable when forming parts, but also, as with any process, it has its drawbacks. Summarized below are the characteristics pertaining to the hydroform technique and resulting parts.

ADVANTAGES

TOOLING: Tooling consists of machining a punch or die which in the majority of jobs can be turned on a lathe in a few hours. Because of the drawing character, tool materials need not posses exceptional physical properties. The resulting tooling cost is approximately 1/5 to 1/10 that of the conventional draw process due to elimination of die matching and alignment, quick tool fabrication and simple setups.

PROCESS FLEXIBILITY: The hydroform machine is usually oriented toward forming short run parts and experimental parts because of easy and fast tool changes. The diaphragm can be used as a die or as a punch.

FORMING TIME: Hydroformed parts are usually formed in one drawing cycle or at most two cycles, thus contributing to high production quantities in very short time.

SURFACE FINISH: Control of forming pressure eliminates wall and flange wrinkles and puckers. Only a light buffing to obtain an 8-RMS finish is required.

PART SHAPE: Both simple and intricate shaped parts featuring sharp right angles and acute compound curves can be formed by the technique. Deep parts are easily formed with no metal tearing.

DIMENSIONAL CONTROL: Unique forming action of the diaphragm produces very good dimensional control of overall shape and prevents wall thinout. Thickness variation of hemispheres from girth to apex is approximately 10% of the nominal.

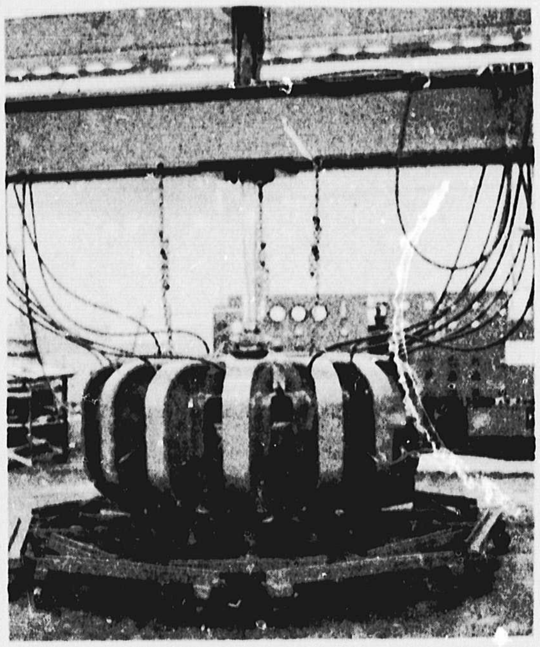
FORMABLE MATERIALS: In general all materials possessing some ductility can be formed. Material hydroformed include Aluminum, Brass, Copper and their alloys, all types of Stainless Steels and Cold-Rolled Steels, the Nickel-alloy family, Molybdenum, Tungsten and Titanium.

DISADVANTAGES

PART SIZE: Hydroforming is not capable of large part fabrication. Current machine capabilities limit part size to approximately 26" in diameter and 14" deep.

MACHINE COST: High initial machine cost has prevented companies from purchasing the 40" machine.

MATERIAL THICKNESS: Available forming power limit blank thickness to 3/4 inch for steels and 1 inch for Aluminum, with corresponding overall part size reductions.



INTURGESCENT FORMING

Inturgescent forming is relatively new to the metalworking industry. It is particularly adapted to the production of large shells of generally hemispherical or ellipsoidal shape. The process is especially advantageous in the manufacture of accurately dimensioned, thin walled shells.

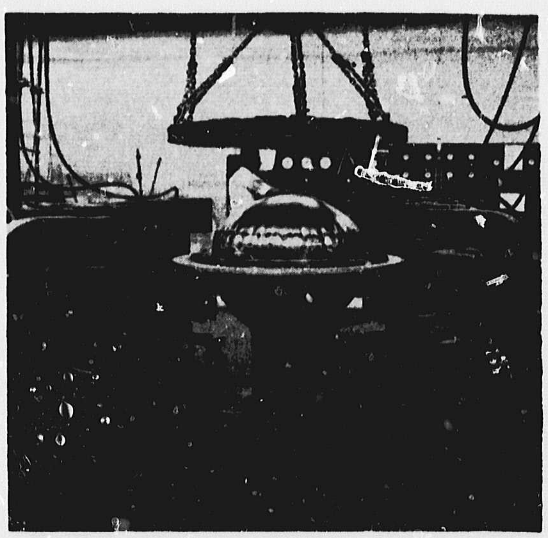
Process Description

Basically, the inturgescent forming process consists of a draw followed by a hydraulic bulge. Completion of the latter step results in a part which has been forced to conform to a female cavity by relatively large hydraulic pressures inside the shell. Inturgescent forming photos are shown at left.

The blanks used in forming a hemisphere, for instance, are flat and disc shaped, normally cut from sheet material. The blank is such that its diameter is approximately 50% larger than that of the initial stages of forming. This procedure is used to limit the amount of thinning which will occur during the bulging of the part.

The blank is clamped tightly between two smooth metal surfaces. The draw ring is located on one side of the blank and on the bed side the blank is exposed to the hydraulic fluid. The pressure exerted by the hydraulic fluid is increased, resulting in the blanks deformation in the form of a bulging. By carefully adjusting the clamping pressure, the draw-in begins to occur. When the draw-in is complete, the draw ring is no longer used.

The hydraulic pressure is increased until the partially formed part beings to deform once again. The shell is forced to bulge out toward the cavity walls. The cavity itself, which is the exact shape desired of the finished part, is machined from cast iron and is provided with vent holes so that there is no build up of air pressure between the shell and cavity walls. A center hole is provided so that the deflection of the apex of the shell can be accurately determined.



The blank continues to expand into the cavity until at some area, or point, it contacts the cavity wall. When this occurs, the area in contact ceases deformation and no tangential motion will occur due to the frictional forces between the shell and cavity wall. Thus, the area of the shell between the point of contact and apex or girth will now deform independently. In fact, by exerting a degree of control over the imminent point of contact, the thinning pattern on the finished part can be controlled.

Further pressure increases cause the shell to deform still further until it is in mechanical contact with the cavity over its entire surface. At this point the fluid pressure rises quickly. The pressure is then removed and the finished part extracted from the die.

At any point during the forming cycle, the part can be removed for intermediate processing steps such as annealing. The inturgescent forming process allows for a slow movement of the metal in comparison to explosive or draw press forming. Thus, there is available a high degree of control of the physical properties of the finished part. A wide range of properties is made available by varying the ratio of the drawing operation to the forming operation along with the intermediate annealing when required. All sections of the part are formed in tension which results in a stable condition of the finished units. Thus, little distortion of the part is likely to occur during post forming operations such as chemical milling.

Since the inturgescent forming process is a combination of drawing and stretching, many metals which are suitable for one or the other of these operations cannot be inturgescently formed. In general, the metal to be worked must be plastic enough to be workable, yet must work harden at a rate fast enough to avoid early and/or excessive "necking down". Many grades of aluminum, stainless steel and titanium have been successfully formed. The work hardening rate of the metal is, in effect, the regulator of the thin-out pattern.

Available Facilities

The inturgescent forming process was developed by the Jaycraft Engineering Co. in El Cajon, Calif. The process, which is considered proprietary in nature, was purchased by the Bendix Corp. in 1965, and is operated exclusively by their Instruments & Life Support Division at their Santa Ana, Calif. facility.

Size and Shape Capabilities

Shell type configurations, such as hemispheres and ellipsoids, are most amenable to the Inturgescent forming process.

At present, a machine with a bed plate area capable of handling parts up to 120 inches in diameter is available and has been used to form ellipsoids of this size. These parts were, however, quite thin due to inadequate hydraulic pressure availability. The difficulty associated with clamping the cavity such that it will remain in place when the part contacts it is very important. For instance, an ellipsoidal shell with major and minor diameters of 120 and 60 inches respectively and which requires 500 psi of forming pressure will exert a force of about 11 million pounds on the cavity when they come in contact. The cavity, to insure proper dimensional control on the part, must be rigidly clamped to the bedplate. To withstand these forces, the clamping devices must be very strong.

Another limiting factor is the availability of large size sheet stock from which blanks are cut. Although it may be possible to use blanks cut from sheets which have been welded together to provide the necessary width, this procedure is considered undesirable. This would result in using a blank of variable strength, as can be expected if a weld zone is included, and it would be difficult to obtain a uniform deformation pattern.

Dimensional Control

The degree of dimensional control is subject to such factors as tooling, process control, material, and the part being formed.

Due to the elastic nature of the part being formed, there is a certain degree of spring back when the hydraulic pressure is released. Since this can affect the overall part size, oversizing the cavity has been found successful in compensating for this spring back. However, determination of the correct amount of oversizing of the cavity requires considerable experience and experimentation.

Wall thickness tolerances are somewhat more complicated. Due to the bulging and stretching nature of the process, thinning of the material can and will occur. The amount of thinning which occurs at a point depends almost entirely upon the amount of stretching which has taken place at that point. Thus, the thinning pattern can be controlled to a certain degree by controlling the amount of stretching which takes place at each point on the part. To a degree, this is possible and, in fact, is often done by properly controlling the draw-in step. This alone, however, is generally inadequate if the degree of deformation is quite large. For instance, in forming a hemispherical shell, thinning of up to 25% can be expected.

These thinning problems can be solved by either tapering the blank prior to forming or machining the part after forming. Tapering the blank can be done by chemical milling or grinding. The second method, that of removing metal after forming, can be done by mechanical means (machining and milling) or by chemical milling.

Surface Finish

Although there is a draw step in the process, there are generally no draw marks upon the finished part. The inturgescent forming process is quite versatile and amenable to control. Thus, through exercising adequate care during the draw-in stage, draw marks are prevented.

Ideally the part being formed is not subjected to any sliding action between it and the cavity in which it is being formed. In reality this condition is very closely satisfied. Some areas of the part do contact the cavity before others, but the high hydraulic pressure forcing these contact areas against the cavity tend to prevent them from sliding as other non-contact areas are stretched further. Thus, the surface of the shell has not acquired any scratches or other degradations.

Since the shells being formed are to be used in cryogenic storage systems, it is desirable to have a surface finish of at least 8 microinches rms. A finish of this quality can be plated to provide the desired low emissivity characteristics. Beginning with a blank of very high quality, an inturgescently formed hemisphere can be expected to have a finish of from 8-12 microinches rms.

Cost

Although there are several items of tooling necessary in the inturgescent process, they are all relatively simple. The major tooling items to be considered are the cavity, the draw ring and wear plate together with various clamping devices.

The actual cost of forming the part is somewhat higher than similar forming processes, such as hydroforming, due to increased process time per part. As part size increases, handling difficulties become quite important and this step becomes more time consuming. This, however, is true of nearly any forming process and cannot be classed as a disadvantage. Thus, as part size increases, part cost increases proportionally.

One distinct cost advantage is displayed by the inturgescent forming process when compared to any other comparable process such as hydroforming. This is the cost of the forming machine itself. For hydroforming for instance, this cost is large enough to prohibit the acquisition of machines with large size capabilities. This is not the case with the inturgescent forming machine as is attested to by the present capability of forming parts of up to 120 inches in diameter. The machine itself is relatively simple and versatile and does not require a prohibitive investment.

In summary, inturgescent forming will normally be cost advantageous in forming parts of 22 inches in diameter or over. Below this size, it is found that hydroforming will be less costly and that hydroform machines are available.

Process Time

The lead time for the inturgescent forming process is similar to that for comparable processes. It consists of the time required to obtain the part material and tooling.

The lead time for the inturgescent forming process is approximately two months. The actual forming time for parts of the size range required for this study is about 24 hours. This includes blank preparation, drawing, stretching and annealing, but does not include any post-forming operations such as buffing, polishing, maching or milling.

Advantages and Disadvantages

ADVANTAGES

PART SIZE: The inturgescent forming process is theoretically capable of handling parts of any size. At present, the basic equipment is available for forming parts of up to 120 inches in diameter, requiring only tooling to form a part in this size range.

SURFACE FINISH: All parts are formed in tension with little or no friction as compared to competing processes. This produces parts which are virtually free of draw or tool marks.

MECHANICAL PROPERTIES CONTROL: As compared to competing forming processes, the inturgescent process utilizes a slow movement of metal which results in good control of the properties of the finished part. A wide range of properties is made available by varying the ratio of the drawing operation to the forming operation along with intermediate annealing steps. Since all parts are formed in tension, the finished part is highly stable and will seldom distort in subsequent operations such as chemical milling.

TOOLING: The tooling for the inturgescent forming process is relatively simple. No punch is used, thus eliminating matching of punch and die, resulting in lower tool cost and reduced lead time.

DIMENSIONAL CONTROL: The degree of dimensional control available in the inturgescent forming process is very good. Although forming a part requiring a large degree of deformation, from a flat blank, results in thinning of from 10-20%, by tapering the blank, a part of nearly constant wall thickness can be obtained. Wall thickness tolerances of ± 0.002 inches can be held, though they are not common. Tapering can be accomplished by grinding or chemically milling the blank. Dimensional tolerances of this magnitude, although practical, result in a far more expensive part.

DISADVANTAGES

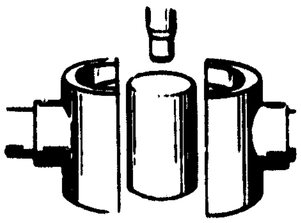
PROCESS TIME: In comparison to its chief competitors, inturgescent forming is a relatively slow process. For this reason, it cannot compare, economically, with hydroforming for parts with diameters of 22 inches or less. For large parts where no hydroform machines exist, the increased cost is unavoidable since other competing processes require more complex and expensive tooling.

FORMABLE MATERIALS: A material to be amenable to the inturgescent forming process must be plastic enough to be workable, but must work harden fast enough to avoid "necking down", that is stretching non- uniformly. This eliminates, for instance, 305 stainless steel. In addition, materials such as magnesium, which require hot forming (forming at an elevated temperature) cannot be formed by the inturgescent process. Since the part is exposed to the hydraulic fluid it cannot be maintained at a high temperature.

PART SHAPE: The inturgescent forming process, due to its hydraulic bulge nature, is applicable only to thin walled, shell type configurations. In addition, the part cannot have any sharp corners or rapid changes in curvature.

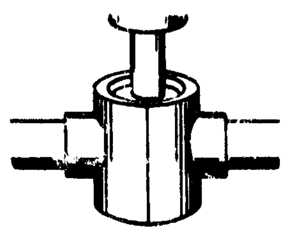
STATE-OF-ART: Inturgescent forming, due to its relatively recent appearance, is not technically advanced. Many of the process control parameters are not well understood and much of the process is a matter of experience and/or trial and error. This situation will be improved only through further application and experience with the process. The major areas in which development is necessary include adaptability of other materials to the process and the part shapes which are amenable to the process.

TYPICAL FORGING CYCLE SEQUENCE



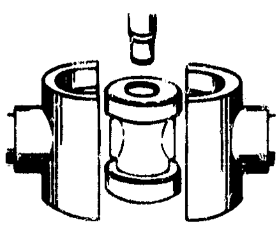
STEP 1

SIDE DIES & RAM RETRACTED
HEATED BILLET POSITIONED IN MACHINE



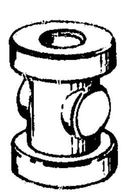
STEP 2

SIDE DIES APPLY PRESSURE
VERTICAL RAM ENTERS CLOSED DIES



STEP 3

SIDE DIES & RAM RETRACTED



STEP 4

FORGED PART

FIGURE 2.1.3-1

FORGING

Forging consists of plastically deforming heated metal billets by applying compressive pressure and/or by imparting impact blows to the material. The metal is forced into a predetermined flow path as described by the forging dies and punches. During the forging process, the metal is usually heated to improve plasticity-flow ability-and reduce the forging forces. A typical forging cycle sequence is shown at left.

The operating sequence of impact forming for all forging machines is as follows:

a. Forming starts with a few light blows of the ram to set the metal and begin developing the direction of metal flow.

b. Heavier blows are then delivered for roughing to shape and at a rapid rate in order to accomplish the major part of the shape changing while the metal is in its maximum state of plasticity.

c. Finally, the loading is tapered off to light blows to bring the work to dimensional accuracy and to refine the grain.

d. Work is stopped within the finishing temperature range to avoid the hazards of hot shortness.

After the forging operation is completed, the forging is removed from the machine and must be heat treated. The combined effect of the working, and of the transition from finishing heat down to room temperature causes an unbalance of residual stresses to be created in the work piece. It is essential that these stresses be removed by heat treating from the standpoint of improving mechanical properties and of avoiding stresses that may promote stress corrosion and ultimate cracking.

Available Facilities

There are hundreds of companies engaged in the forging business. However, very few possess the facilities required to forge large hemispheres for shells. The following companies appear to possess these capabilities.

COMPANY	LOCATION
Ladish Company	Cudahy, Wisconsin
Taylor Forge	Chicago, Illinois
Arcturus Manufacturing Co.	Oxnerd, California
Cameron Iron Works	Houston, Texas

Shape and Size Capabilities

The ability to forge parts of large size and intricate shape is a prime advantage of this forming technique. Through extensive research, experimentation, and development effort, the forging process is capable of producing intricate parts of uniform high strength not feasible by any other forming technique.

Dimensional Control

Forging does not exhibit good dimensional control. During the forming process, the source of energy and the rigidity of the unit, die blocks, and material impart certain characteristics to the part which define a geometry. Tolerances used in forging are not always of the desired final dimensions, but rather dimensions which modify the geometry so that there is sufficient excess material at critical dimensions to enable machining these locations. Machining forged parts is necessary not only because of poor tolerance control, but also because of the irregularities produced during the process. Forgings are thus not used in the as-forged condition when critical dimensions are required on the part, but must have these areas machined to obtain the final dimensions.

Surface Finish

Generally, the surface finish of forgings is very poor compared with other forming techniques. Typical "as-forged" parts have scale, pits and other irregularities which constitute coarse, non-uniform surface finishes. As a consequence, all surfaces requiring low RMS finishes must have additional machining performed on them. Occasionally, the scale and pits are to such a depth that the tolerances required for machining the part to size are governed predominately by the required surface finish, such that the resultant surface is beneath these degrading factors.

The scale on the forgings is attributed to the heating and reheating cycles during forging that are above the scaling temperature limits and to the heat treating and quenching procedure required after forging. Surface pitting results from foreign matter on the billet or dies and from an accumulation of solid particles of graphite lubricant between the part and the die. The irregularities in surface finish other than pits, including cracks, distortion and areas of non-complete part formation are results of raw material laminations, shrinkage of complex geometries during cool down, cold spots and poor metal flow.

For the current application of forging hemispherical and cylindrical shells, the as-forged surface is not acceptable. Consequently, the forgings will require additional machining to obtain the desired size and surface finish. Due to shell geometry, all necessary machining can be performed on a lathe.

Process Time

Since no dies exist for a desired forging, actual design and machining of the die or dies will account for the majority of the process time. There is a wide variation in this time, however, which is governed by the part configuration. The geometry dictates the number of dies required and the complexity of each. Thus, the time required to form the dies can vary from that required for two simple dies to that required to form four die-punch assemblies which involve many complicated machining processes to produce the desired geometry. In addition to die forming, set up and alignment of the more complex die assemblies represents additional process time.

Although Bendix, has not procured any hemispherical forgings, it has been found that a rule of thumb for processing time and delivery is five-months for the first forging. The above factors of the forging process account for but a small portion of this period. The primary reason for the long period is not due to the process itself, but to the time required to obtain the raw material - either Inconel or Stainless Steel. It must also be pointed out that the delivery period does not include final machining. Since the shells are not usable in the as-forged state, the time for forging and machining should be considered together. A total delivery period for the finished forging thus might be seven months or more.

Advantages - Disadvantages

As with all forming techniques, there are advantages and disadvantages peculiar to the process. Listed below is a general summary of the forging process characteristics.

ADVANTAGES

SHAPE VERSATILITY: The forging technique is capable of forming many complex geometries not possible by any other forming method. Very intricate detail can be produced regardless of the part size.

PART SIZE: A primary advantage of the forging process is to produce parts from very small size to large sizes weighing up to 20,000 lbs.

INTEGRAL COMPONENTS: Forged integral components permit reduction in the number of mechanical and welded joints and the elimination of welds in critical areas. For the current application, the shells and fittings can be formed integrally.

STRENGTH: Deformation during forging, grain flow, is characterized by alignment of the crystal structure of the base metal. This alignment of crystals into grain flow lines produces maximum tensile strength potential parallel to the lines and maximum shearing strength across the flow lines.

MATERIAL VERSATILITY: All ductile metals can be forged including high strength alloys, stainless steels and high strength alloy steels. Refractories and other special metals such as Magnesium, Tantalum, Titanium, Columbium, Molybdenum and Tungsten have also been forged in many shapes and sizes.

POROSITY: Forged parts are adaptable to high pressure service since multi-direction grain flow characteristics exhibit a minimization of porosity across these flow lines.

DISADVANTAGES

SURFACE FINISH: "As-forged" parts exhibit scale, pits and other surface irregularities which present poor quality finishes. Final cleaning removes scale and residues of the process, but the surface still remains coarse.

SUPPLEMENTAL MACHINING: Because of the surface irregularities and poor dimensional control, the shells must be finished on a lathe to obtain the correct size and surface requirements.

DIMENSIONAL CONTROL: Because of factors in the forming process such as die wear, heat distortion, die shift, cold spots, material flow, lubricant buildup, temperature range and shrinkage, the desired dimensional tolerances cannot be obtained on an "as-forged" part. Tolerances are normally used as correction factors and to obtain material for the necessary finishing operations. In general, it is advisable to allow 1/16" for finish machining.

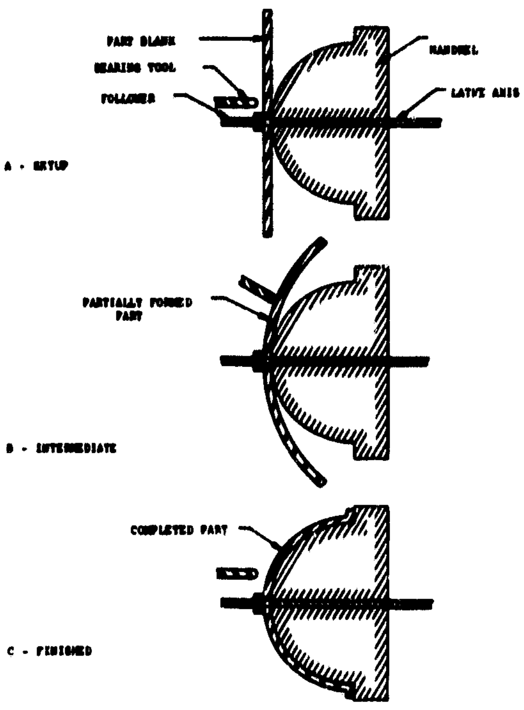
HEAT TREATING: After being forged, parts must be heat treated to remove residual stresses that can promote stress corrosion and reduce full design load ability.

PROCESS TIME: Process time is a function of the part geometry complexity. A five-month delivery period is typical for the desired "as-forged" shells, not due directly to forging but because of the procurement period for the material to be forged.

SPINNING

The art of metal spinning dates back to early civilization, and became popular in the United States with the immigration of German craftsmen following World War I.

While an integral part of the metal working industry, the spinning process is limited to forming shell-type parts with minimal wall thickness, normally less than three inches.



SPINNING PROCESS

Process Description

The basic components of the spinning process are the mandrel, lathe axis, follower and bearing tool. The metal to be formed consists of a flat disc with a hole in the center. A schematic of a typical spinning process is shown at left.

The blank is centered with the mandrel on the lathe axis and is held securely in place by a follower which is mounted on a live center on the tailstock of the spinning lathe. The blank is in intimate contact with the leading portion of the mandrel which lies along the lathe axis and which must be the axis of symmetry of the projected part.

The concentric blank and mandrel are set into rotational motion. The velocity of the spinning motion is somewhat dependent upon part size, ranging from about 2500 rpm for small parts to 100 rpm for large parts. A bearing tool is advanced toward the blank on the side away from the mandrel. This tool generally consists of a smooth roller with rounded edges or a blunt, rigid tool. It is mounted upon a movable base and its motion is hydraulically or mechanically controlled.

The tool contacts the rotating workpiece near the center and a predetermined pressure is applied. The tool is then moved outward while the pressure on the workpiece is maintained. The blank is forced away from the tool, toward the mandrel. The tool is worked back and forth over the workpiece surface between the center and the periphery, the pressure being steadily increased, causing the revolving metal to flow around the mandrel. As is shown, the bearing tool is held perpendicular to the tangent of the surface at the point of contact or close to perpendicular at all times, and controls the amount of thinning.

As the tool is worked back and forth over the part, the metal continues to flow down and around the mandrel. At the conclusion of the spinning process, the part is in tight contact with the mandrel at all points.

The mandrel must be of the exact shape as the inside surface of the part being formed. Since the part is formed around the mandrel and there is total contact between it and the part, the mandrel shape will be reproduced with great accuracy.

Available Facilities

The basic simplicity of the spinning process to with its flexibility and relative low capital investment have contributed to the large number of companies doing this type of work.

The commercially available equipment is capable of a wide working range. For instance, one type of spinning lathe is capable of handling parts ranging from 30 to 108 inches in diameter. At present, lathes capable of handing parts more than 14 feet in diameter are in use. Parts of the size of interest herein should be expected to present no particular difficulties. Adequate experience is available in forming parts in the size range under consideration.

The presence of capable facilities and personnel is perhaps one the major advantages of the spinning process.

Listed below are some of the companies active in spin forming and which possess the capability of producing parts of the size of interest herein.

Phoenix Products Company, Inc.
Milwaukee, Wisconsin

Spincraft Inc.
Milwaukee, Wisconsin

Super Metals Company
Santa Fe Springs, California

C. W. Torngren Company, Inc.
Somerville, Massachusetts

Shape and Size Capabilities

The spinning process is restricted to shells which are surfaces of revolution, such as hemispheres, domes, cups, cones, parabolic and torroidal sections, and appears adaptable to forming cylindrical vessels with hemispherical or dome type ends.

With respect to size, spinning is advanced perhaps further than any of the conventional processes. Equipment, facilities and a considerable degree of experience are available in forming parts up to and over 150 inches in diameter. Parts of the size range which is of interest herein (up to 48 inches in diameter) are quite commonplace.

The spin forming process is also capable of handling shells with relatively thick or thin walls. Aluminum and its alloys up to 3 inches thick have been spun as have many of the high strength steel alloys in thicknesses as large as 1-1/2 inches. Thicknesses of 0.050 inches to 0.200 inches, typical of those necessary in this application, are also quite common to spin forming. Very thin material would present difficulties in spinning. The material tends to wrinkle and distort due to its radial acceleration and the resulting stresses introduced by the induced forces. Reduced rotational velocities are desirable in this case, but this poses problems in maintaining uniformity in deformation rate, and results in varying material properties over the finished part.

Dimensional Control

Wall thickness control is extremely difficult to exercise in spin forming. Shells often are very non-uniform in thickness, and the thinning can be very pronounced. These problems become increasingly prevalent with decreasing wall thickness.

For example, a hemisphere with a diameter of nearly 60 inches was formed from a 2 inch thick aluminum (6061) blank. The apex of the formed part was 2 inches thick, while at about 30° above the equatorial plane, the thickness was over 35% less. This was the thinnest region of the hemisphere. In the present application, thinning to this extent is not only undesirable, but is unacceptable. Non reproducability is due primarily to the poor control over the various system parameters from part-to-part. These factors include tool pressure, forming rate, tool rate (across part face), and part temperature. In addition, the physical properties of the blank material vary from part-to-part. In effect, two parts will not be deformed in exactly the same manner and pattern since there is a lack of precise control over the process.

Spinning is often followed by machining of the part. The reason for this is quite obvious. However, this negates some of the advantages of spinning, since forming time would increase, tooling quantity and cost would rise and the process would increase in complexity.

Surface Finish

The spin forming process is not characterized by smooth "as formed" surfaces. In fact, surface finish is one of the two major drawbacks of spinning, the other being dimensional control.

The nature of the spinning process itself is primarily responsible for the relatively poor finish, since the material is deformed during the process. The deformation is generally due to the stretching of the material.

On parts of the size and thickness required for this application, the "as formed" surface finish can be expected to be exceedingly poor, perhaps as much as 200 microinches rms. The tighter the dimensional tolerances being held on the part, the longer the part must be spun. Thus, with decreasing size tolerances, decreasing surface finish characteristics can be expected.

Process Time

Lead time for the spinning process is extremely short when compared to other processes. Tooling requirements are minimal since only one tool, a mandrel, need be produced. This can generally be cast or turned on the forming lathe in a very short time. Total lead time can be expected to be measured in several hours or, at a maximum, a few days.

Job setup time is also relatively short. The mandrel is often turned on the same lathe that is to be used in forming the part, thus eliminating the added necessity of mounting it on the lathe.

For parts the size and shape of interest herein spin forming is expectedly much more rapid than other conventional processes. The reasons for this are two fold. First, the equipment and facilities are presently available, as is a certain amount of experience in this area, and this is perhaps the most advantageous aspect of spin forming when compared to many of the other metal forming techniques. Second lead time and setup time are quite short; shorter than most other processes. For these reasons, this process has received broad application in short run and prototype production.

Advantages - Disadvantages

Spin forming appears to display some particularly advantageous characteristics. As with any process however, there are several features of the process which tend to deter from its applicability. These features are summarized below.

ADVANTAGES

TOOLING: Tooling consists primarily of a mandrel. This device can be turned on a lathe in a few hours, and need not display any exceptional strength characteristics. Tooling costs may be as low as 20% of those for a drawing process.

FLEXIBILITY: The lathe on which a part is spun is capable of handling a large variety of part sizes and shapes. Tool changes and setup are simple and rapid, enhancing the use of the process for short run or experimental applications.

FORMING TIME: The rapid set up time and short lead time contribute to a short process period, which are also advantageous in short run and prototype production.

FORMABLE MATERIALS: Nearly any material displaying some ductility can be spun. In addition, it is quite simple to form a material at an elevated temperature.

PART SIZE: The spinning process is presently capable of handling parts of well over 10 feet in diameter. Facilities, equipment and experienced personnel are available at this time, thus reducing the need for a costly development program to determine the feasibility of the process to large part production.

DISADVANTAGES

SURFACE FINISH: The as formed surface finish on the side of a spun part exposed to the bearing tool is extremely poor. A large amount of grinding, buffing and polishing would be necessary to obtain a suitable finish that would, through plating, provide a low emissivity surface.

DIMENSIONAL TOLERANCE: Overall size tolerances on spun parts can, with care, be held within an adequate range. In insuring these characteristics, the ability to hold wall thickness tolerances is destroyed. For the intended application it would be practically mandatory to machine the part after spinning to provide suitably close tolerances on both overall size and wall thickness.

TOTAL COST: The total cost of obtaining spun parts for this application would be very high. The necessity of following the spinning by machining, grinding, buffing and polishing is responsible for this factor.

PART SHAPE: The spinning process is applicable only to highly symmetric parts. The nature of the process demands that a part must be a surface of revolution. In this application, this does not appear to be a major limitation, but may become so in the future.

ELECTROFORMING

Electroforming is described as "the art of producing or reproducing metallic objects by electrodeposition upon a master form, matrix or mandrel which is then removed in whole or in part." As defined, this process employs the word "art" rather than "science", thus recognizing that the success of the process depends primarily upon the skill and experience of the practitioner, and not upon a set of "prior" rules.

Although the process has been known for years, it has only been recent that advantages of the process have evolved. As a result, electroforming has developed rapidly as a low cost method of producing highly precise parts.

Process Description

It is rather apparent that the mechanics of the electroforming process are identical to electrolytic plating. The end product differs, however, in that in electroplating, the mandrel on which the deposition occurs and the deposit itself integrally serve as the finished part while in electroforming, the deposit alone serves as the part. Common to the two procedures is the electrochemical nature of the deposition.

The rate of deposition of material on the mandrel is subject to wide variation. For relatively simple shapes, rates of from 0.01 to 0.02 inches per hour are possible by using higher than normal current densities. The usual rates are, however, considerably lower, ranging from 0.002 to 0.005 inches per hour. For thin walled structures, but for somewhat thicker structures, a higher rate is desirable and may be expected to be possible with a reasonable growth and state-of-art improvement.

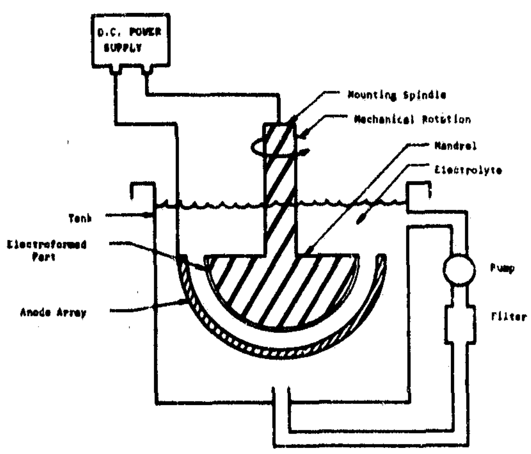
During forming of a part, it is generally not desirable to stop the process prior to completion and restart later. A procedure such as this tends to produce a "layered" part; that is, the layer of material deposited prior to the interruption will not be well integrated with the layer deposited after the interruption. In some applications, the existence of this "interface" between material layers may be desirable, but in general, structural properties of the part will be degraded, making the laminated type part unacceptable.

Electroformed parts are usually made of nickel; however, cobalt, iron, copper, gold, silver, platinum, aluminum and titanium have been used. Aluminum and titanium are somewhat troublesome and dangerous because of the equipment and control problems associated with the anhydrous organic bath used for aluminum and the molten salt bath used for titanium.

The relatively poor distribution of electrical current at different areas on complex shapes limits electroforming of certain contours and shapes, even when specially shapped anodes are employed to equalize the current distribution as much as possible. Deep and narrow recesses in mandrel surface receive much less current and therefore, less deposition of metal than the surfaces lying closer to the anodes for example. While specially shaped anodes can be inserted in the recess to compensate for the unequal current distribution, this can be difficult and costly.

The matrix or mandrel used in electroforming has a dual purpose. Its most obvious function is the provision of a negative form which will, by deposition on its surface, permit the formation of the required part. It may also provide some reference points for the exact location of the cavity in the indefinite form which the electroform may take. In addition, if any machining or polishing of the exposed surface of the electroform is necessary, the mandrel may be left intact and may serve as a holding jig. Similarly, the mandrel may serve as a plating jig if it is desirable to plate the exposed surface of the electroform. A schematic of an electroforming process is shown at left.

ELECTROFORMING PROCESS



Most electroformed metals deposit in a rather highly stressed state. In some cases, this has been serious enough to cause curling, bending or fracturing of the part when removed from the mandrel. Needless to say, this is an undesirable situation and has contributed to the slow development of the process. Recently, however progress has been made in rectifying the problem. New bath additives and new bath compositions have been developed which provide much improved results. This still is a problem area since not all metals respond in the same manner to the differing additives.

Available Facilities

There are a large number of companies which have electroforming facilities. Many of these companies, however, have not been active in producing large parts. Instead, they have specialized in relatively

small, precision type parts. Listed below are the companies which appear to have facilities capable of producing parts of the size being considred in this study.

1. **Allied Research and Engineering Company**
   Los Angeles, California

   Part size capability (ft.)
   6 x 12

2. Bart Manufacturing Company
   Newark, New Jersey

   Part size capability (ft.)
   4 x 12 x 12

3. Columbia Record Company

   Part size capability (ft.)
   4 x 10 x 10

4. Electro-Optical Systems Inc.

   Part size capability (ft.)
   10 x 10 and 4 x 20

5. Gar Precision Products Inc.
   Danbury, Connecticut

   Part size capability (ft.)
   3.33 x 3.33 x 7

6. General Dynamics Corporation
   Fort Worth, Texas

   Part size capability (ft.)
   6 x 6

The companies shown above electroform primarily nickel, nickel-colbalt alloy and copper. At present, none of these materials appear to be adequate for application to the subject matter of this report. The inadequacy is primarily due to poor strength characteristics.

At least one company has, on an experimental basis, electroformed aluminum. This is the General Electric Company in Philadelphia, Pennsylvania. Due to lack of demand, there appears to be no company with adequate facilities capable of electroforming these materials on mandrels of the size required by this application.

Size and Shape Capabilities

The primary limitation on the size of parts which may be electroformed is the size of the electrolytic bath in which the forming occurs. As may be expected however, the magnitude of the problems encountered is related to the part size. As part size increases, it becomes more difficult to maintain an adequate degree of control over the process.

The shape capabilities of the electroforming processes are considerably greater than most conventional processes. Both open parts, such as hemispheres, and closed parts, such as spheres, can be formed. The major limitation is in avoiding deep narrow recesses and sharp corners. This can be rectified, totally or in part, by correct and critical control of the process which is feasible, but in general, not economically advantageous.

Dimensional Control

Due to the nature of the elctroforming process, parts of high dimensional fidelity can be produced with relative ease. The major factors affecting both the thickness and diametral tolerances are the tooling accuracy, bath control and control of the current density over the part.

Diametral accuracies of from .002 to .05 inches are relatively easy to obtain on parts of practically any size if the mandrel is of a geometric configuration which is highly symmetric (such as a hemisphere). To obtain tolerances of this order, the mandrel must be made of a relatively strong material which is easy to machine. This of course, assumes an absence of large, distorting internal stress levels. By employing conforming anodes, wall thickness variations of from 5 to 15% are quite common.

Surface Finish

Perhaps the greatest advantage demonstrated by the electroforming process is its capability of providing surface finishes of very high quality.

Normally the mandrel side surface finish on an electroformed part is from 8 to 16 rms microinches. Surfaces of much higher quality (up to 2 rms microinches) have been obtained by applying an identical finish to the mandrel itself. This can be done on practically any part size or shape at a premium cost. The high cost results from the necessity of a large amount of buffing and polishing of the mandrel. When much polishing must be done, it is quite difficult to hold tight tolerances on the size of the mandrel, and the care which must be exercised increases the cost even more.

The exterior surface finish (the side exposed to the bath) is considerably more difficult to control. For thin walled parts it is often possible to obtain a finish nearly equal to the mandrel surface finish. This is limited to wall thicknesses of much less than 0.050 inch. A high degree of agitation and temperature control of the depositing bath is necessary to obtain this result. For thicker parts, up to 0.100 inch, it is normally possible to obtain finishes of from 16 to 32 rms microinches. Once again, to obtain this quality, both composition and temperature must be well controlled. As wall thickness increases still further, the finish deteriorates steadily. At a wall thickness of about 0.250 inch, particle roughness begins.

Process Time

Process time for the electroforming technique is expectedly longer than for most conventional processes, and much longer than for the high energy rate techniques.

Lead time for the process is exceedingly short. Only a mandrel need be machined, and this can be made of a material which is quite amenable to machining or casting.

If conforming anodes are used, a slight increase in lead time can be expected, but this factor generally will not be very important. Total lead time can generally be expected to be a matter of several hours with a few days as a maximum.

Job setup requirements are also quite easily met, since the mandrel and anodes need only be positioned and placed in the electrolytic bath.

It is the process itself that is quite time consuming, especially for the parts as large as are being considered in this context. The process rate is inherently slow. Many investigators feel that this is the greatest disadvantage of the process, and has been the major cause of the relatively slow development of the process. Forming time for very small parts can be as long as for 5 hours. Many of these parts can be formed in a press in a matter of minutes or seconds. Larger parts may take up to 250 hours to form. It should be noted that the electroforming process, unlike most conventional and high energy techniques, will require no intermediate part processing such as annealing or stress relieving. For large parts, these intermediate steps can be very time consuming. Thus, in some cases, the total forming time for electroformed parts can be considerably shorter than for any of the other processes.

Advantages - Disadvantages

Until recent years, electroforming has not received broad application. However, interest has increased because of particular advantages of the process. These advantages, together with its disadvantages, are summarized below:

ADVANTAGES

PART SIZE: At present, facilities are available for forming parts as large as, and larger than, required by the application herein considered. Increasing part size capability is neither prohibitive in cost nor difficult.

TOOLING: Necessary tooling consists of a mandrel, and in some cases, conforming anodes. These items are generally quite easy to produce and do not require long lead or setup time.

TOLERANCES: The dimensional characteristics of an electroformed part can, with care, be made better than those of any other process. This is especially true of the size tolerances, such as the radius of a sphere. Maintaining tight thickness tolerances on shells is not easy, but quite possible.

SURFACE FINISH: Here again, electroforming shows distinct advantages over nearly every other forming process. The finish on the mandrel side of the part can be of any quality whatsoever assuming it is possible to obtain the desired finish on the mandrel. The exterior surface, although not of as high quality, can be polished to a sufficiently smooth surface for the present application.

FLEXIBILITY: The electroforming process is well suited to either experimental, short run or production applications. The versatility of the process is attributable to the simplicity of the facilities and equipment necessary. Tooling cost is relatively low and setup is rapid. Tool rework is virtually unnecessary.

DISADVANTAGES

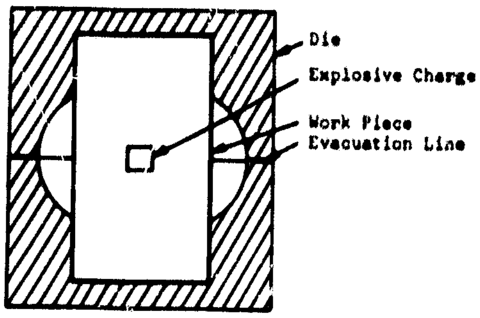
FORMABLE MATERIALS: Presently, the process is limited to few materials. Nickel has been found to be the most suitable material, and is most widely used. However, the strength of nickel is inadequate for the present application.

PROCESS TIME: Due primarily to the very low rate of deposition of the metal, the process time is generally longer than for the conventional processes.

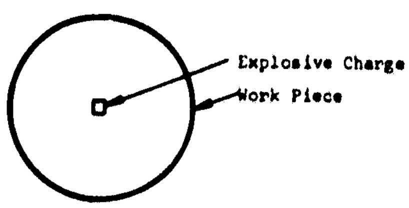
PART SHAPE: Parts with sharp corners and/or deep narrow recesses are very difficult to form by this process. Though this can sometimes be corrected by employing "thieves" to limit deposition in certain areas, their use requires a time consuming, trial-and-error type of experimental program.

MATERIAL STRENGTH: The metals which are presently used in electroforming applications demonstrate a wide range of strength properties from part-to-part. In general, the nominal or average value of the particular property is somewhat below the value obtained through other forming processes. The actual values obtained depend primarily upon the type of bath, type and concentration of bath additives, and degree of control over the bath parameters. To obtain adequate results in this application, a much greater ability to control the resulting strength properties is necessary, and, in addition, it would be desirable to obtain increased strength characteristics.

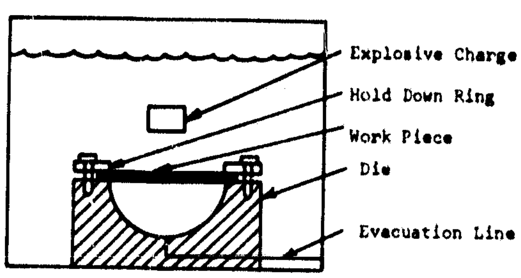
EXPLOSIVE FORMING



A. Confined With Die



B. Unconfined "Free" Form



C. Unconfined With Die

EXPLOSIVE FORMING

Basically, explosive forming is a metal-working process that utilizes the high rate of energy release obtained from the detonation of an explosive charge as its source of energy.

Description of Process

As in all energy rate forming processes, explosive forming consists of an impulse of large magnitude, which deforms the metal very rapidly. When certain materials are subjected to an impulsive load, they can withstand momentary stresses whose magnitude is well above their static fracturing stress. Explosive forming takes advantage of this phenomena by utilizing an explosive charge to provide an impulse which suddenly and violently deforms the metal to the desired configuration. The impulse often creates stresses in excess of the fracture stress, but, due to the rapidity of the impulse, and short duration of the induced stress, the material does not fracture.

The most common explosive forming techniques involve the application of either contact or stand-off charges. In contact operations, the explosive is placed in intimate contact with the work piece, while in stand-off operations the charge is located at some predetermined distance from the workpiece and the energy is transmitted to the workpiece through a transfer medium. A schematic of one type explosive forming process is shown at left.

Available Facilities

A present, one of the major drawbacks of the explosive forming process, with respect to the present application, is the general lack of facilities which are capable and experienced in forming large parts to close tolerances. Explosive forming has developed to its present state primarily due to its capability of forming exceedingly large parts with a minimal financial investment and short lead time.

Listed below are some of the companies which, it is believed, have the capability of producing parts of suitable quality for the application being considered herein. Each, however, would require a process development program to insure proper dimensional control prior to forming production parts.

1. General Dynamics
   Fort Worth, Texas

2. Aerojet-General Corp.
   El Monte, California

3. Explosiform, Inc.
   Belvedere, California

4. North American Aviation Inc.
   Los Angeles, California

Size and Shape Capabilities

The major limitations governing the size, thickness or material to be explosively formed are the ability to produce the required tooling and the ability of the explosive forming facility to withstand the shock wave generated by the increased amount of explosive needed to produce large parts. Larger and deeper domes and hemispheres can be explosively formed because greater degrees of deflection and deformation of many materials are possible.

Explosive forming is quite versatile with respect to shape. The primary limitation is the ability to produce dies to the desired shape, except in the free expansion where no dies are employed. In this case however, the process is applicable only to simple shapes such as spheres, ellipsoids and other highly symmetrical configurations.

The process is suitable primarily to shapes which may be formed in a female die. Since only one die is employed and no die matching is necessary, it is much easier to obtain suitable tolerances on the finished product. Also, since there are a limited amount of frictional effects between die and material to affect the deformation pattern, reproducibility is very good. Thus, the formation of complex geometries is limited primarily by die production.

Dimensional Control

There is considerable ambiguity amongst the industry over the degree of dimensional control. This is believed due to the process control procedures which stem from the relative newness of the process and the multitude of possible control parameters. Presently the state-of-art is not advanced beyond the emperical state.

The establishment and maintenance of close tolerances on explosively formed parts can be expected to be time consuming, and therefore a rather expensive procedure. In addition, reproducibility is questionable due to the relatively poor reproducibility of the explosive charges. Placement of the charge and its shape, standoff distance and quality of the transfer medium are critical in obtaining reproduction of close tolerance parts.

Surface Finish

The surface finishes of explosively formed parts are comparably equal to other forming processes. Since the explosive forming process is not a drawing operation, it does not produce draw marks which mar and degrade the surface.

If the original part blank finish is of very high quality, it is generally possible to obtain an outside surface finish very nearly equal to that of the die cavity.

The expected surface finish of a hemispherical shell is approximately 14-18 RMS, and would require buffing and polishing prior to use.

Process Time

Lead time is considered to be very short. This is due to the necessity of only one tool, a female die, which can be turned on a lathe within a few hours.

As in all of the high energy rate forming techniques, close dimensional control is highly dependent upon the accuracy of the die. Thus, close tolerances tend to increase lead time.

Set-up time for the explosive forming process is quite short. In forming hemispheres for instance, it is only necessary to bolt the part blank over the die cavity with the hold-down-ring, locate the explosive charge at the predetermined distance from the blank, and lower the entire assembly into the transfer medium in the tank to the desired depth. Since there is no press or other large machinery, there is minimal tool change time in going from job-to-job. There is generally no change in set up time in going from one material and/or thickness to another.

The actual forming time is, as may be expected, exceedingly short, and is a negligible part of the total process time. The fact that most materials are more formable under high velocity methods than under conventional methods, reducing the number of necessary intermediate annealing steps contributes to this rapid process time.

Advantages - Disadvantages

Explosive forming appears to demonstrate some especially advantageous properties when compared to the conventional and other high-energy-rate forming processes. These advantages, as well as its disadvantages, are discussed below:

ADVANTAGES

PART SIZE: There appears to exist no theoretical or practical limitation to the size or thickness of parts which can be explosively formed. The cost penalty encountered in increasing part sizes is, very low, depending primarily on tooling.

TOOLING: Tooling consists of machining a femal die which is normally not a time consuming or expensive operation. Tool material is cheaper, since it need not possess any special strength properties.

PRODUCTION COST: In general, production cost will be less since the process is simple and flexible, short set-up time is probable, forming time is reduced and intermediate processing procedures (annealing and/or stress relieving) are limited.

FORMABLE MATERIALS: Most materials are more formable under explosive techniques and in some cases, materials which are particularly difficult to form conventionally have presented no serious problems in explosive forming.

SURFACE FINISH: Absence of die and punch marks make possible very good surface finishes. The workpiece surface exposed to the die will assume about the same finish as the die cavity while the side exposed to the explosion will, if properly protected, experience only slight degradation due to stretching.

FLEXIBILITY: The simplicity of the process provides a high degree of flexibility, not only in part size but in materials amenable to forming.

DISADVANTAGES

DEVELOPMENTAL COST: The cost encountered in establishing a suitable process (i.e., determination of explosive size, shape and substance, stand-off distance and transmittal medium) may be very high since it is primarily a trial-and-error procedure.

FACILITIES: Explosive forming facilities must be located in a remote area, far distant from population centers.

SAFETY: Very stringent safety measures must be in effect at all times to prevent premature explosions.

PERSONNEL: In general, there is a lack of persons with adequate backgrounds in handling explosives, especially in this application. Those personnel available must be paid a premium rate due to the dangers inherent in the work.

EXPLOSIVES REPRODUCIBILITY: In close tolerance applications, it will be necessary to employ explosives whose detonation velocity is very nearly constant, through one charge and from charge to charge. At present, these conditions are not in general adequately met. The storage conditions, atmospheric conditions and handling and placing of the charge have a large effect upon the explosive properties. This, in effect, nullifies the advantage of the broad degree of control parameters.

LACK OF EXPERIENCE AND FACILITIES: Explosive forming has not received broad application in close tolerance applications, It is not known to what extent the problems which will undoubtedly arise will detract from the process, but until adequate facilities and experience are available, the process will not, in most applications, be found advantageous when compared to other processes.

MAGNETIC AND ELECTROHYDRAULIC FORMING

Magnetic and Electrohydraulic forming are both considered to be high energy rate forming techniques. They are loosely termed capacitance discharge forming by virtue of their common energy source.

Both processes are referred to as "high velocity metalworking" because metal velocities of several hundred feet/second are common as opposed to about 15 feet/second for conventional processes.

Until the advent of high strength super alloys, these processes received little attention.

Presently, neither process is considered adaptable to forming large size hemispheres for use in Cryogenic Gas Storage Systems. Thus, this review of these forming processes is limited to citing the advantages and disadvantages which are predominant for both processes.

MAGNETIC FORMING ADVANTAGES

TOOLING: Tooling consists of either machining a die and/or a field shaper, both of which are quite easily turned on a lathe in a few hours. The tool material need not possess any exceptional physical properties, and results in a tool cost which is quite low.

PROCESS FLEXIBILITY: Due to the variety of possible process control parameters, there is a broad, and precise, degree of control over the process. The amount of energy which can be delivered to the workpiece is subject to a very high degree of control. The basic process equipment is applicable to a wide variety of part shapes, sizes and blank thickness.

FORMABLE MATERIALS: Most materials display increased formability under magnetic and other high energy rate forming techniques. Although the part blank must possess good conductivity to allow efficient eddy current production, this is easily accomplished by plating or using a driver on low conductivity metals.

PRODUCTION COST: Due to the basic process simplicity and flexibility, the per part cost of a production application is very small, and the forming time is quite short.

SURFACE FINISH: The surface finish is controlled primarily by the blank surface finish, with very little degradation encountered. In addition, forming can be performed quite easily in an inert atmosphere, since the coil, die and part blank require a minimum of space.

MAGNETIC FORMING DISADVANTAGES

PART SIZE: At present, the major applications have been in small part production. Though this does not reflect any basic process limitations, it would require a rather lengthy and costly experimental program to determine the applicability of the process to large parts (such as 30 in. diameter hemispheres).

COIL DESIGN: The coil design presents a major problem. For the present applications of the process, the coil design is relatively easy, by virtue of its cylindrical tube shape that is amenable to field shapers. For producing large spheres, coil design would be very difficult, and the use of shapers, which decrease process efficiency, would increase energy requirements.

DEVELOPMENTAL COST: Based upon the present volume requirements, the cost of developing this process is considered prohibitive. The coil design represents the major cost item influencing the overall development costs.

FACILITIES: Though the basic equipment is flexible, its cost is very high. This, and the rather narrow range of applicability which the process has had, have contributed to a lack of available facilities for forming parts of any but cylindrical shapes.

ELECTROHYDRAULIC FORMING ADVANTAGES

PART SIZE: This process is theoretically capable of producing very large parts. The practical limitations on part size which do exist are, in no way, reflections of process inadequacies, but are due to a lack of experience. Equipment for forming large hemispheres (up to 4 feet in diameter) is available, but lack of demand has limited its use.

TOOLING: Since only a female die is necessary, tooling cost is comparatively low. This has been a contributing factor in the use of the process for short run production applications. Elimination of the punch and matching of a punch and die also contribute to a reasonably short lead time. As compared to the other high energy rate forming processes, the tooling requirements are nearly identical.

PROCESS FLEXIBILITY: Due to the basic simplicity of the process, and to the wide range of parameters governing the process, the electrohydraulic forming system is very flexible. The basic high cost items, such as the energy storage system, are applicable to a wide variety of parts and sizes, limiting the need for many machines of various sizes.

OPERATING COST: The basic energy source, electricity, is far less costly than that of any other forming process. In a production type application, specially trained personnel are not needed to any greater extent than in any other forming process.

FORMABLE MATERIALS: As with all of the high energy rate forming processes, many materials possess better forming properties with the electrohydraulic technique than with conventional processes. This allows much more severe deformations of a material without cracking or fracturing. This process has been used in forming many of the high strength, high temperature resistant super alloys and the refractory metals.

REPRODUCIBILITY: Due to the wide degree of control inherent in the system, electrohydraulic forming has been found to have very good reproduction characteristics. This is limited primarily by the ability to furnish blanks or preforms of consistent size and material properties, since it is not difficult to insure good reproduction of the shock wave which does the forming work. This is its prime advantage over other high energy rate systems, as well as most conventional processes.

ELECTROHYDRAULIC FORMING DISADVANTAGES

EQUIPMENT COST: The basic cost of setting up an electrohydraulic forming facility is as high, or possibly higher, than conventional forming facilities.

AVAILABLE FACILITIES: Although there are many companies which perform electrohydraulic forming, the major applications are on small parts. Due to the small demand and high cost, few facilities are available for large parts.

DEVELOPMENTAL COST: Although this disadvantage is shared universally with all forming processes, it is somewhat more prevalent in electrohydraulic forming. This is due to the greater degree of engineering participation required to establish the most advantageous values of control parameters. Due to the multitude of parameters through which the process is controlled, the developmental time is usually longer.

MACHINING AND MILLING

Machining and Milling, like Chemical Milling, are not considered as forming processes. Rather, they are used to improve the quality of parts following forming. Since machining and milling are dissimilar in application from chemical milling, the latter is discussed separately in the following section.

Process Description

Machining and milling involve the mechanical removal of metal. This is accomplished by bringing the tool, which is made from a "hard" material into physical contact with the part to be finished. By maintaining a high relative velocity between the part and the tool, this results in a grinding, scraping or abrading action that removes the metal surface layer in the form of chips.

Machining and milling are most adaptable to symmetrical parts which are, at least in part, surfaces of revolution. In this case, the part (or tool) can be rotated about the axis of symmetry of the area to be machined, thereby producing the necessary relative motion between the tool and part. There is also a variety of different machining and milling machines which will perform many different operations. By combining these machines with a tracer process, a wide range of applicability is possible.

The tool must necessarily be made of a very "hard" material relative to the material being worked. Since the tool is subjected to the same abrading forces as the workpiece, eroding must be kept minimal to maintain a uniform cut. Tooling material must therefore be harder than the material used in the part.

Nearly all metals can be machined, although some do present particular problems. Machinability involves three general factors:

1. Ease of chip removal.

2. Ease of obtaining good surface finish.

3. Ease of obtaining good tool life.

Many of the high temperature alloys, for instance, fail to give good tool life due to their hardness and strength. In many cases, however, through experience and care, these materials have been made quite amenable to machining.

There is a wide variance in the machinability of metals. The following table lists the factors affecting machinability and points out the effect these factors have on machinability, finishability and tool life.

EFFECTS OF MATERIAL PROPERTIES
PROBABLE EFFECT OF DECREASE IN MATERIAL FACTOR

MATERIAL FACTOR	MACHINABILITY	FINISHABILITY	TOOL LIFE
Strength/Hardness	Improves	None	Improves
Ductility	Improves	Improves	Improves
Strain Hardenability	Improves	Improves	Improves
Coefficient of Friction	Improves	Improves	Improves
Heat Conductivity	None	None	Decreases
Heat Capacity	None	None	Decreases
Chemical Reactivity	None	Improves	Improves
Grain Size	Improves	Improves	Decreases
Abrasive Insolubles	Improves	Improves	Improves
Free-Machining Additions	Decreases	Decreases	Decreases

Available Facilities

Machining and milling has received broad application in the metalworking industry. While its application on shell type configurations has been confined to relatively small and highly symmetric parts, it has been especially suited for many other geometric configurations.

Facilities capable of handling parts in the size range of interest herein are not plentiful. Machining and milling have developed to their present position due to their excellent dimensional and surface finish control capabilities. This advantage is not realized when working large shell type parts. This results from the difficulty in holding the part rigid during the process. Any deformation of the part during machining will tend to move the shell away from or into the tool, resulting in a nonuniform cut. To prevent this, great care and attention to detail must be exercised, resulting in a prohibitively expensive process. Although there are a large number of machining and milling facilities in existence, only the following possess the capabilities of handling large size hemispheres.

Diversey Engineering Company
Chicago, Illinois

Merz Engineering Division
Indianapolis, Indiana

California General Inc.
Chula Vista, California

Electrada Corporation, Airite Division
Los Angeles, California

Dimensional Control

Quantitatively, machining and milling is capable of producing parts with tolerances of from ± 0.001 inches to ± 0.005 inches in normal applications. If necessary, tolerances as low as ± 0.0005 can be obtained. The application herein considered cannot be termed a "normal application" of the process due to the part size and therefore the dimensional control cannot be expected to be this good. Presently, it is estimated that tolerances of ± 0.005 to ± 0.010 inches would be minimal. With some development however, improvements could be reasonably expected.

Surface Finish

The surface finish quality of milled or machined parts is affected by many factors. Normally, a material that machines easily will be characterized by smooth surfaces and vice versa.

Generally, a highly ductile metal is more difficult to machine and the machined surface is comparably rough. Highly ductile material tends to be gummy or stringy when machined, and as a result the metal "tears" from the surface rather than being cleanly cut. Thus, the "as machined" surface will contain voids when the metal has torn out.

Since a harder material is more machinable, surface finishes can be improved by heat treating or cold working a part prior to machining.

A rather smooth "as machined" surface can be realized for most metals, with the surface finish varying from 5 to 60 microinches RMS. Of the metals being given the most emphasis in this study, magnesium and titanium can be expected to give "excellent" surface finishes of about 25 RMS or better. Aluminum will give a somewhat inferior finish depending on the alloy.

Advantages - Disadvantages

Machining and milling have received broader applications than perhaps any other forming or finishing process. This results from several of the advantages demonstrated by the process when compared to other processes. In the application considered herein, these advantages are not felt in their entirety. Listed below are the advantages and disadvantages of these processes as related to this application.

ADVANTAGES

PART SIZE: The machining and milling processes are capable of handling parts as large as those of interest herein. Though parts of this size are not common to the process, some experience is available.

PART SHAPE: The forming of parts by the mechanical removal of material is very versatile with respect to part shape. In general, the process is most amenable to simple, highly symmetric shapes, but through specialized types of machining or milling processes, nearly any shape can be sucessfully worked.

DIMENSIONAL CONTROL: Machining and milling are capable of supplying parts with excellent geometric and thickness control when compared to most competing processes. Though special care may be necessary in a particular case, this statement is valid for nearly all part sizes and shapes.

FORMABLE MATERIALS: Nearly any metal can be worked with these processes, though some are better suited than others. In general, the process has little or no effect upon the properties of the material being worked.

DISADVANTAGES

PROCESS TIME: Due primarily to the predicted extremely long lead time, total process time can be expected to be somewhat long in comparison to most other processes. This disadvantage is emphasized by the necessity of holding tight tolerances and by part complexity and size.

AVAILABLE FACILITIES: Due to the rather small demand for machining parts of the size and shape of interest, few subcontracting facilities are interested in this type of job.

CHEMICAL MILLING

Chemical milling is recognized as a special type of finishing because of its variety of capabilities, Through this process, it is possible to control the selective chemical dissolution of metal at planned areas. It is used to shape metals to an exacting tolerance, and provides a means of forming parts of light weight and/or high strength.

Process Description

Basically, chemical milling involves the submergence of a part into an erosive-type bath. The type of bath to be used for a particular application is dependent on the material. It may either be a caustic or acid bath. The etching rate (the depth of etch per unit time) is determined by the etchant bath properties, primarily concentration and temperature.

Since the etching of a particular part is in many cases selective, this is accomplished by masking the areas of the part not subject to milling. Several types of rubber that are impervious to the effects of the etchant are used as the maskant. Normally the entire part is coated with the maskant, after which the part is scrubbed and the maskant removed from the areas to be chemically milled.

This process is particularly suited to the production of shells or hemispheres. It can be used either for tapering sheet material or preformed blanks, or to uniformily reduce the thickness of shells. A continuous taper is provided by submerging the part into the etchant solution and withdrawing it at a constant rate. Thus, the area of the part which is submerged the longest will be the thinnest.

The taper normally cannot exceed 0.010 inches per lineal foot for most steels and 0.100 inches per lineal foot for aluminum. By varying the rate of withdrawal in a predetermined manner, varying, though continuous tapers can be produced. A stepped taper is produced by withdrawing the blank in discrete steps. This procedure is used to provide blanks or preforms which, during actual forming, will deform in the desired manner. Thus, for example, a part of constant wall thickness can be obtained by milling regions of the blank which will not be subject to a large amount of stretching and thinning.

There are several limitations on the size of the area to be etched. Although cuts of up to 2.0 inches in depth have been made in plate stock, the normal maximum is 0.500 inches. The maximum for forgings is 0.250 inches and 0.150 inches for extrusions. Land width (between cuts) must be twice the depth of cut, but never less than 0.125 inch. The width of the cut should be at least twice the depth plus .060 inches. These limitations are present to allow normal production tolerances to be held.

While chemical milling of most metals is possible, this process has been commonplace for aluminum, titanium, many grades of steel and exotic alloys.

Available Facilities

This process was developed and patented by North American Aviation and licensed by this company to Turco Products Incorporated. This company has in turn licensed other companies to perform chemical milling operations. As a result, there are few companies which do this type of work. Many of those which do exist are not active in milling parts of the size and range being considered.

Listed below are the companies which appear to have facilities capable of processing parts of large size.

1. Chemical Contour Corporation
   Gardena, California

2. Brooks & Perkins Incorporated
   Detroit, Michigan

3. Chem-tronics Inc.
   Santee, California

Each of these companies have the ability and experience to chemically mill parts much larger than needed in this application. In addition, they all have procedures and processes necessary for milling the metals which are of interest herein including aluminum, stainless steels, Inconel, titanium, magnesium and many of the exotic superalloys developed during the past several years.

Size and Shape Capabilities

Theoretically, there is no limit to the size of parts that can be chemically milled. However, from a practical standpoint there is a relationship between part size and the ability to hold tight tolerances. Thus, for the application being considered, the final tolerance will dictate size limitation.

In order to provide tolerances of the magnitude of interest herein, a high degree of bath temperature and composition uniformity is required. This necessitates a well controlled bath heating system and a high degree of agitation of the etchant. Although not common practice, good results have been obtained on parts of this size and it may be expected that, with sufficient care, close tolerances could also be obtained on hemispheres and cylinders.

While chemical milling is very versatile, there are limitations on the shape of parts that can be milled. These limitations generally result from the inability to insure a high degree of agitation of the etchant bath on certain areas of a part. For instance, deep and/or narrow recesses, grooves and undercut corners cannot be reproduced through chemical milling. Since none of these conditions exist with spheres or cylinders, this process could be used to improve dimensional control, effect weight reduction, or increase the quality of the surface finish on preformed parts.

Dimensional Control

There is a wide variance in the degree of dimensional control that can be obtained by chemical milling. The following factors directly affect the degree of control.

1. Blank or preform tolerances.
2. Blank or preform material.
3. Etchant type.
4. Bath control.
5. Part shape and size.
6. Amount of etching.

The factor that most affects the tolerances on chemically milled parts is the depth of cut. For steel and titanium, tolerances of $\pm$ 0.010 inches are standard for etch depths of over 0.100 inches. For lower etch depths, tolerances as low as $\pm$ 0.003 inches are unusual. For aluminum and magnesium, the tolerances normally encountered are $\pm$ 0.006 inches or less for cuts up to 0.500 inches deep. Chemical milling tolerances can be improved by using premium or close tolerance stock, or by pre-grinding the stock. Using this procedure, and with special care throughout the process, tolerances of ± 0.002 inches or less can be obtained on most materials when making cuts of depths up to 0.500 inch.

If stretch forming, machining or forging precedes the chemical milling process, additional tolerance of ± 0.001, ± 0.005 or ± 0.015 respectively, must be added to the above tolerances.

Surface Finish

Ideally, it would be expected that chemical milling removes a uniform thickness of metal and that surface imperfections would be reproduced. Contrarily, however, the surface finish can either be improved or degraded.

The primary influencing factor is the part material and condition. Of secondary importance are the type of etchant used and the etch depth.

The following surface finishes can be expected.

ALUMINUM - the surface finish will generally be from 70-160 microinches RMS depending primarily upon the alloy and depth of the cut. For etch depths up to 0.250 inches, the finish will be from 70-125 RMS with an average of about 90 RMS, while for depths up to 0.500 inches, the higher numbers will apply, averaging about 115 RMS. These numbers assume that the blank surface is of about the same quality since surface imperfections in aluminum are reproduced, but not enlarged. If a better blank surface is assumed, correspondingly better finished part surfaces can be expected.

MAGNESIUM - a smooth shiny surface finish varying from about 30-70 microinches RMS can be expected. The average will be about 50 RMS. In this case, chemical milling improves the surface finish of the blank. This is due to the tendency of the process to "wash-out" the imperfections. The greater the depth of cut which is used, the more improved will be the finish of the milled part over the blank.

TITANIUM - the chemically milled surface finish on titanium is quite smooth and shiny, being about 15-50 microinches RMS, the average being about 25.

Process Time

Due to the minimal tooling requirements, lead time is very short. In many cases, the template used to trim the maskant can be produced in a few hours.

Since there is no mating or matching of tools, or aligning of tools and part, set up time is very short. The maskant is trimmed using the template as a pattern, and while scribing the maskant is a critical process it can be performed quite rapidly by a skilled, experienced worker.

While the actual milling rate is quite slow, the amount of time the part spends in the bath is short. The most time consuming portion of the process is obtaining part dimensions between etching steps.

With all time factors taken into consideration, chemical milling rates favorably as a finishing process.

Advantages - Disadvantages

Due to its increased application in the aerospace field, chemical milling has received considerable attention in recent years. As with all processes, it has its advantages and disadvantages. These are discussed below.

ADVANTAGES

PROCESS FLEXIBILITY: The chemical milling process is applicable to nearly any job for which machining can be used. In addition, many jobs which can be performed by machining only at extremely high cost, are simply and easily done by chemical milling. An excellent example of this is the forming of integral stiffening ribs on a spherical shell.

PART SIZE: There are, at present, facilities available for milling parts of much larger size than necessary in this context. In addition, considerable experience is available on parts of this size.

FORMABLE MATERIALS: Nearly all metals are capable of being chemically milled. Due to the nature of the process, the metal need not display any particular properties (such as ductility or machinability), but must be consistent and free of pits or voids. The only limitation upon the material to be chemically milled is the availability of an etchant which will dissolve the metal in the proper manner.

COST: Chemical milling of a part is, in general, much lower in cost than machining or milling by mechanical means. This is especially true of some of the applications for which the process could be used in this context. For instance, chemical milling of integral stiffening ribs into shperical shells would be quite low in cost when compared to machining.

PROCESS TIME: Due to the very short lead and set up time, chemical milling is very rapid for short run or prototype application. For large volume production however, the process time should be quite similar to mechanical processes.

SURFACE FINISH: On some metals, notably magnesium, the chemical milling process will "wash out" surface imperfections, thereby resulting in an improved surface finish after processing.

DIMENSIONAL CONTROL: With adequate care and suitable processing procedure, tight tolerances can be held on chemically milled parts.

DISADVANTAGES

SURFACE ROUGHNESS: Any uneveness in the surface or thichness of a blank or preform will be reproduced on the finished part. In addition, the surface of some materials will be somewhat degraded by the chemical milling process, resulting in a rough and uneven surface.

DEPTH OF CUT: Normally, it is undesirable to make cuts greater than 0.250 inch. In so doing, dimensional control is sacrificed.

SHAPE LIMITATIONS: Holes, deep narrow recesses, narrow lands, inside corners and "steep" tapers must be avoided since they are not amenable to chemical milling.

CHAPTER III

SUMMARY REVIEW

MATERIAL AND FORMING

RELATIVE COST OF PRESSURE VESSEL FABRICATION

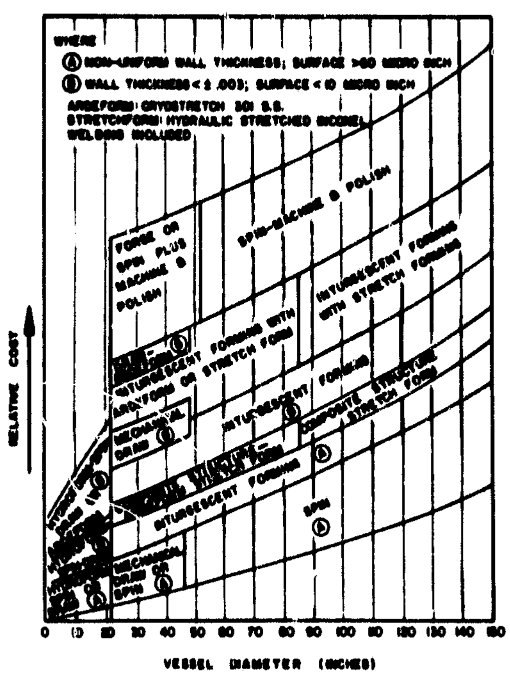


FIGURE 3-1

RELATIVE TOOLING COST FOR THE VARIOUS STEPS USED IN PRESSURE VESSEL FABRICATION

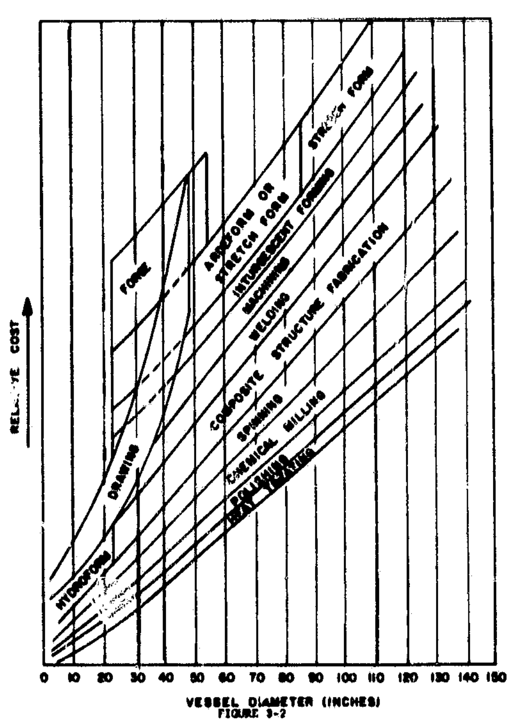


FIGURE 3-2

The previous chapters have been devoted to highlighting those features that were unique to the various metals and forming processes under consideration for cryogenic gas storage systems.

This chapter is designed to compare those factors that have a basic commonality for each process and/or material. In addition, those factors influencing the choice of a particular process or material are further discussed.

Cost Comparison

Due to the significant variations in cost due to material, quantity, size, quality control, tolerances, and recurrence factors, the costs for the various forming techniques are presented as relative values rather than as fixed dollars.

Figure 3-1 at left shows the relative fabrication cost of forming processes and combinations of forming processes which can be used to produce a pressure vessel. Also incorporated in this figure is an estimate of the cost variation due to uniform wall thickness and surface finish variations. Figure 3-2 shows the relative tooling cost for some of the steps used in pressure vessel fabrication.

Figures 3-3 and 3-4 on the last page of this chapter show the relative tooling and hemisphere costs to form one hemisphere by four of the more prominent forming techniques. The Ardeform process does not appear since this technique is not classified as a forming process, but more realistically a sizing-strengthening process used to stretch undersized vessels. Hydroforming is also not shown since no machines exist to form parts of the desired size range.

While these cost curves were obtained by adjusting quotations received during the 1962-1966 period, they are considered to be realistic for depicting comparative costs.

Material Comparison

In selecting material for shell applications, it is necessary to evaluate the formability of a material and its compatibility to a particular fabrication process.

The following table shows by fabricating technique the formability rating of those materials considered as the most logical candidates for cryogenic tankage usage. The nomenclature used in the table to indicate process capabilities and formability rating is given below the table.

FORMABILITY RATING:

1. Good
2. Fair
3. Poor

MATERIAL - FORMABILITY

FORMING PROCESS	INCONEL X-750	INCONEL 718	STAINLESS STEEL 301	STAINLESS STEEL 304	STAINLESS STEEL 304-L	Ti (Pure)	Ni Steels	Al 6061-0	COMMENTS*
Arde-Forming	E	E	A^*_1	E	E	E	E	E	301 modified-spec. AES-256, AES-252
Hydroforming	E	B	B	B	B	E	E	B	
Forging	B_1	B_2	C	C	C	C	C_2	E	
Spinning	C	C	A^*_2	A^*_2	A^*_2	B	E	A^*_1	Surface Finish 200
Inturg. Forming	A	A	A	A	A	E	E	A_1	
Mach. & Milling	B_2	B_2	B_2	B_2	A_2	B	B	B	
Chem. Milling *	C_1	E	E	C_1	C_1	A_1	E	A_1	Used as a finishing technique
Electroforming	E	E	D	D	D	D^*_2	E	C^*_2	Dangerous because of bath solutions
Explosive Forming	C_2	E	C_3	C_1	C_1	D_3	C_2	A_1	
Magnetic Forming	E	E	E	E	E	D*	E	B	Formed @ elevated temperature
Electro-Hydraulic Forming	E	E	C	C	C	C	E	A	

A: Process capable of forming material into desired shape and size with current facilities.
B: Process capable of forming material into desired shape but not desired size.
C: Process capable of forming material but no information on shapes and sizes.
D: Process has been used to form material on an experimental basis.
E: No information available.

Change Response

All dimensional or quantity changes have a varying degree of affect on part delivery. Ardeforming is probably the least affected by dimensional changes since any variations are compensated for by merely increasing or decreasing the forming pressure to correspond with the dimension change.

The rough forming processes, such as forging and spinning, are also relatively unaffected by dimensional changes since they do not require tool changes. Conversely, such processes as hydroforming, inturgescent forming and explosive forming must undergo tooling modification to meet size changes. The length of delay required by these modifications is based on the extent of change and can involve as much as the original tooling lead time for major changes.

Ardeforming is most affected by quantity changes due to its rigid material specifications and material testing requirements. Otherwise, for quantity increases, the response of the techniques is dependent on the type of material being used and its availability.

Summary

The table at the top of the following has been developed to present an overall comparative rating of the process factors for each of the forming processes discussed in Chapter II. Quality points are assigned which describe the relative value of the process, according to the point code shown below the table.

Shell size capability was intentionally omitted from the preceding table, since this factor is very dependent upon the material being formed, shell thickness, and quantity and thus could not be adequately presented in the table. Therefore, the following Figure 3-5 is used to evaluate this factor for all forming techniques except magnetic and electroforming. They were omitted due to insufficient information.

Presented here is a graphical representation of the shell diameter-thickness combinations which can be made by the forming techniques for five possible shell materials. Shell thickness, is based upon forming stainless steel 304. The thicknesses corresponding to the other materials are obtained by using the conversion factors given below the graph. The information in this figure is based upon the available knowledge of previously formed shells, existing process physical

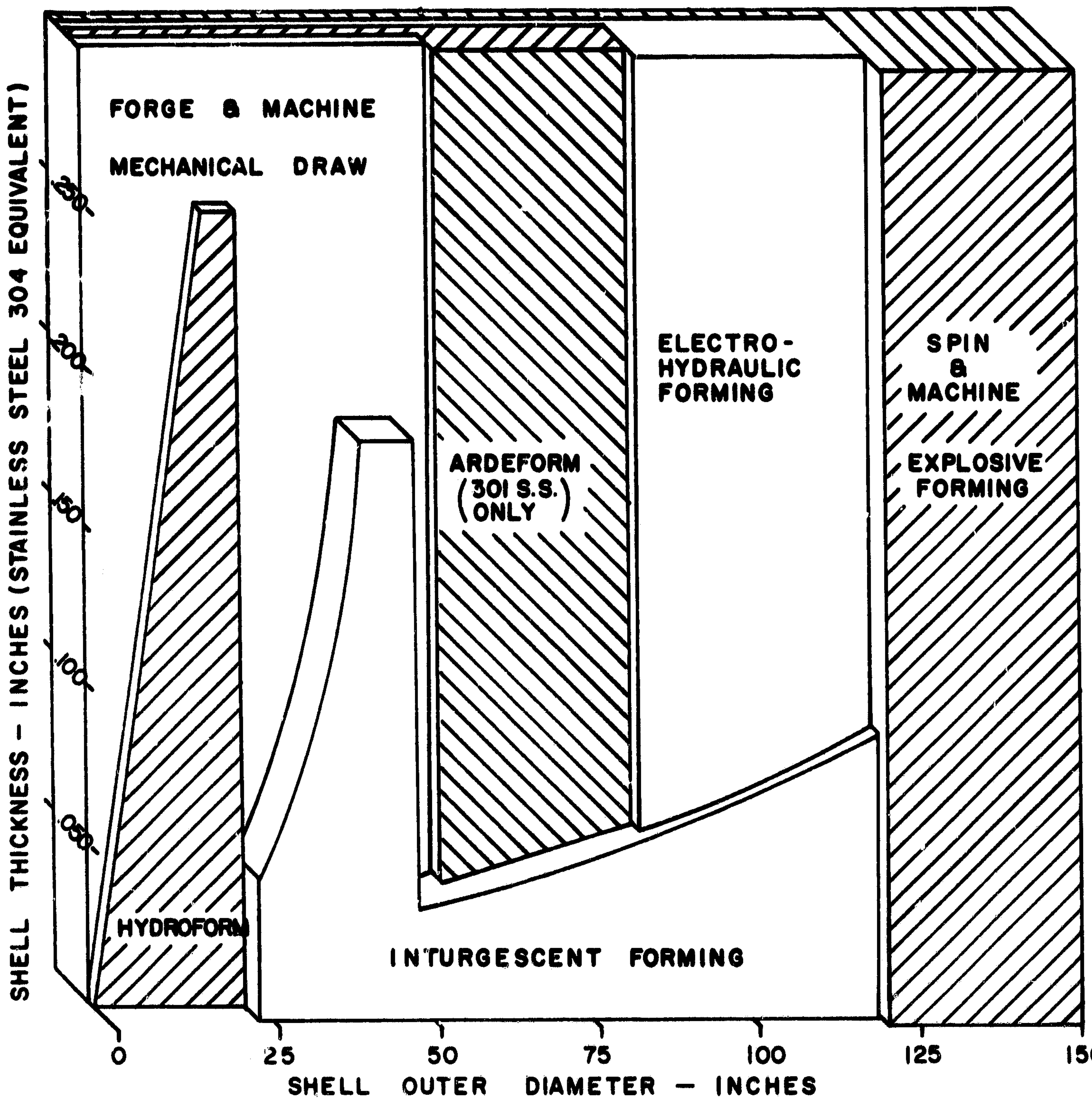
RATING OF PROCESS FACTORS FOR FORMING PROCESSES

FORMING PROCESSES

PROCESS FACTORS	POINT CODE	ARDEFORM	MECHANICAL DRAW	HYDROFORM	INTURGESCENT FORM	FORGE & MACHINE	SPIN & MACHINE	ELECTROFORM	EXPLOSIVE FORM	MAGNETIC FORM	ELECTROHYDRAULIC FORM
Vessel Strength to Weight	c	4.0	3.0	3.0	3.0	2.0	3.0	1.0	2.0	2.0	2.0
Discontinuity Stress	b	4.0	2.8	3.0	3.0	3.5	3.0	3.5	3.0	3.0	3.0
Dimensional Control	a	2.8	3.0	3.0	3.0	3.5	3.5	3.0	2.5	2.5	2.5
Surface Finish as Formed	a	3.0	2.8	3.0	3.0	2.5	2.5	3.0	3.0	3.0	3.0
Existing Facilities	a	1.0	2.5	2.0	2.0	3.0	2.5	2.0	1.0	2.0	1.0
Development Required for 39" Dia. Part	b	3.0	3.0	1.0	3.0	2.5	2.5	1.0	1.5	1.0	1.0
Productibility	a	2.0	2.0	2.0	3.0	2.5	3.0	2.0	1.5	1.0	1.5
Material Usage	c	2.5	3.0	3.0	3.5	1.0	1.5	4.0	3.0	3.0	3.0
Material Formability	a	2.0	3.0	3.0	3.0	3.0	3.5	1.0	1.0	1.0	1.0
Change Response	a	2.5	2.0	2.0	2.5	3.0	3.0	1.5	1.5	1.5	1.5
Prior Applications	c	2.5	3.5	3.5	1.5	2.5	2.5	1.0	1.0	1.0	1.0
Process State of Art	c	3.5	4.0	4.0	3.0	4.0	3.5	3.0	2.0	2.5	2.0
Shape Capabilities	a	3.5	3.0	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.5
Delivery Time	a	2.5	3.0	3.5	3.5	2.5	3.0	2.0	2.0	1.0	2.0
Supplemental Operations Required	b	3.8	3.2	3.5	3.5	3.0	3.0	3.0	3.2	3.0	3.2
Inherent Quality Control Due to Processing	c	4.0	3.5	3.5	3.8	2.2	2.0	1.5	3.0	1.5	3.0
Weld Failure Susceptability	b	4.0	3.5	3.5	3.5	3.8	3.5	3.8	3.5	3.0	3.5

	a	b	c
4	Excellent	Very Low	Very High
3	Good	Low	High
2	Fair	Medium High	Medium Low
1	Poor	High	Low

PROCESS SPHERICAL VESSEL SIZE & MATERIAL THICKNESS CAPABILITIES FOR FIVE SHELL MATERIALS



CONVERSION FACTORS

STAINLESS STEEL 304	— 1.0
ALUMINIUM 6061	— 1.9
INCONEL 718	—0.6
STAINLESS STEEL 301	—0.7
STAINLESS STEEL 321	—0.97

Figure 3-5

size limitations and/or power capacities of the forming processes. It is emphasized again that the Ardeform process is not a shell forming process but a sizing or enlarging operation which stretches a completed vessel to the desired geometry and dimensions.

HEMISPHERE PART PRICE AS A FUNCTION OF HEMISPHERE INTERNAL DIAMETER

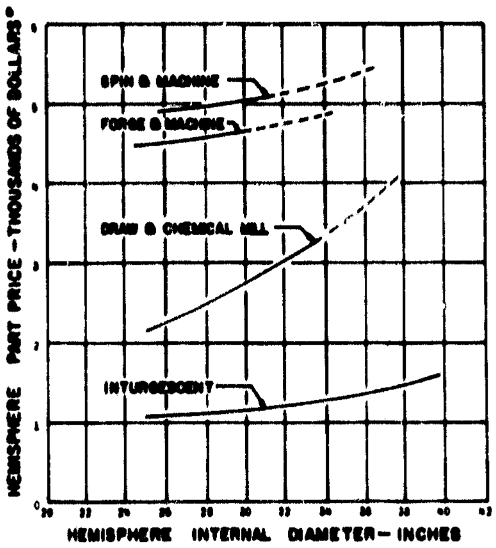


FIGURE 5-3 *BEST ESTIMATE COST

TOOLING COST AS A FUNCTION OF HEMISPHERE INTERNAL DIAMETER

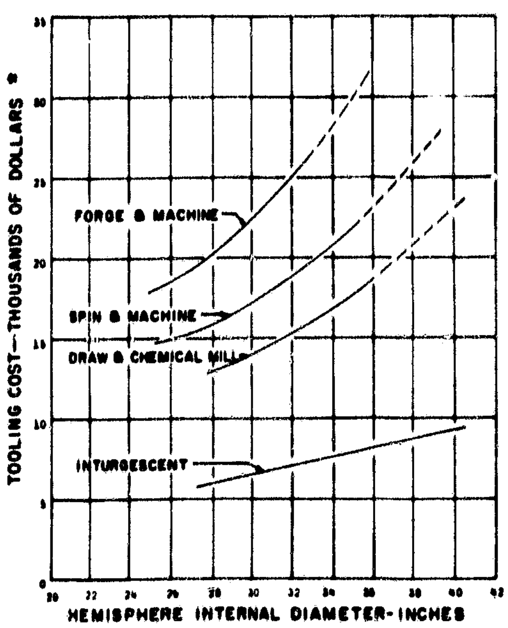


FIGURE 5-4 *BEST ESTIMATE COST

CHAPTER IV

PRESSURE VESSEL CHARACTERISTICS

The integrity of a pressure vessel is governed by the design parameters used for the intended service environment, the inherent properties of the materials used in its construction and the techniques of manufacture used in the fabrication and assembly process.

Generally, cryogenic pressure vessels are fabricated by weld assembly of suitable shell pieces, and usually contain components, bosses, fluid and electrical lines. Basically, there are three pressure vessel design approaches used to fabricate a vessel. These approaches provide criteria for component design and assembly. The three approaches are described as follows:

1. Minimum Boss Discontinuity:

   This design approach is concerned with fabricating the completed pressure vessel such that the minimum discontinuity is produced at the pole region of the vessel, i.e. the area where the fluid and electrical lines protrude from the vessel. To minimize the discontinuity in this region, the bosses for these lines are made as small as possible either integral with the hemisphere or welded into the hemisphere prior to heat-treat strengthening. The internal components are assembled into the hemisphere prior to girth welding. Since heat treating for strength is performed in the hemisphere stage, a suitable girth weld land is required for girth strength due to the localized annealing effects from welding.

2. Minimum Girth Weld Discontinuity:

   This approach is the opposite of that above in that the vessel is made in such a manner that the girth junction will have minimum discontinuity instead of at the boss junction. Here the internal components are assembled into the vessel through a reasonably large boss opening after the hemispheres are welded together and the vessel is heat treated to strength. An increased weld land is provided in the fitting-boss region to account for the large access hole and the weakened material due to welding during vessel closure.

3. Stretch Forming for Optimum Strength Properties:

Stretch forming is a design approach which utilizes the maximum cold worked and/or age hardenable strength properties of a material. The technique consists of fabricating an undersized vessel and hydraulically stretching it to size. This process can be performed at room temperature on materials such as Inconel X-750, 718, stainless steel 301, 304 and 304-L, or at liquid nitrogen temperature on materials such as stainless steel 301. The undersized vessels, preforms, are generally of the following designs:

   a. Composite Structure: This preform consists of flat plate, conical and cylindrical sections welded together to form an undersized vessel.

   b. Similar Structure: This preform is of similar geometry as the desired vessel but is undersized.

Design Parameters

With regards to pressure vessel safety factors, it can be said that a safety factor is theoretically developed in a vessel by virtue of the engineering design, fabrication and test procedures established prior to actual vessel construction. These procedures are traditionally based upon a failure theory, either yield or ultimate material strength, such that when the system requirements specify, for example, a proof safety factor of 1.5 or a burst safety factor of 2.0, the fabrication and test procedures assure that 1.5 or 2.0 are the minimum real values for each vessel. Each vessel (100% of vessels) is tested to the minimum acceptable requirement, and in addition, 1 to 10% of the vessels are tested to destruction to prove the minimum burst requirement, depending upon the production rate and need for statistical evidence of control.

These type of procedures are empirical in nature and truly applicable only to static stress systems. Recent pressure vessel failures have occurred in Aerospace programs, while the vessels were operating within the acceptance test load limits. These vessels were manufactured to specifications that traditionally provided proof safety factors in the region of 1.3 - 1.5 thus casting doubts on the validity of the design theory under cyclic loading. It would appear, therefore, that the design safety factor no longer exists under a cyclic stress system. The reasons for this deterioration of physical properties in these vessels would appear to be associated with the inherent material properties and their mode of manufacture. It is imperative that an investigation is made of the properties of materials under cyclic loading conditions, with a view to establishing new design criteria for incorporation into engineering specifications. An attempt is made herein to evaluate these properties in a context of pressure vessel reliability, safety factors, and performance expectations.

Properties of Materials

Investigation of low cycle fatigue failure mechanisms has indicated that failure initiates by the growth of voids (dislocation coalescence) in the structure. Micro cracks then form at these voids, ultimately linking up and resulting in failure. It is believed that the presence of stress raises, such as surface seams, stringer inclusions and voids will aid generation of micro cracks and accelerate failure. Material finish and cleanliness are thus considered to be highly important in determining vessel life expectation.

It is generally accepted that materials which undergo extensive working operations, such as wire and sheet, are usually more homogeneous and free from defects than other wrought products. The extreme severity of the working operations destroys segregation of alloying elements, promotes homogeneous grain structure and usually induces surface tears or complete failure if defects such as seams, pipe, pits, laps or gross inclusions are present. Porosity and fusing will be at a minimum in sheet materials compared with other wrought products, because the high thickness reduction in rolling will promote welding up of such defects by atomic diffusion.

Tests on forged and rolled plate specimens have revealed a significant tendency to surface discontinuity and porosity in the forged specimens after straining. Little evidence has ever been found of this occurring in rolled sheet or plate specimens. Thus rolled sheet material appears to offer the best potential fatigue properties over all others for formation into hemispheres. No other basic vessel fabrication process offers such inherent material quality.

After consideration of the importance of intrinsic material properties in assuring high quality pressure vessels, the forming technique must be evaluated on the basis of such factors as strength to weight, and vacuum characteristics. The relationship of these factors to pressure vessel fabrication are discussed in greater depth in the succeeding paragraphs.

Strength to Weight

In the design of a pressure vessel, the ultimate goal is to determine the material and fabrication process that will result in the optimum strength to weight ratio for the vessel.

Except for the Ardeformed vessel, the maximum strength of a vessel is ultimately determined by the annealed or annealed and aged properties of the materials. The thickness, inner diameter dimension and material density measurements are used in calculating the weight of a vessel.

The table on the following page shows a weight breakdown of pressure vessels formed by the five most prominent forming processes as well as the effect of machining and milling, and chemical milling. A 39" I.D. spherical vessel is used in the weight analysis for both the oxygen and hydrogen applications. The calculations are based on the strength and thickness of the material in the shell region. The corresponding internal burst pressure loading for these two vessels is 2000 and 600 psi respectively.

As noted below the tables, weights indicated by an asterisk are based on annealed or annealed and aged material properties rather than the cold worked material properties. These weights are thus not truly representative of the pressure vessel formed from the material - process combination. Since no information is available on cold worked material properties, this added strength could not be taken into account for the present. The lesser strength employed in the calculations thus gives a vessel of larger weight than that obtained in reality. Comparison of vessel weight should thus be made with this fact in mind.

Vacuum Characteristics

Since all forming processes require a subsequent operation to obtain an outer surface finish more receptive to plating, vacuum characteristics are dependent on the vessel material rather than the forming process.

Of basic interest is the class of vacuum termed ultrahigh vacuum, which includes the pressure range of 1 x 10^{-7}

PRESSURE VESSEL WEIGHT FOR 600 PSI VESSEL

FORMING PROCESS	VESSEL - MATERIAL INCONEL X-750	718	STAINLESS STEEL 301	304	304-L	Al 6061
Arde-Forming	N.A.	N.A.	30.6	N.A.	N.A.	N.A.
Hydroforming	N.A.	42.5	67.1	89.6	89.6	75.6*
Forging	50.2*	43.2	73.0	100.8	100.8	N.A.
Spinning	N.A.	N.A.	67.1	89.6	89.6	75.6*
Inturgescent Forming	50.2*	42.5	67.1	89.6	89.6	75.6*
Machining & Milling	50.2	42.8	73.0	100.8	100.8	75.6
Chemical Milling	Finishing Process - No Material Strength Influence					

PRESSURE VESSEL WEIGHT FOR 2000 PSI VESSEL

FORMING PROCESS	VESSEL - MATERIALS INCONEL X-750	718	STAINLESS STEEL 301	304	304-L	Al 6061
Arde-Forming	N.A.	N.A.	102.3	N.A.	N.A.	N.A.
Hydroforming	N.A.	143.5	226.2	303.2	303.2	258.6*
Forging	168.9*	145.8	247.4	399.1	399.1	N.A.
Spinning	N.A.	N.A.	226.2	303.2	303.2	258.6*
Inturgescent Forming	168.9*	144.2	247.1	399.1	399.1	258.6*
Machining & Milling	168.9	144.2	247.1	399.1	399.1	258.6
Chemical Milling	Finishing Process - No Material Strength Influence					

N.A. - No information available on material properties and or process incapable of forming vessel shells.

* - No information on cold worked material properties - Based on annealed or annealed and aged properties.

torr*. The materials intended for this vacuum range must be scrupulously clean. Visual examination is not adequate. Gases may be adsorbed on the surfaces or adsorbed in the interior of the material forming the vacuum barrier. When the evacuation process (pump-down) is begun, the effects of these gases will become more important. At first the regular atmospheric gas will be pumped from the space which is to contain the vacuum. When the pressure approaches the vapor pressure of the contamirants within the system, then the pressure will drop more slowly, the rate depending on the nature and extent of the contaminants. The contaminants, such as water vapor, greases, oils, solder fluxes, etc., which are evolved (outgassed) from the material under the vacuum stem from three sources: evaporation (or chemical decomposition), desorption from the surfaces and diffusion out of the material. The amount of sorbed contaminants released from the surfaces and from the interior of a material will vary widely with the type of material and with its history.

Two important properties to consider when analyzing the behavior of material during evacuation are permeability and vapor pressure. The material permeability to gases, i.e., the ease with which gases pass through it, determines an approximate possible contamination and a relative ease of removal. The vapor pressure of a material is the pressure which exists when the material is in equilibrium with its own vapor, i.e., vapor from chemical decomposition. The vapor pressure of a material is a function of the substance and the temperature. Increasing the temperature of the material increases the vapor pressure. For ultrahigh vacuum, it is thus desirable to minimize those materials which have high vapor pressures since these will degrade the vacuum.

It has been found from experience and/or experiment that materials presently being used or considered for pressure vessels exhibit very low vapor pressure and are therefore not considered detrimental to the quality and integrity of the vacuum obtained.

* One torr is the pressure exerted by a column of mercury one millimeter high at 0°C, 45° latitude at sea level.

Summary

As the preceding pages have indicated, all of the various design approaches present criteria for pressure vessel construction that can be achieved more readily by using one specific forming process than another. The following two-page foldout table shows the forming processes and the design approaches for which the process is most advantageous. The design approach for which each forming process is most applicable is used to delineate the major steps of each process and the subsequent fabrication of a pressure vessel from the component parts. The table also shows the attributes which are most outstanding for the forming or finishing process.

TABLE[...]
DESIGN APPROAC[...]
PROCESSING & VESSEL FABRICATION [...]

FORMING PROCESS	MOST APPLICABLE DESIGN APPROACHES	DESIGN APPROACH DELINEATED	MAJOR PROCESSIN[G ...]			
ARDEFORM (COMPOSITE)	#3—OPTIMUM STRENGTH PROPERTIES	#3	2-PT. 1-PT. CUT & TRIM FLAT SHEET STOCK 2-PT.	FORM DETAILS OF UNDER SIZE PREFORM	PRE-WELDING OPERATIONS a. HEAT TREAT b. MACHINE c. FITUP	WE[...] HEA[...] LEA[...] X-R[...]
ARDEFORM (SPHERICAL PREFORM)	#3 - OPTIMUM STRENGTH PROPERTIES	#3	CUT & TRIM FLAT SHEET STOCK	MECHANICALLY OR HYDRAULICALLY FORM SHELLS	TRIM SHELLS FORM FITTING FITUP	W[...] X-[...] HEA[...]
HYDROFORM	#1—MINIMUM BOSS DISCONTINUITY #2—MINIMUM GIRTH WELD DISCONTINUITY	#1	CUT BLANK CIRCLE FROM SHEET STOCK	FORM-HEAT TREAT ANNEAL TO FINAL SIZE	TRIM SHELLS FORM FITTING CUT FITTING HOLES	W[...] L[...] X[...] H[...]
FORGE & MACHINE	#1—MINIMUM BOSS DISCONTINUITY OR #2—MINIMUM GIRTH WELD DISCONTINUITY	#1	FORGE BLANK POSSIBLE STRESS-RELIEF & ANNEAL	ROUGH MACHINE CONTOUR MACHINE CHEMICAL MILL MACHINE PLUG HOLE WELD BOSS PLUG HEAT TREAT	INSERT INTERNAL COMPONENTS SILVER SOLDER LINES LEAK TEST	WE[...] X[...] LE[...] P[...]
SPIN & MACHINE	#1—MINIMUM BOSS DISCONTINUITY OR #2—MINIMUM GIRTH WELD DISCONTINUITY	#1	CUT BLANK CIRCLE FROM SHEET STOCK	ROUGH FORM POSSIBLE HEAT TREAT ANNEAL	CONTOUR MACHINE OR CHEMICAL MILL FORM FITTING CUT FITTING HOLE	WE[...] WE[...] LE[...] X-[...] HE[...]
INTURGESCENT FORMING	#2—MINIMUM GIRTH WELD DISCONTINUITY #1—MINIMUM BOSS DISCONTINUITY	#2	CUT BLANK CIRCLE FROM SHEET STOCK	FORM-HEAT TREAT ANNEAL	TRIM SHELL CUT FITTING HOLE FORM FITTING FITUP	W[...] W[...]
MACHINING & MILLING	——	——	NOT APPLICABLE—CONSIDERED AS FINISHING PROCESS			
CHEMICAL MILLING	——	——	NOT APPLICABLE—CONSIDERED AS FINISHING PROCESS			
ELECTROFORM	#1—MINIMUM BOSS DISCONTINUITY OR #2—MINIMUM GIRTH WELD DISCONTINUITY	#1	FORM ANODE FROM SHELL MATERIAL FORM MANDREL	FORM SHELL ON MANDREL STRESS RELIEVE MACHINE BOSS CONTOUR MACHINE OR CHEMICAL MILL	MACHINE PLUG HOLE WELD BOSS PLUG HEAT TREAT	IN[...] C[...] SILV[...] LEA[...]
EXPLOSIVE FORM	#2—MINIMUM GIRTH WELD DISCONTINUITY #1—MINIMUM BOSS DISCONTINUITY	#2	CUT BLANK CIRCLE FROM SHEET STOCK	FORM SHELL—HEAT TREAT ANNEAL TO SIZE	TRIM SHELLS FORM FITTING CUT FITTING HOLE FITUP	[...]
MAGNETIC FORM	#2—MINIMUM GIRTH WELD DISCONTINUITY #1—MINIMUM BOSS DISCONTINUITY	#2	CUT BLANK CIRCLE FROM SHEET STOCK	FORM SHELL—HEAT TREAT ANNEAL TO SIZE	TRIM SHELLS FORM FITTING CUT FITTING HOLE FITUP	[...]
ELECTRO-HYDRAULIC FORMING	#2—MINIMUM GIRTH WELD DISCONTINUITY #1—MINIMUM BOSS DISCONTINUITY	#2	CUT BLANK CIRCLE FROM SHEET STOCK	FORM SHELL—HEAT TREAT ANNEAL TO SIZE	TRIM SHELLS FORM FITTING CUT FITTING HOLE FITUP	[...]
MECHANICAL POLISHING	——	——	NOT APPLICABLE - CONSIDERED AS FINISHING PROCESS			

TABLE 2.2.11-2
PPROACH - FORMING PROCESS
RICATION STEPS FOR SPHERICAL PRESSURE VESSELS

OR PROCESSING & FABRICATION STEPS					ATTRIBUTES
NS	WELD PREFORM HEAT TREAT ANNEAL LEAK TEST X-RAY	CRYOGENIC STRETCH – HEAT TREAT ANNEAL TO FINAL SIZE	FINAL PROCEDURES a. HEAT TREAT AGE b. PROOF PRESSURE c. MACHINE BOSS	INSERT INTERNAL COMPONENTS WELD BOSS PLUG LEAK TEST PROOF TEST	EXTREMELY HIGH STRENGTH VESSEL REQ. HIGH QUALITY CONTROL FORM ONLY MODIFIED 301 S.S. VERY LITTLE STRESS DISCONTINUITY LONG INITIAL DELIVERY FORM EXTREMELY LARGE VESSELS OF VARIOUS GEOMETRY WITH EXISTING EQUIP.
LLS TING	WELD FITTING & SHELLS X-RAY HEAT TREAT ANNEAL	CRYOGENIC STRETCH – HEAT TREAT ANNEAL TO FINAL SIZE	FINAL PROCEDURES a. HEAT TREAT AGE b. PROOF PRESSURE c. MACHINE BOSS	INSERT INTERNAL COMPONENTS WELD BOSS PLUG LEAK TEST PROOF TEST	EXTREMELY HIGH STRENGTH VESSEL FORM ONLY MODIFIED 301 S.S. WAY TO ADAPT UNDERSIZE TOOLING LONG INITIAL DELIVERY FORM MEDIUM SIZE VESSELS
LES	WELD BOSS PLUG WELD FITTING LEAK TEST X-RAY HEAT TREAT AGE	INSERT INTERNAL COMPONENTS SILVER SOLDER LINES LEAK TEST	WELD HEMISPHERES TOGETHER X-RAY LEAK TEST PROOF TEST		22" DIA. MAX. SHELL SIZE CAPABLE OF FORMING MOST ALL MATERIALS GOOD DIMENSIONAL CONTROL HIGH MACHINE COST HIGH MATERIAL USAGE LOW TOOL & PIECE PART COST GOOD DELIVERY
ERNAL ENTS ER LINES EST	WELD HEMISPHERES TOGETHER X-RAY LEAK TEST PROOF TEST				INTEGRAL BOSS-FITTING NO REQ. INTERMEDIATE ANNEALING CYCLES MINIMIZED WELDING VERY LOW MATERIAL USAGE VERY LITTLE STRESS DISCONTINUITY LONG INITIAL DELIVERY HIGH COST
ACHINE MILL TING G HOLE	WELD BOSS PLUG WELD FITTING LEAK TEST X-RAY HEAT TREAT AGE	INSERT INTERNAL COMPONENTS SILVER SOLDER LINES LEAK TEST	WELD HEMISPHERES TOGETHER X-RAY LEAK TEST PROOF TEST		LOW MATERIAL USAGE CAPABLE OF FORMING MOST MATERIALS PRESENT EQUIPMENT CAPABLE OF FORMING 10 FT. DIA. SHELLS AS SPUN SURFACE & DIMENSIONAL CONTROL POOR GOOD DELIVERY
ELL G HOLE IG	WELD FITTING WELD SHELLS	FINAL PROCEDURES a. X-RAY b. LEAK TEST c. HEAT TREAT d. PROOF TEST	INSERT INTERNAL COMPONENTS WELD BOSS PLUG LEAK TEST PROOF TEST		FORM PARTS UP 120 IN. IN DIA. FORM VERY THIN WALL SHELLS FORMS MOST ALL MATERIALS GOOD TOLERANCE CONTROL HIGH MATERIAL USAGE RELATIVELY NEW PROCESS NOMINAL DELIVERY
					EXCELLENT GEOMETRIC & THICKNESS CONTROL ALL MATERIALS ARE APPLICABLE EXPERIENCE & EQUIPMENT IS AVAILABLE TO PROCESS VARIOUS SIZES & SHAPES HIGH COST
					NOMINAL DIMENSIONAL CONTROL NOMINAL COST ALL MATERIALS CAN BE PROCESSED EXPERIENCE EXISTS FOR THE PART SIZE
IG HOLE G PLUG REAT	INSERT INTERNAL COMPONENTS SILVER SOLDER LINES LEAK TEST	WELD HEMISPHERES TOGETHER X-RAY LEAK TEST PROOF TEST			INTEGRAL BOSS-FITTING MINIMIZED WELDING LOW STRENGTH AS FORMED GOOD INTERNAL & EXTERNAL SURFACE FINISH REQUIRES INTERNAL STRESS RELIEF PREVIOUS EXPERIENCE LIMITED TO SMALL PARTS
S NG G HOLE	WELD FITTING WELD SHELLS	FINAL PROCEDURES a. X-RAY b. LEAK TEST c. HEAT TREAT d. PROOF TEST	INSERT INTERNAL COMPONENTS WELD BOSS PLUG LEAK TEST PROOF TEST		FORM VERY LARGE DIAMETER SHELLS VERY POOR DIMENSIONAL CONTROL MOST ALL MATERIALS FORMABLE LACK OF EXPERIENCE & FACILITIES MOST APPLICABLE TO THICKWALL SHAPES
S NG G HOLE	WELD FITTING WELD SHELLS	FINAL PROCEDURES a. X-RAY b. LEAK TEST c. HEAT TREAT d. PROOF TEST	INSERT INTERNAL COMPONENTS WELD BOSS PLUG LEAK TEST PROOF TEST		CAN NOT FORM DESIRED SIZE OF SHELL USED EXPERIMENTALLY TO FORM SHAPE MAJOR APPLICATION HAS BEEN LIMITED TO SMALL PARTS
S NG G HOLE	WELD FITTING WELD SHELLS	FINAL PROCEDURES a. X-RAY b. LEAK TEST c. HEAT TREAT d. PROOF TEST	INSERT INTERNAL COMPONENTS WELD BOSS PLUG LEAK TEST PROOF TEST		PRESENT EQUIPMENT CAPABLE OF FORMING 4ft. DIA. SHELLS HIGH EQUIPMENT & DEVELOPMENTAL COST INEXPERIENCED AT FORMING MATERIALS & SIZE
					HIGH QUALITY "MECHANICAL" SURFACE FINISH LOW COST APPLICABLE TO ALL MATERIALS

CHAPTER V

OUTER SHELL CHARACTERISTICS

The outer shell is subject to the same material and forming requirements as specified in the previous chapter for pressure vessels. Thus, the design of an outer shell must take into consideration such factors as material and process formability, vacuum stability, weldability and plating. The reasons thereof, are basically similar to those previously enumerated for the pressure vessel.

During the course of designing and fabricating an outer shell, however, greater emphasis must be placed on its buckling strength and weight than heretofor discussed. In view of their importance to outer shell design, these factors will be discussed in greater depth in the following sections.

BUCKLING STRENGTH

While being treated separately for discussion purposes, in actual application buckling strength and weight must be considered simultaneously. For instance, for the materials considered in this study, Poisson's ratio has a near constant value of 0.3. The modulus of elasticity, however, varies from 10×10^6 for aluminum 6061 to about 30×10^6 psi for Inconel 718 and 304L Stainless Steel. Therefore, the latter two materials show a distinct buckling strength advantage. Conversely however, aluminum, with a density of .098 lb/in^3 is lighter.

Most references for calculating the critical value of the external buckling pressure on spheres refer to the following classical equation derived by Zoelly:

$$P = \frac{2\,E\,t^2}{R^2\sqrt{3(1-y^2)}}$$

where:

- P = External buckling pressure
- E = Modulus of elasticity
- t = Wall thickness of the shell
- R = Spherical radius
- y = Poisson's ratio

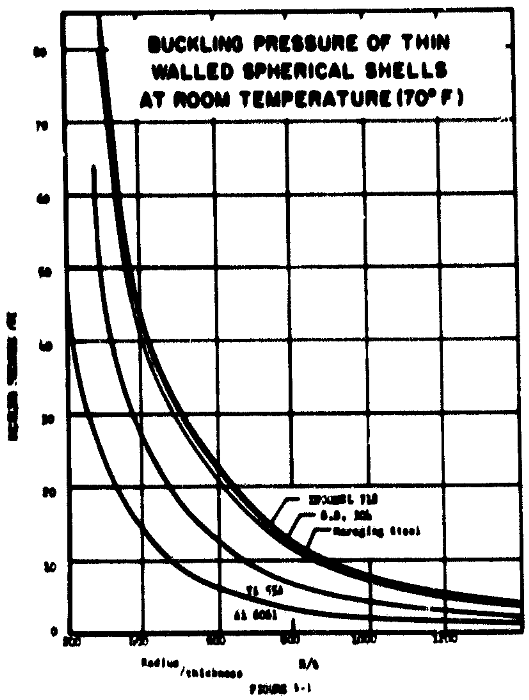
This equation is based on the ideal spherical shell. Many attempts have been made to modify the equation based on deviations from the ideal. However, results have been marginal.

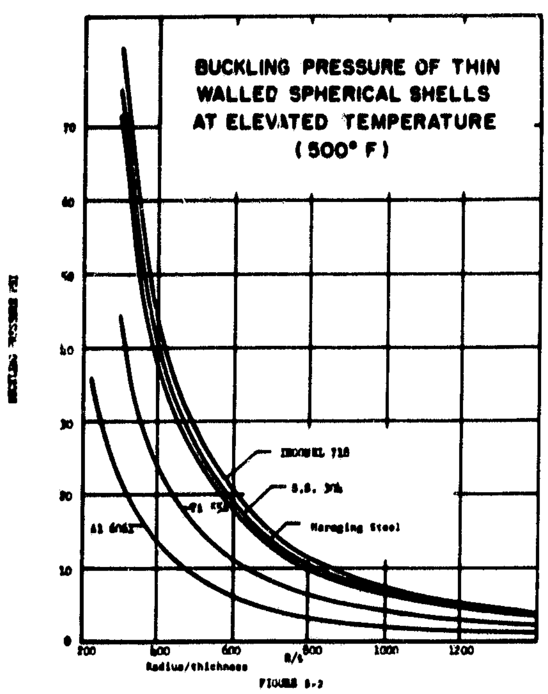
Experimental tests run at David Taylor Model Basin on accurate machined hemispheres and described in their report 1601 (ASTIA AD 278075) indicate that the critical external pressure at which the samples collapsed is from 53% to 69% of the value predicted by the Zoelly equation.

The Bendix Corporation has performed a series of buckling tests on hemispherical shells that were fabricated of aluminum and stainless steel. These shells were representative of the type and quality of shells used in a cryogenic tankage program. The results of these tests are summarized in the following table.

HEMISPHERE BUCKLING TESTS SUMMARY

TEST		1	2	3	4	5	6
Nominal Inside Diameter (2R)	in.	13.60	21.00	18.00	22.00	22.00	22.00
Nominal Wall Thickness (t)	in.	.0140	.0175	.0057	.0099	.010	.015
Material		Alum 1100	Alum 5052	SS AISI304	SS AISI304	SS AISI304	SS AISI304
Forming Process		Spun	Hydro-form	Intru-gescent	Hydro-form	Hydro-form	Hydro-form
Failure Pressure	PSI >	14.7	14.61	3.69	8.60	7.50	13.77
Zoelly Predicted Failure	PSI	51.40	34.00	14.00	28.50	29.00	64.50
Actual Failure / Zoelly Failure	>	.286	.430	.263	.302	.259	.214
R/t		485	600	1580	1111	1100	734
$E \times 10^{-6}$	PSI	10	10	29	29	29	29





As shown, the lower limit of actual failure occured at 21.4% of the value predicted by the Zoelly equation. This figure is therefore, considered a realistic value by which to miltiply the Zoelly prediction to give a pressure which will not result in buckling of the shell.

To establish a stable, high quality vacuum between the outer shell and the inner vessel of a cryogenic tank, the vessel must be evacuated at an elevated temperature to insure proper outgassing of the all vacuum exposed surfaces. The temperature at which evacuation is to be carried out is often as high as 500°F, and at this temperature, the modulus of elasticity decreases and must be taken into consideration.

This can be overcome by evacuating the region external to the shell during evacuation of the vessel at high temperatures, thus eliminating, or at least reducing the pressure differential across the shell during the period of minimum modulus of elasticity. This procedure is demanded if a weight optimization approach is being considered.

In cases where a weight penalty is admissible, an alternate method can be used. By using the value of the modulus of elasticity at the elevated temperature in the Zoelly equation, which has been multiplied by the aforementioned modification factor, a new value of t, the shell thickness, is calculated. This, of course, results in a shell with a considerably larger nominal wall thickness and subsequently, a greater weight.

The two figures at the left summarize the results of the preceding analysis. The top figure (5-1) is a plot of the P, the external buckling pressure, versus R/t, the ratio of the spherical radius to the shell thickness, as determined from the modified Zoelly equation (.214 Zoelly). The lower figure (5-2) is identical, except that the value of the modulus of elasticity at the elevated temperature has been taken into consideration. These test results were obtained by clamping the gerth of the hemisphere to a rigid plate which prevented any deformation at the gerth region as would occur on a spherical vessel.

CYLINDRICAL SHELLS

The classically derived equation for the critical pressure differential which will result in the buckling of a cylindrical shell is*

$$P = \frac{Et}{R}\,\frac{2}{2n^2 + (\pi R/L)^2}\left\{\frac{1}{[n^2\,(L/\pi R)^2 + 1]^2} + \frac{t^2}{12R^2\,(1-y^2)}\,[n^2 + \frac{\pi R}{L}\,2]^2\right.$$

where:

P = External buckling pressure
n = Number of circumferential lobes.
E = Modulus of elasticity
R = Cylincrical radius
t = Wall thickness
L = Cylindrical length
y = Poisson's ratio

A series of cylindrical shells have been collapsed by The Bendix Corp. to determine the extent of agreement between the predictions of the theoretical equation and emperical results. These cylinders were constructed from cold rolled steel sheets, formed into cylinders and butt-welded. The test fixture was such that the cylinder and plates were rigid and themselves would not buckle, thus requiring the collapse of the cylindrical section to which the theory applies. The results of this test are summarized in the following Table. As shown, the greatest error encountered in these tests was 23%. We must then modify the classical equation by multiplying it by the factor .77 to produce an equation applicable to actual shells. The modified equation is then used to determine the buckling pressure as a function of wall thickness, employing figure 5-3 to determine the number of lobes which will appear in the shell at the buckling pressure.

* Timoshenko, Theory of Elastic Stability, McGraw Hill Book Co., N. Y., 1936, Page 478.

CYLINDER BUCKLING TESTS
SUMMARY

TEST		1	2	3	4	5
Inside Diameter	in.	11.75	11.75	11.75	11.75	11.75
Wall Thickness	in.	.036	.031	.024	.021	.016
n = No. of Lobes at Failure			5	5	6	6
Actual Failure Pressure	PSI	14.7	13.1	6.4	5.1	2.1
Predicted Failure Pressure	PSI		13.4	7.2	5.3	2.6
Actual Failure Pressure / Predicted Failure Pressure			.98	.89	.96	.77
$t/D \times 10^3$		3.06	2.64	2.04	1.79	1.36

Material: Cold Rolled Steel

$$\frac{L}{D} = \frac{24 \text{ in}}{11.75 \text{ in}} = 2.04$$

$$E = 29 \times 10^6$$

NUMBER OF CIRCUMFERENTIAL LOBES INTO WHICH A THIN WALLED CYLINDRICAL SHELL WILL BUCKLE UNDER AN EXTERNAL PRESSURE

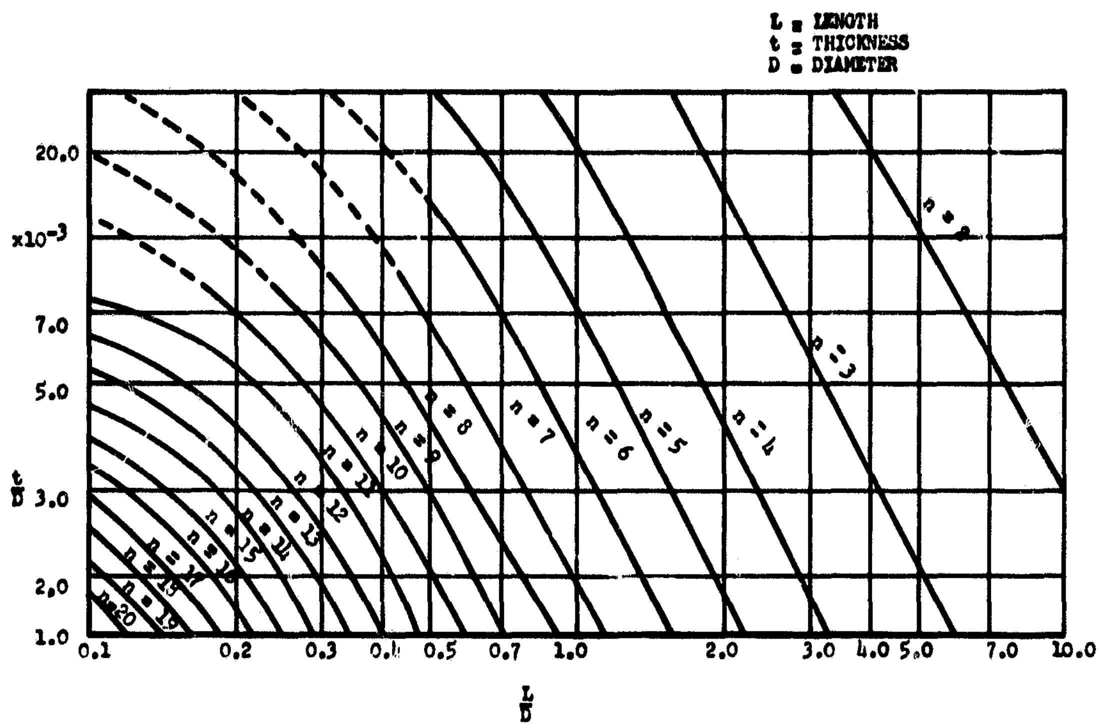


FIGURE 5-3

It is noted that this result was obtained from shells fabricated from cold rolled steel and it may not be justifiable for application to shells made from other materials.

Application of the theoretical equation is quite complicated, and for this reason, is limited.

In practice, the L/D ratio (length ÷ diameter) of the shell will be known, as will be the maximum pressure differential across the shell, and the material from which the shell will be fabricated. Given this information, it is desired to determine the shell thickness, t, which is necessary to prevent buckling. Solution of the theoretical equation gives the result

$$\frac{t}{D} = \left[X + (X^2 - Z^3)^{1/2}\right]^{1/3} + \left[X - (X^2 - Z^3)^{1/2}\right]^{1/3}$$

where

$$X = \frac{3P\ (L/D)^2\ [2n^2\ (L/D)^2 + (\pi/2)^2]\ (1 - y^2)}{8E\ [n^2\ (L/D)^2 + (\pi/2)^2]^{2}}$$

$$Z = \frac{(\pi/2)^4\ \ (L/D)^4}{3(1-y)^2\ [n^2\ (L/D)^2 + (\pi/2)^2]^{4}}$$

and the other factors are as previously defined.

The problem which arises in solving this equation is that n is a multivalued function of t/D, as shown in Figure 5-3. A computer program has been developed to solve the above equation by an iterative process.

The results of this analysis are shown in Figure 5-4. This figure shows the value of the ratio of the shell thickness to the shell diameter, (t/D), as a function of the ratio of the buckling pressure to the modulus of elasticity of the shell material, (P/E), for various values of L/D. This plot assumes that the value of Poisson's ratio is, y = 0.3. For the materials being considered, this approximation is quite valid and introduces a negligible error.

WEIGHT FACTORS

The weight of a spherical shell is given by

$$W = \rho v = \rho A t = \rho 4\pi R^2 t$$

BUCKLING PRESSURE OF A THIN WALLED CYLINDRICAL SHELL

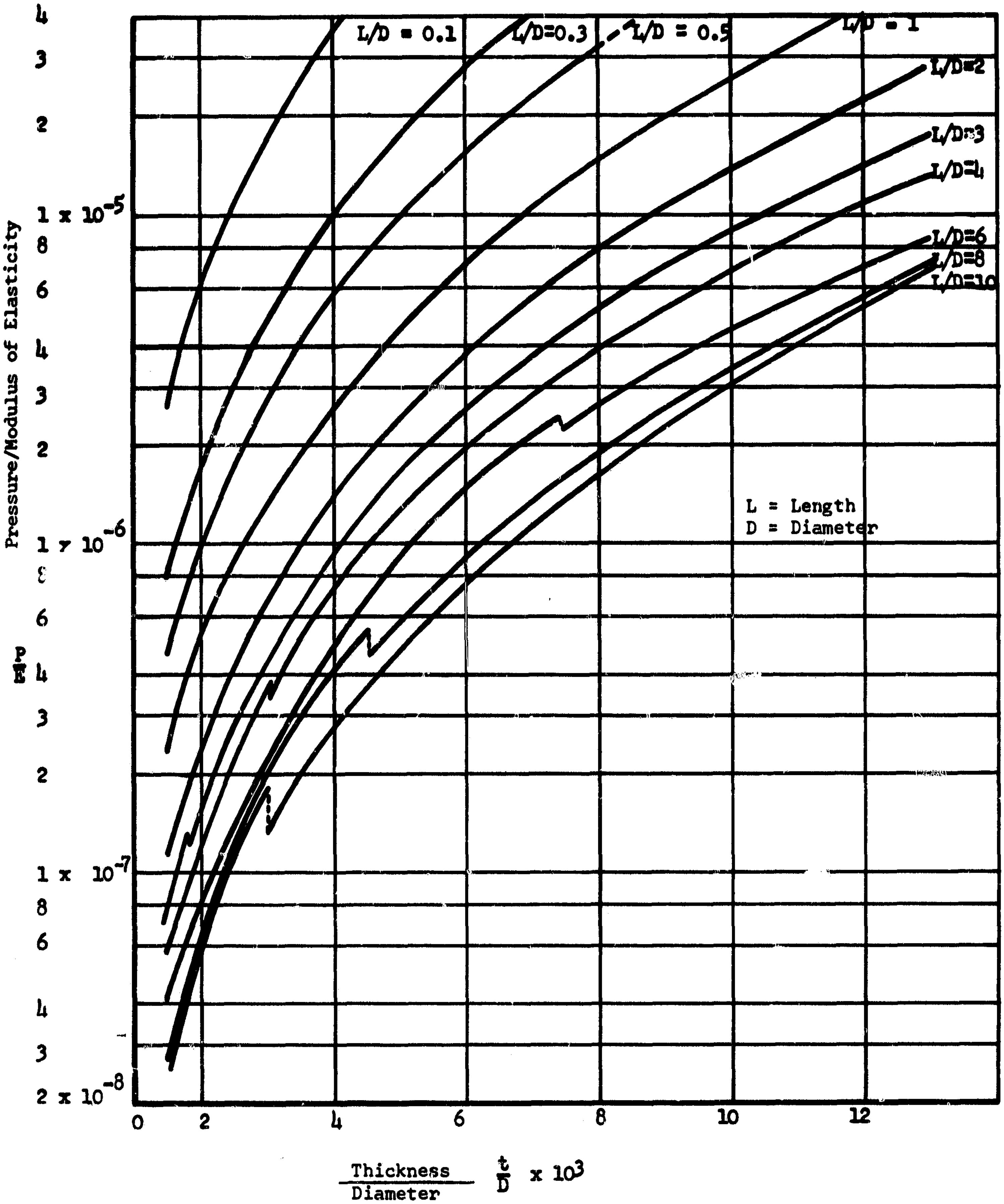


Figure 5-4

where

W = Shell weight
ρ = Material density
R = Spherical radius
t = Shell thickness
A = Surface area of shell
v = Material volume

An alternate form of the modified Zoelly equation which gives the shell thickness in terms of the known parameters is

$$t = R\left\{\frac{P\,[3(1-y^2)]^{1/2}}{.428E}\right\}^{1/2}$$

where

P = External pressure
y = Poisson's ratio
E = Modulus of elasticity
R = Spherical radius

This equation then gives the thickness of the shell which has a buckling pressure differential P.

Employing this result, the shell weight becomes

$$W = 4\pi\rho R^3\left\{\frac{P\,[3(1-y^2)]^{1/2}}{.428E}\right\}^{1/2} = 3\rho V\left\{\frac{P\,[3(1-y^2)]^{1/2}}{.428E}\right\}^{1/2}$$

where

V = Enclosed volume

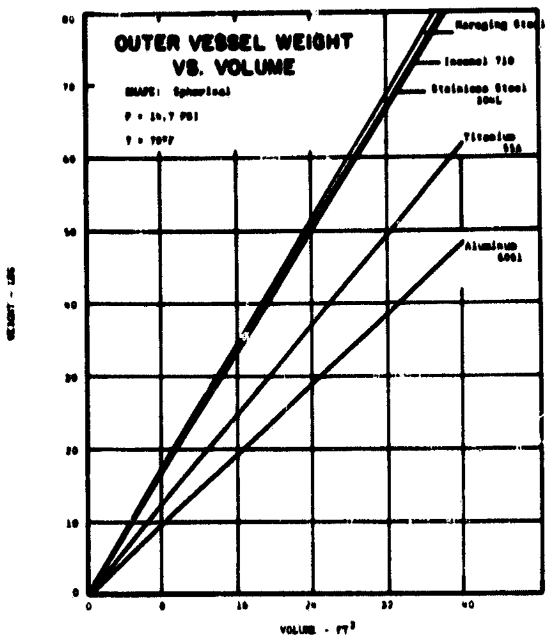
and the other factors are as previously defined.

The following table gives the values of the physical properties which appear in these equations for the various material being considered.

PHYSICAL PROPERTIES

Material	Density (ρ) lb/in^3	Modulus of Elasticity (E) x 10^6 PSI
Inconel 718	0.296	29.6
Stainless Steel 304L	0.290	29.0
Aluminum 55A	0.163	16.8
Maraging Steel	0.289	27.5

Figure 5-5 is a graphical comparison of the shell materials showing the weight of a spherical vessel as a function of its volume for a pressure differential of one atmosphere. As is shown, aluminum shows a definite weight advantage over the rest of the materials.



FIGURE

<u>Cylindrical Vessels</u>. The weight of a cylindrical shell with hemispherical ends is given by

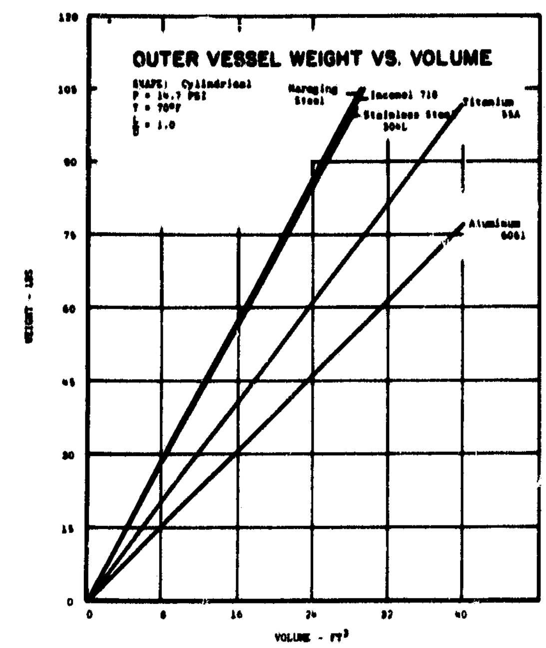
$$W = \rho v = \rho A_c t_c + \rho A_s t_s$$

$$= \rho[(\pi DL)t_c + (\pi D^2)\, t_s]$$

where

A_c = Cylinder surface area
A_s = Sphere surface area
t_c = Cylindrical shell thickness
t_s = Spherical shell thickness
ρ = Material density
D = Cylinder diameter
L = Cylinder length
V = Material volume

Figure 5-6 is a graphical comparison of shell materials showing the weight of a cylindrical vessel as a function of its volume for a pressure differential of one atmosphere.



FIGURE

SAFETY MARGINS

The method used to provide a margin of safety in the equations governing the shell weight is to multiply the predicted differential pressure maximum by the desired safety factor. This is then identical to predicting that the shell may be exposed to greater external pressures and thus results in a thicker and subsequently heavier shell.

The data plotted for Figures 5-5 and 5-6 was based upon one atmosphere 14.7 PSI. Figures 5-7 and 5-8 show the effect of adding a safety factor of 1.50.

As may be expected, increasing the safety factor requires a large sacrifice in weight. For a spherical aluminum vessel, a safety factor of 2.0 requires a shell which is more than 40% heavier than predicted, while a safety factor of 1.25 requires a shell only 12.5% heavier. For the other materials considered, the weight penalty is a greater percentage of the predicted weight which itself is higher than aluminum. For cylindrical vessels, these percentages increase even more, though following the same general trend; that is, the heavier materials

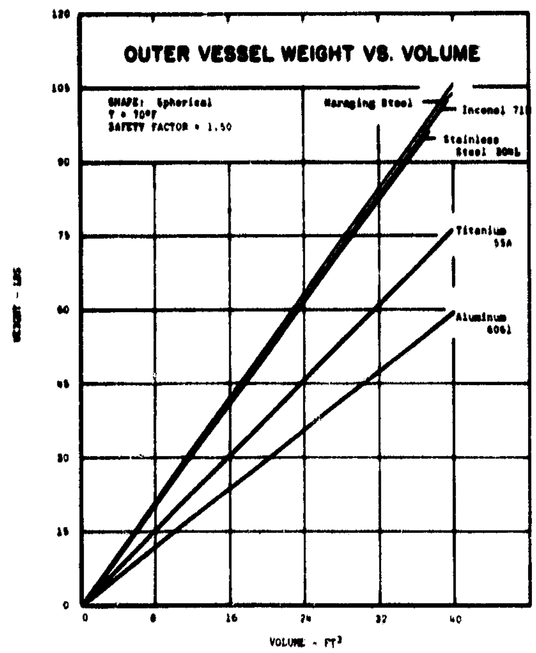


FIGURE 5-7

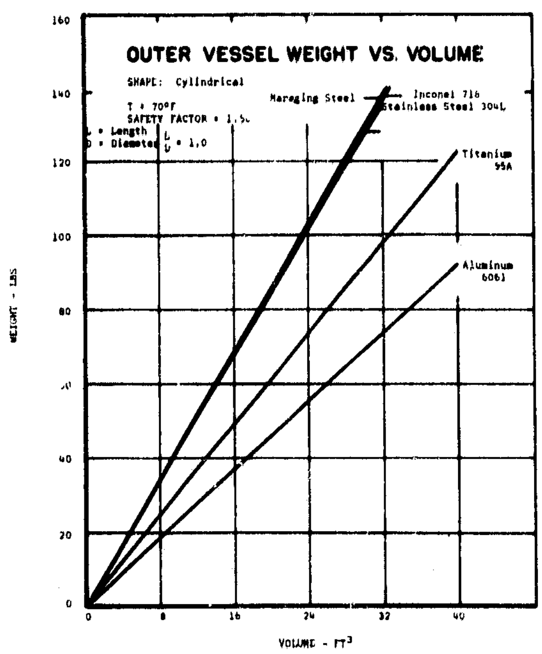


FIGURE 5-8

show a greater percentage weight penalty for a given safety factor than do the aluminum vessels.

CRITICAL PROCESSING

While the majority of the critical design and fabrication aspects of the outer shell have a basic commonality with the pressure vessel, there are two features that are primarily unique to the outer shell. These involve the shell openings and the loads placed on the shell by the inner vessel mounting arrangement.

The shell openings are necessary as passage ports for tubing and wiring, and thus create a need for welded fittings. These welded fittings act as major discontinuities in the shell which affect the buckling analysis.

Considerable theoretical work has been performed with marginal results. With the demands for weight optimized storage systems become more stringent, there is a great need for more complete buckling analyses that are experimentally verified to meet weight limitations.

All regions of the shell in which welding is necessary are potential trouble areas in the design of a shell. Welding causes the area around a weld joint to become annealed, and it is considered impractical to harden the shell after welding. Therefore, one alternative is to increase the shell thickness in the regions of the weld which would provide strength to resist buckling and give weight optimization. This would require a shell design wherein the thickness tapers away from the weld area.

The design technique for loads placed upon the shell by the inner vessel mounting system is dependent on the type of external mounting structure used. For instance, if an external mounting system is used wherein its areas of contact are identical to those of the inner vessel, the load is not carried by the shell itself and need not be designed to carry the load.

COST

As with the pressure vessel, no definitive statement can be made concerning outer shell cost because of the various design parameters involved. The degree of weight optimization and the type of insulation used are two factors that weigh heavily in the cost variance for outer shells.

CHAPTER VI

HONEYCOMB SANDWICH FABRICATION

As the overall size of outer shells become larger, they become increasingly vulnerable to buckling. While this could be compensated for by using heavier gage high strength material, this would concurrently result in a weight penalty.

Also, buckling of monolithic spheres is a function of their true sphericity, and any dents or surface irregularities of varying degrees will markedly increase buckling tendencies. To provide a safety factor to compensate for this danger would mean designing to a heavier shell thickness. As a result, the overall weight of the cryogenic storage vessel would be increased, rendering it neither practical nor economical for extended mission aerospace usage. It is for these reasons that construction of outer shells of the "honeycomb sandwich" design is considered a necessary evolutionary step in the development of aerospace cyrogenic tankage.

The previous chapter pointed out that aluminum possesses superior strength-to-weight qualities over the other material candidates for monolithic outer shells. By the same token, aluminum has proven to date to be the best skin (or facing) material for honeycomb sandwich outer shells. Commercially, aeroframe companies use aluminum skins, as well as aluminum honeycomb, when fabricating honeycomb sandwiches for wing sections, fuselages and other aircraft components.

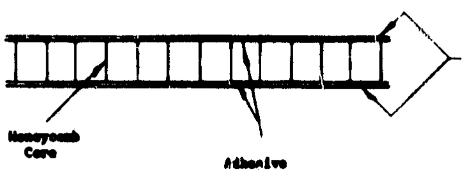
The following table shows that the buckling pressure to weight ratios for honeycomb spheres are larger than for monolithic spheres. Since the buckling of honeycomb aluminum spheres occurs in the inelastic range, the table cites both the upper and lower limits for buckling pressures and buckling pressure to weight ratios. The criteria for inelastic buckling is determined by the yield stress (lower) and the ultimate stress (upper) in the facing. Experimental results to date have shown the actual buckling pressure to fall midway between the upper and lower limits.

TABLE I

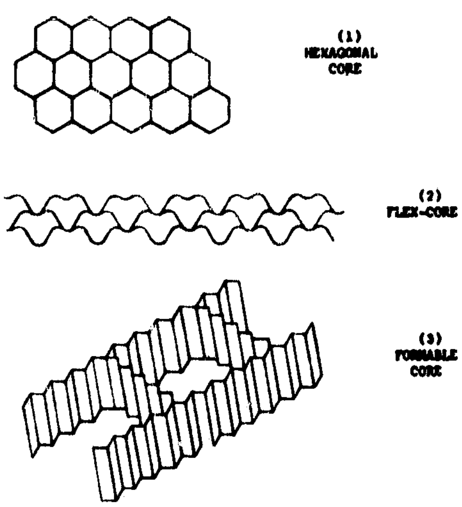
BUCKLING PRESSURE AND BUCKLING PRESSURE TO WEIGHT RATIO FOR ALUMINUM 6061 SPHERES MONOLITHIC VERSUS HONEYCOMB

CONSTANT RADIUS = 20"   CONSTANT CORE THICKNESS = 0.2"

Facing Thickness (Monolithic)	Buckling Pressure (Monolithic) PSI	Wt. Mono. Lbs.	Facing Thickness (Honeycomb)	Buckling Pressure Hnyco.-PSI	Wt. Hnyco. (Lbs.)	PCR/Wt. Mono.	PCR/Wt. (Hnycb.)
.02	2.7	10.0	.01	15 - 23	15.26	0.27	0.91-1.51
.04	10.3	20.0	.02	30 - 46	25.26	0.515	1.18-1.82
.10	64.0	50.0	.05	75 - 115	55.26	1.25	1.34-2.04



HONEYCOMB SANDWICH STRUCTURE



HONEYCOMB CORE GEOMETRY
FIGURE 2.4.2-2

Materials Adaptability

The three basic components in a honeycomb sandwich are the facings, core and adhesives.

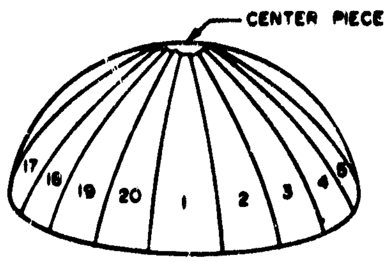
The "facing material" consists of the skins which are attached to the honeycomb core to make up the composite honeycomb structure. "Core" is defined as the honeycomb cell structure which makes up the heart of the honeycomb sandwich. "Adhesives" are the materials which bond the facings to the core. A simple honeycomb sandwich structure is shown in the upper left column. The three lower photos represent three of the most common designs of honeycomb core.

During the course of investigating the adaptability of honeycomb for outer shells, two hemispherical honeycomb sandwich structures were fabricated under contract for NASA-MSC. These hemispheres had a 25.82" inner diameter, a 26.36" outer diamter and weighed 6.2 lbs. each.

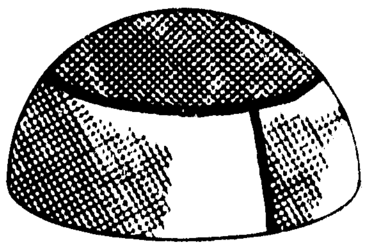
This honeycomb investigation involved numerous contacts with various material suppliers and the fabrication and testing of honeycomb sandwich samples using the various materials available. The remainder of this report is therefore based upon those materials and fabrication techniques that proved most adaptable.

Facing Material

In the selection of facing material, it is an utmost requirement that the material have excellent bonding characteristics. Aluminum was found to possess better



EPOXY FILM LAYUP USING SPHERICAL TRIANGLE SECTIONS



FLEX-CORE SPLICED AND ASSEMBLED TO HEMISPHERICAL FACING
FIGURE 2.4.7.2

surface characteristics than stainless steel due to its higher degree of etching. This etching is believed to be the reason that epoxies are more tenacious when used with aluminum. T-peel tests run on these materials showed the aluminum yielding approximately 19 lbs/in compared to 16 lbs/in for stainless steel. In addition to its better bonding characteristics, aluminum proved more favorable from the standpoints of availability, cost, relative ease of forming, corrosion resistance and strength to weight, and was thus selected as the facing material.

Core Material

Although there are a multitude of core materials, flex-core was chosen for this application since it is especially designed for lay-up over compound shapes. Flex-core is a registered trademark of the Hexcel Co. The configuration of flex-core is shown on the preceding page. Flex-core is available in various ribbon and core thicknesses. For this particular application, flex-core made from 5052 aluminum, with a 0.0019" ribbon thickness and 0.200" core thickness was used. This particular core material possessed typical shear strength values of 160 psi in the longitudinal or ribbon direction and 93 psi in the transverse or expended direction.

Core Splicing

During the course of fabricating a honeycomb sandwich, core splicing is usually necessary.

This is especially true of a honeycomb hemisphere as shown in the lower photo at left. Due to its previous favorable use by Bell Helicopter Co., Shell Epon 934 was used. Epon 934 has a thixotropic consistency when applied, and possesses high temperature strength properties after curing.

Bonding Compounds

Epoxy adhesives are considered as conventional material for honeycomb sandwich binding, especially when the core and facings are aluminum because of the temperature compatibility between the aluminum and the epoxy. Film epoxy was found to be more adaptable than paste epoxy.

Film epoxy is more readily controlled in the distribution of weight. It can be pre-cut and assembled in a more exacting manner and will not "run" when applied to a curved surface.

There are a great variety of epoxies available. For this particular application, the Minnesota Mining and Manufacturing Company's AF-111 was used because of its superior T-Peel strength. It has a density of 0.08 lb. per ft.^{2} and a thickness of 15 mils. It possesses a curing cycle of 250°F for one hour at 10 to 15 psi bonding pressure.

Epoxy adhesive film is easily applied to a hemisphere shape by cutting the epoxy film into spherical triangle segments and fitting to the facing to minimize wrinkling. It was found that great care had to be exercised, because any dimensional buildup affected final assembly. The photo upper left shows the layup of epoxy film.

Summary

The fabrication and testing program conducted on honeycomb hemispherical shells have helped establish the feasibility of honeycomb outer shells. While considerable progress has been made, further developmental work is necessary to achieve a honeycomb outer shell that possesses the ultimate strength and structural characteristics required for a cryogenic gas storage system.

Presently, the major problem areas involve improving the bonding strength between the epoxy film, facing and core material, and obtaining epoxy films capable of withstanding the high bakeout temperatures required in the fabrication of cryogenic storage systems.

CHAPTER VII

Insulations

There have been several insulation techniques, including various combinations, used in the design and development of cryogenic gas storage systems. The type of insulation, its effectiveness and compatibility, is contingent upon many factors governing the intended usage of the system. This chapter is therefore, designed to discuss briefly the most common insulation techniques and to highlight by way of comparison the applicability of the technique.

Laminar and powder insulations, discrete shields and vapor-cooled shields have received the broadest application. As the result of recent technology, a cryogenic filled-shield tank has shown its capabilities for certain mission requirements. Thus, while there are several insulation techniques, only through comparison can their salient features be highlighted. This will be accomplished with an individual discussion of each insulation followed by an overall discussion of the various factors influencing their effectiveness.

PART I

Laminar Insulation

Generally, laminar insulation consists of several alternate layers of radiation shielding material and low conductivity spacing material surrounding the pressure vessel, and located within the dewar annular space.

Commonly used laminar radiation shields are made of aluminum foil and the metallic surface of thin flexible aluminized plastic. These shields are separated from each other by thin layers of insulating material such as fiberglass paper or cloth, or nylon netting. The layers are usually loosely spaced or purposely crinkled to minimize contact between layers. A complete shield assembly consists of from about 20 to several hundred layers per inch of thickness, depending on materials and compactness. The usual practice is to build up the insulating layers on the outside of the pressure vessel.

The effectiveness of laminar insulation depends upon the effective emissivity and thermal isolation between shields and the number of shields that can be applied in a given space.

The actual calculation of thermal transfer through laminar insulations is difficult because of the great number of variables. The presence of gas results in gas conduction between layers. Laminar insulation must be used in a high vacuum. A vacuum better than 0.0001 mm Hg is required to minimize gas conduction. Contaminants such as water and carbon dioxide must be eliminated for best performance. The performance of laminar insulation is usually expressed as an apparent mean thermal conductivity between surfaces at given temperatures. Experimental values in the neighborhood of 0.3 μ watts cm^{-1} deg K^{-1} (0.0175×10^{-3} btu hr^{-1} ft^{-1} deg F^{-1}) are possible with good laminar insulations between room temperature and liquid oxygen temperature (-297 deg F). Slightly lower values would be obtained at lower cold surface temperatures.

The application of laminar insulation to other than flat or cylindrical surfaces is exacting. It is also difficult to achieve ideal performance because the spacing of layers is generally not uniform. Since supports and access lines require piercing and piecing of the insulation, its effectivity is reduced. Evacuation of the annular space is increasingly difficult and more time consuming due to the large quantity of material and multilayer configuration.

Laminar insulations vary in density from about two to ten pounds per cubic foot depending upon the materials and spacing. Because of the added heat capacity of the material, the time to reach the equilibrium heat transfer rate after filling is increased over that of simple dewars but the effect is usually less than that incurred with powder insulations because thinner layers are usually used and heat capacities may be less.

Powder Insulation

Powder insulations consist of finely divided solid materials with low thermal conductivity. The average density of the powder is generally low so that there is a relatively small ratio of solid material to gas filled spaces between the particles. The powder is usually placed in a space between the cryogenic tank and a rigid shell enveloping the tank. Construction is sufficiently strong and leak free to permit evacuation of the space. The powder is usually non-load bearing.

Heat may be transferred through the insulation by conduction through the solid particles, conduction and convection through the interstitial gas, and radiant transfer through the partially transparent powder and from particle to particle. When gas at atmospheric pressure occupies the interstical spaces the significant part of the total heat transfer through the low conductivity powder insulation is found to be the result of conduction and convection through the gas. Conduction through the solid particles is much less than the thermal conductivity through a single particle because of the resistance to heat flow that occurs at the numerous and relatively poor contacts between particles and the long path lengths which are formed. Presence of the powder tends to inhibit gaseous convection and radiant transfer somewhat.

For the majority of powders, the thermal heat transfer will be approximately that of the gas occupying the interstical spaces when the pressure is one atmosphere and equal to the solid conduction plus the radiant heat transfer through the powder at pressure below one micron. This amounts to a very significant reduction. The solid conduction is a function of bulk density and particle size. By decreasing the particle size at constant density the number of resistance contacts is increased and the conductivity lowered. Decreasing density reduces the thermal conductivity and increases transparency to radiation.

A vacuum of one micron is sufficient to produce the best insulating properties of a powder and higher vacuum does not produce significant improvement. In addition, pressures 10 to 100 times this value produce adequate insulating properties with good powders.

A problem that may be encountered in the use of powder insulations is the settling or packing of the particles. Vibrations and movements during usage may break down the powder particles causing them to come into closer contact with each other and resulting in an increase of solid thermal conductivity.

Other factors that must be considered in the use of powder insulation include weight added to the system, the heat capacity of the powder which may supply considerable heat during initial cool down, cost of the powder, and its processing and compatability with system requirements such as combustibility when used for liquid oxygen tanks.

Many powders of varying particle size, density, and mixtures, as well as mixtures with metallic particles have been tested and used. Examples of powders are silica aerogels, diatomaceous earth, charcoals and lampblack, calcium silicate and perlite.

Discrete Shields

Discrete shields, as considered in this discussion, are defined as freely suspended, thermally isolated radiation shields that completely surround the pressure vessel. In practice, the shields are separated and positioned by a minimum number of supports with very low thermal conductance. They are located within the annulus which is maintained at high vacuum.

The heat transfer between surfaces in discrete shielded vessels is composed of solid conduction through the supports and interconnecting lines, thermal transfer by the residual gas, and thermal radiation.

The rate of thermal transfer by the process of thermal radiation between two surfaces of a discrete shielded dewar is given by the expression

$$Q = \sigma EA (T_2^4 - T_1^4)$$

σ = Stefan-Boltzmann constant
E = Emissivity factor between surfaces
A = Area of enclosed surface
T_1 = Absolute temperature of enclosed surface
T_2 = Absolute temperature of enclosing surface.

The emissivity factor between surfaces is a dimensionless fraction with values between 0.0 and 1.0. It is a function of the emissivities of the two surfaces. The emissivity of a surface (also a dimensionless fraction with values between 0.0 and 1.0) is equal to the fraction of the total radiation, of all wave lengths falling on it, which it absorbs. The emissivity varies with the temperature of the surface and the wave length of radiation. The emissivity generally decreases and the wave length for maximum energy increases for decreasing temperature. The total radiant energy decreases rapidly with decreasing temperatures. The emissivity factor between surfaces is related to the emissivities of the two surfaces in cryogenic dewars by the expressions

$$E = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_2 + (1 - \varepsilon_2) \varepsilon_1} \quad \text{for specular (mirror-like) reflection}$$

$$E = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_2 + A_1/A_2 (1 - \varepsilon_2) \varepsilon_1} \quad \text{for diffuse reflection}$$

ε_1 = Emissivity of enclosed surface
ε_2 = Emissivity of enclosing surface
A_1 = Area of enclosed surface
A_2 = Area of enclosing surface

These expressions apply to surfaces for which the emissivity is independent of wave length. The two expressions also give values approximately the same for actual dewars as the ratio of areas is usually 0.8 to 1.0 for well designed discrete shielded dewars.

The heat transfer to the cryogenic fluid in a high vacuum insulated vessel with well designed supports and plumbing may be considerably over half the result of radiation. When a dewar has established equilibrium heat transfer, the temperatures of the surfaces remain constant and the emissivity factor limits the rate of radiant heat transfer. The interpositioning of discrete shields with good thermal isolation in the vacuum space will substantially reduce the radiant heat transfer. It can be shown, that when the emissivity factors between surfaces are the same between all pairs of surfaces of a dewar and shields are thermally isolated, that the thermal transfer rate to the inner tank may be expressed.

$$Q = \sigma A \frac{E}{n + 1} (T_2^{\ 4} - T_1^{\ 4})$$

n = Number of discrete shields

The unshielded radiant heat transfer rate will be reduced by a factor of one greater than the number of shields added. Surfaces with poor thermal isolation would tend to assume the same temperature and their radiation shielding ability would be reduced or lost. As the number of shields is increased, in a limited space, approximation to the ideal system becomes increasingly difficult to attain. This is due to the increasing effect of inter-shield conductive heat transfer.

Vapor-Cooled Shields

By definition, a vapor-cooled shield is a discrete radiation shield that is cooled by the effluent fluid from the tank it is shielding. The same thermal isolation requirements that apply to discrete radiation shields apply to vapor-cooled shields.

In practice, fluid issuing from the pressure vessel, either from venting or usage, is routed through tubing attached to the discrete shield. This provides for an efficient heat exchange between the fluid and shield before the fluid exits from the dewar.

The fluid enters the shield at the temperature of the fluid in the inner tank (or that of the nearest enclosed cooled shield for multiple cooled shield dewars) and leaves the shield at the shield temperature if heat exchange is complete. Considering equilibrium heat transfer conditions, a discrete shield with no vapor cooling passes all of the heat it receives from the outside of the dewar, and a portion passed on to the inner tank. The vapor cooled shield is divided into a portion absorbed by the fluid passing thru, which is carried to the outside of the dewar, and a portion passed on to the inner tank. The vapor cooled shield will come to a lower equilibrium temperature and, therefore, the heat transferred to the inner tank will be less than that for a non vapor cooled shield. The heat absorbed by the fluid as it passes thru the vapor cooled shield will be equal to its change in enthalpy within the shield if the pressure remains constant.

The concept of the vapor cooled shield is applicable to all cryogenic fluids. The effectivity varies considerably with the fluid properties. Fluids that exhibit a large specific enthalpy and a small ratio of latent heat will produce the greatest lowering in radiant heat transfer to the fluid in the inner container. Helium and hydrogen have very favorable properties. A single vapor cooled shield may theoretically reduce the radiant heat transfer to a value one-third to one-tenth or less than that of a similar dewar with the same number of non-vapor cooled shields, when used with these fluids. Additional vapor cooled shields also are very effective. Fluids such as oxygen and nitrogen have less favorable properties, but reductions to values from three-fourths to two-thirds or less of the radiant transfer of similar dewars with non-vapor cooled shields may be possible. Additional vapor cooled shields are less effective with these fluids.

In practice, ability to achieve theoretical performance depends upon construction of shilds with low emissivity, a high degree of thermal isolation and efficient heat exchange. Vapor cooled shields require more space, are more complex, heavier and more costly than non vapor cooled shields and a high vacuum is necessary. After consideration is given to all these factors, the vapor cooled shield may still be advantageous over other insulation systems when very low heat transfer rates are a requirement.

Cyrogenic Filled-Shield Tank

While a cryogenic filled-shield tank has not had actual flight usage to date, this concept has been advanced sufficiently for it to warrant consideration.

The description "cryogenic filled-shield-tank" refers to dewars constructed so that the pressure vessel, containing the primary fluid, is surrounded by a second cryogenic fluid.

This secondary fluid can be contained within a separate shroud tank located between the pressure vessel and outer shell, or come directly in contact with the outer surface of the pressure vessel. Separate fill and vent lines for the two cryogenic tanks are routed through the outer shell.

The function of the cryogenic filled-shield tank is to reduce radiant and conductive heat to the cryogenic fluid in the inner tank. By using a cryogenic fluid with a sufficiently low boiling point for the shield fluid, the radiation shield may be cooled to temperatures below those which are obtained by discrete shield and vapor cooled shield dewars. Radiant heat transfer is proportional to the difference in the fourth powers of the shield and inner temperatures while conductive heat transfer is directly proportional to the temperature difference. This method is particularly effective in reducing radiant heat transfer. Because of the additional weight of the shield fluid, shield supports must be stronger than those used with lighter shields and therefore, may have higher thermal conductivity which tends to offset the lowering of conductive heat transfer.

Cryogenic filled-shield-tank insulated dewars are capable of transferring less heat to a cryogenic fluid in the inner tank than any other type of insulated dewar. Limitations are imposed by the temperatures of the existing cryogenic fluids. A disadvantage of this type of insulation is the complexity and difficulty of construction when compared to simpler systems. The cost of fabrication and maintenance are greater than simpler systems so this type of dewar can only be considered for containing high cost cryogenic fluids or for applications requiring exceedingly low loss rates. If the cryogenic fluids in the inner tank and the shield-tank are both required for a particular operation, this storage method may be more attractive.

Cryogenic filled-shield-tank dewars have been constructed and used successfully for the storage and transportation of liquid hydrogen and helium with a shield fluid of liquid nitrogen.

PART II

Insulation Comparisons

When comparing the attributes of the various insulation techniques, it is necessary to analyze the capabilities and effectiveness of an insulation relative to its intended usage.

This analysis must include such factors as:

1. Weight
2. Strength
3. Reliability
4. Thermal Comparison

Following is a general discussion of each of these factors.

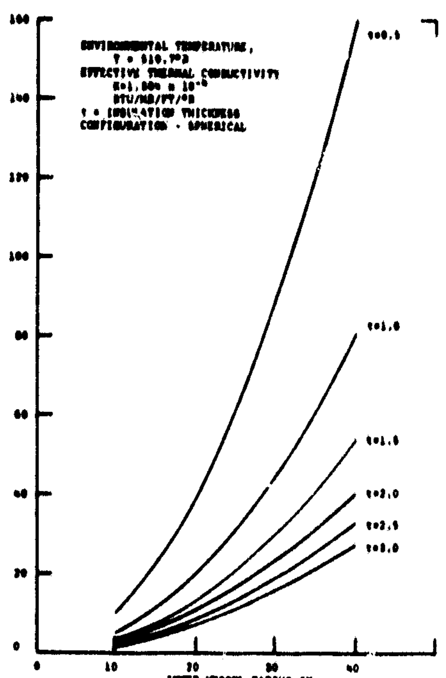
Weight

In considering the weight of insulation, it is necessary to take into consideration its thermal capabilities to arrive at a comparative analysis. The graphs on the following pages are symbolic of the data obtained in computing the thermal effectiveness of the various insulations, with corresponding graphs showing insulation weight for various sized dewars. In addition, eight tables in tabular form are included to show the generation of this data.

The weights shown are for insulation only. They do not include the inner vessel and outer shell since they would be common in each system, regardless of the insulation used. Mounting system weights are also not included.

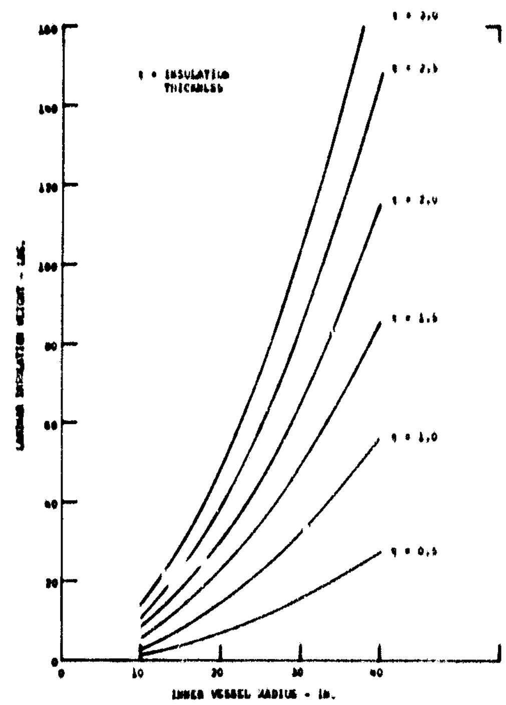
The weights of laminar and powder insulations are simply the volume of the annular region times the optimum density of the insulation.

Computing shield insulation weights are somewhat more complicated. The shields are fabricated of aluminum with a diameter thickness of .010 to .022 inches thick at 20 to 80 inch diameters respectively. The shield plating and substrate weights are included, as are these weights for the inner vessel and outer shell surfaces. Shield spacings are 0.25 and 0.50 inches, depending on whether the adjacent shield is discrete or vapor cooled. For vapor cooled, the weight of the vapor cooling tubes are included. All shield hangers, connectors, doublers and latches are included in the shield insulation weight.



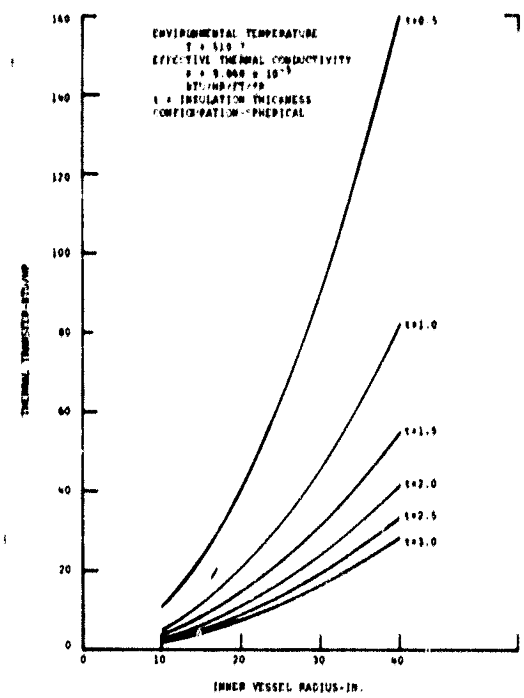
THERMAL TRANSFER THROUGH SI-62 LAMINAR INSULATION TO STORED OXYGEN

FIGURE 7-1



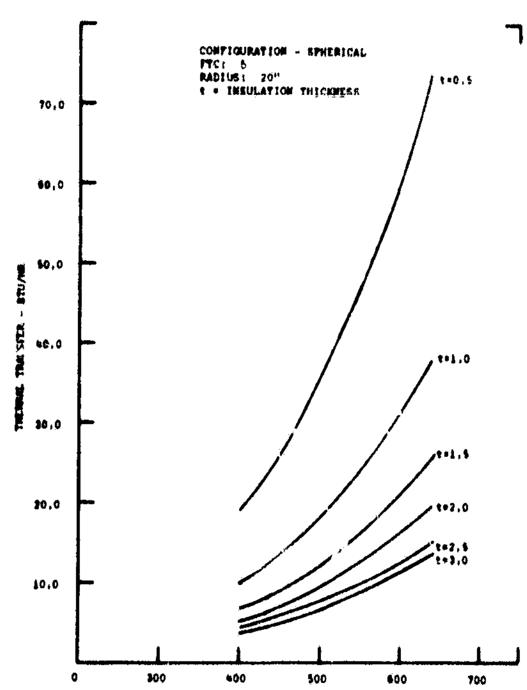
SI-62 LAMINAR INSULATION WEIGHT AS A FUNCTION OF SPHERICAL VESSEL RADIUS

FIGURE 7-2



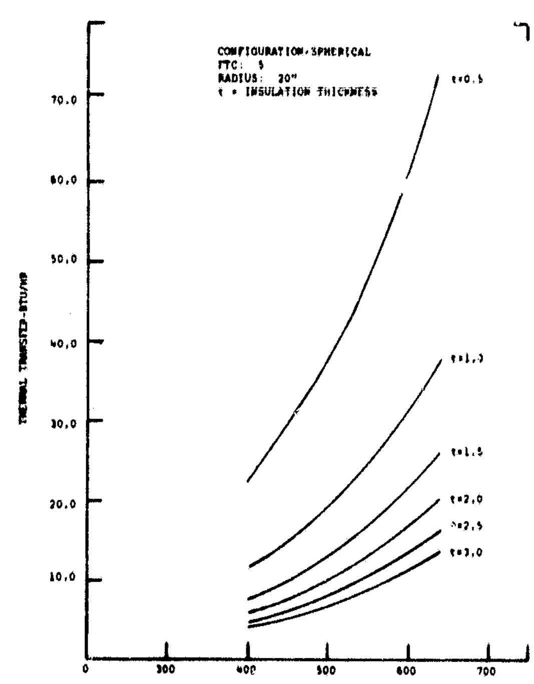
THERMAL TRANSFER THROUGH SI-62 LAMINAR INSULATION TO STORED HYDROGEN

FIGURE 7-3



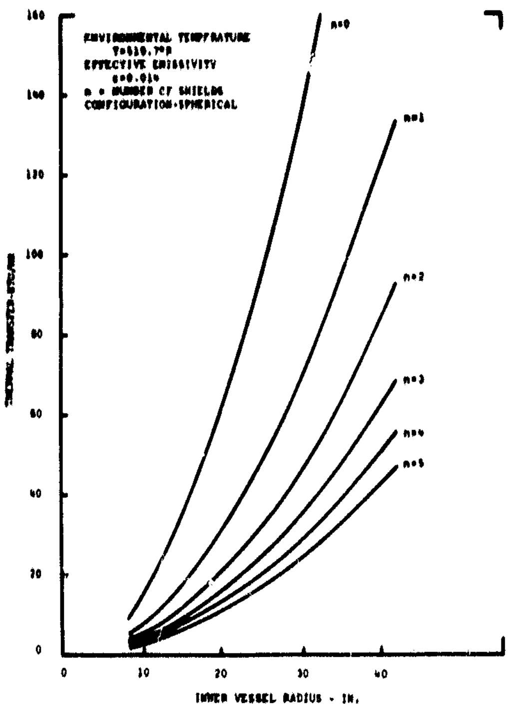
THERMAL TRANSFER THROUGH SI-62 LAMINAR INSULATION TO STORED OXYGEN

FIGURE 7-4



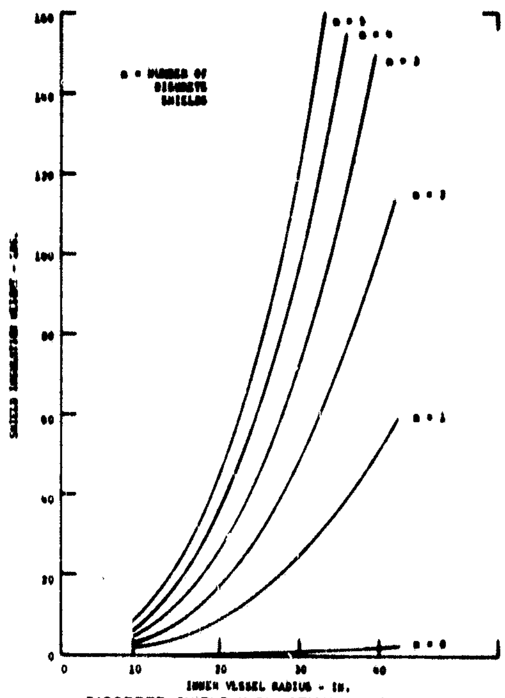
THERMAL TRANSFER THROUGH SI-62 LAMINAR INSULATION TO STORED HYDROGEN

FIGURE 7-5



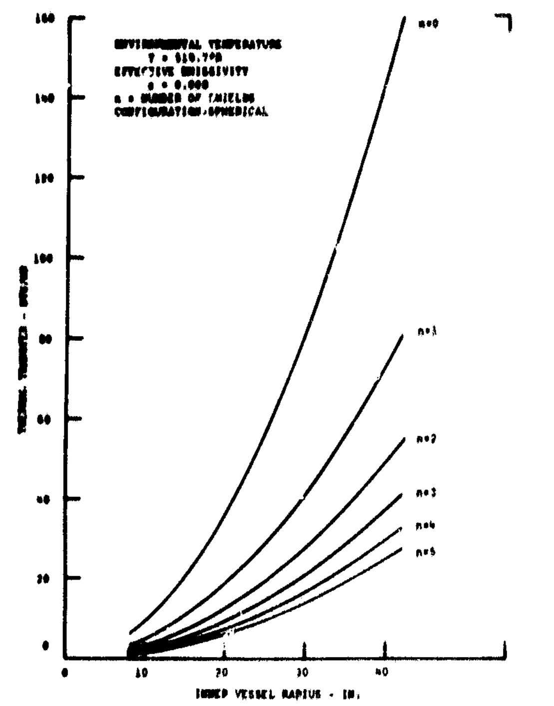
THERMAL TRANSFER THROUGH DISCRETE RADIATION SHIELD INSULATION TO STORED OXYGEN

FIGURE 7-6



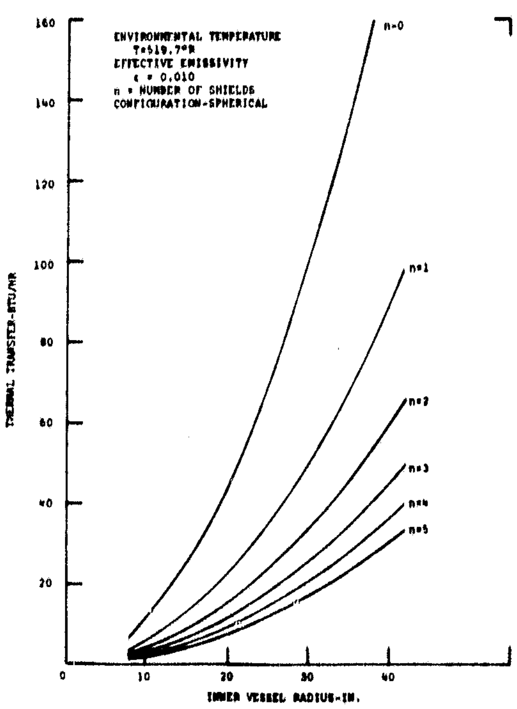
DISCRETE SHIELD INSULATION WEIGHT AS A FUNCTION OF SPHERICAL VESSEL RADIUS

FIGURE 7-7



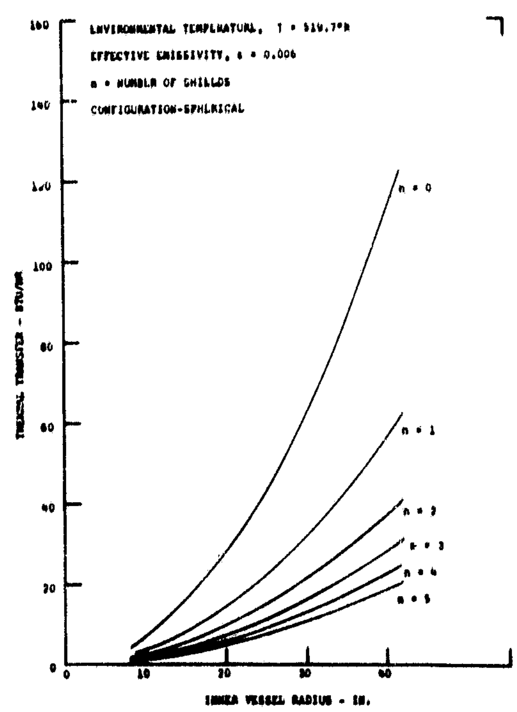
THERMAL TRANSFER THROUGH DISCRETE RADIATION SHIELD INSULATION TO STORED HYDROGEN

FIGURE 7-8



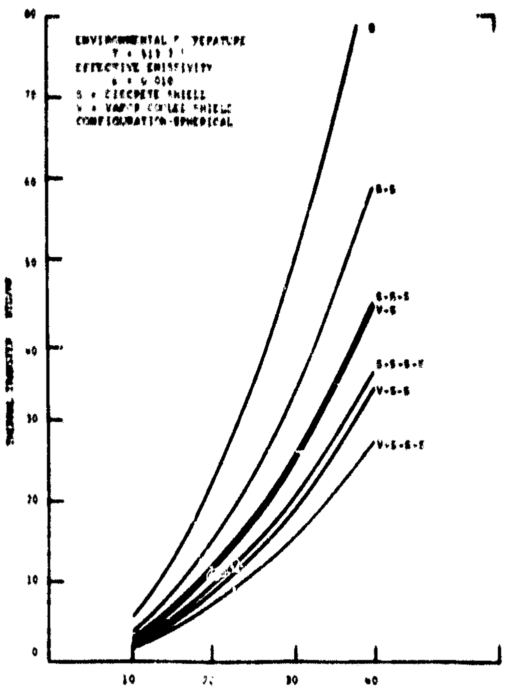
THERMAL TRANSFER THROUGH DISCRETE RADIATION SHIELD INSULATION TO STORED OXYGEN

FIGURE 7-9



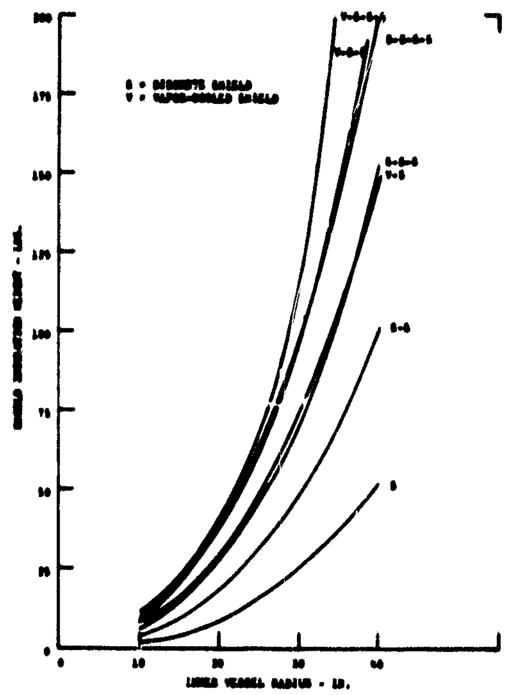
THERMAL TRANSFER THROUGH DISCRETE RADIATION SHIELD INSULATION TO STORED HYDROGEN

FIGURE 7-10



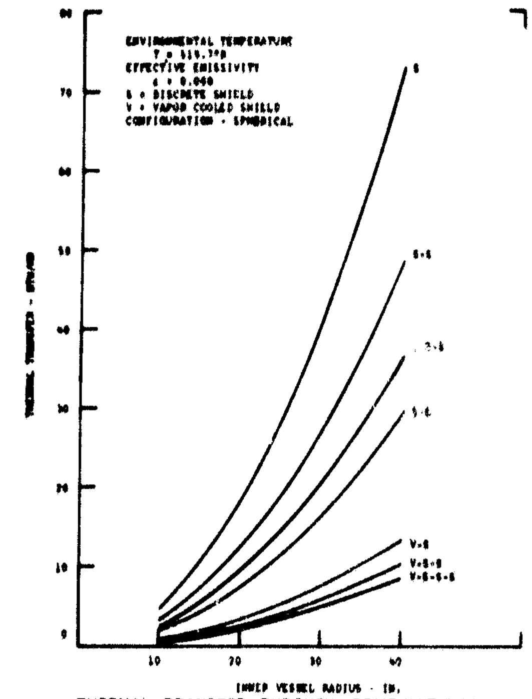
THERMAL TRANSFER THROUGH COMBINATION OF VAPOR COOLED AND DISCRETE RADIATION SHIELD INSULATION TO STORED OXYGEN

FIGURE 7-11



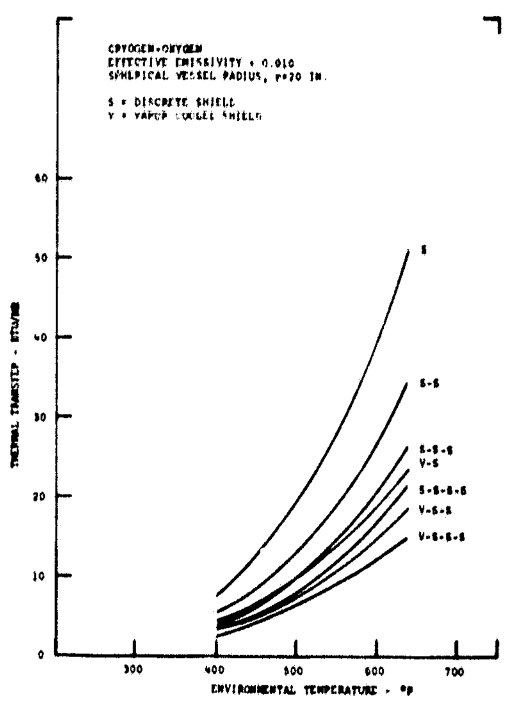
WEIGHT OF COMBINATIONS OF VAPOR COOLED AND DISCRETE RADIATION SHIELDS AS A FUNCTION OF SPHERICAL VESSEL RADIUS

FIGURE 7-12



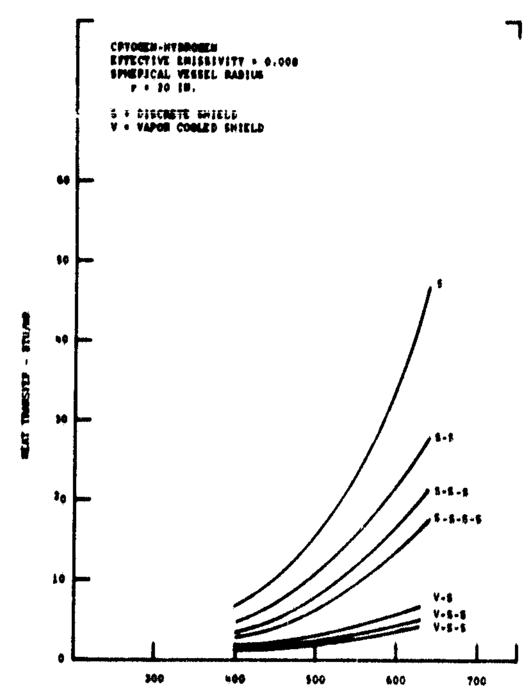
THERMAL TRANSFER THROUGH COMBINATIONS OF VAPOR COOLED AND DISCRETE RADIATION SHIELD INSULATION TO STORED HYDROGEN

FIGURE 7-13



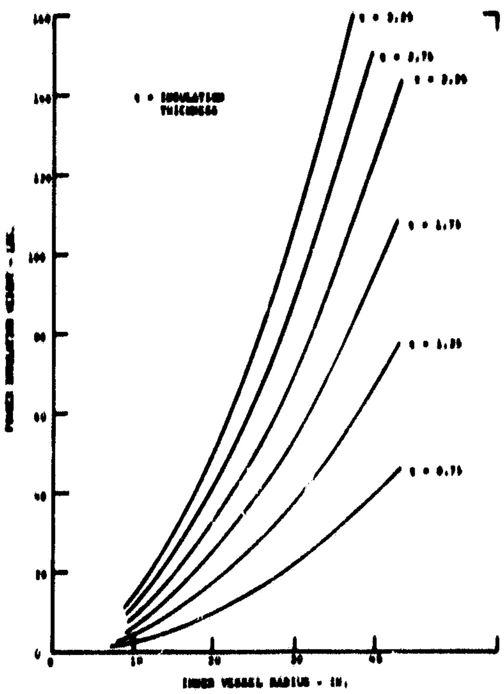
THERMAL TRANSFER THROUGH COMBINATIONS OF VAPOR COOLED AND DISCRETE RADIATION SHIELD INSULATION TO STORED OXYGEN AS A FUNCTION OF ENVIRONMENTAL TEMPERATURE

FIGURE 7-14



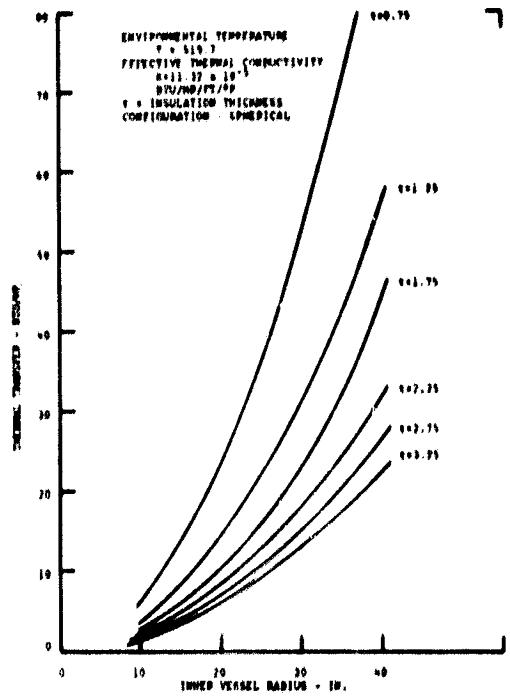
THERMAL TRANSFER THROUGH COMBINATIONS OF VAPOR COOLED AND DISCRETE RADIATION SHIELD INSULATION TO STORED HYDROGEN AS A FUNCTION OF ENVIRONMENTAL TEMPERATURE

FIGURE 7-15



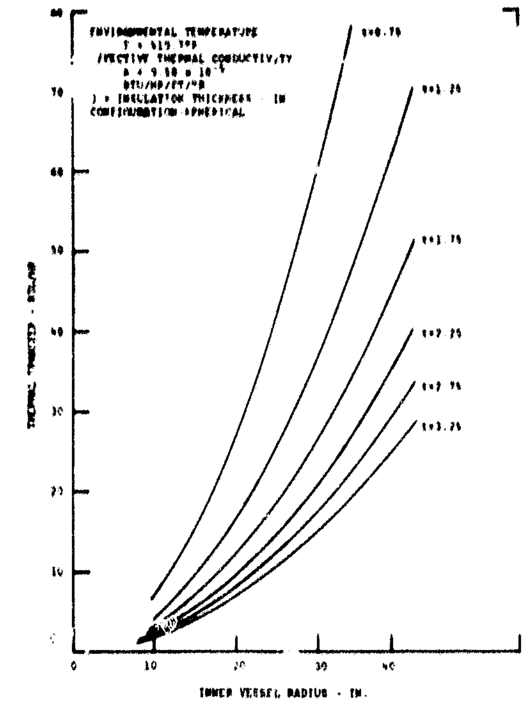
POWDER INSULATION WEIGHT AS A FUNCTION OF SPHERICAL VESSEL RADIUS

FIGURE 7-16



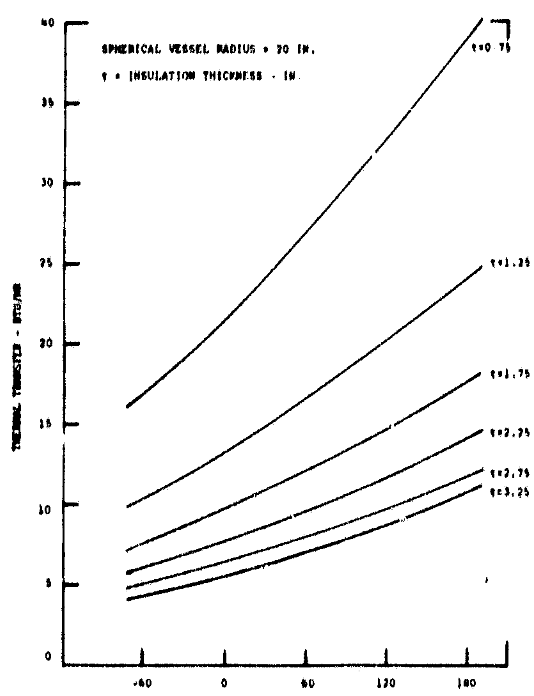
THERMAL TRANSFER THROUGH CAB-O-SIL H-5 POWDER INSULATION TO STORED OXYGEN

FIGURE 7-17



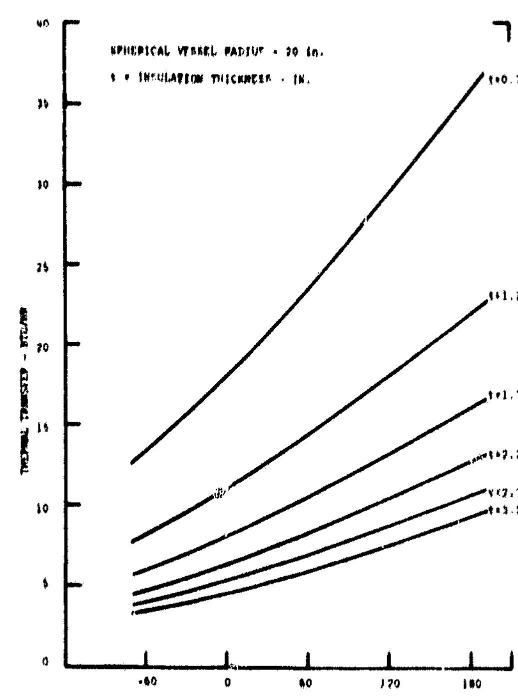
THERMAL TRANSFER THROUGH CAB-O-SIL H-5 POWDER INSULATION TO STORED HYDROGEN

FIGURE 7-18



THERMAL TRANSFER THROUGH CAB-O-SIL H-5 POWDER INSULATION TO STORED HYDROGEN AS A FUNCTION OF ENVIRONMENTAL TEMPERATURE

FIGURE 7-19

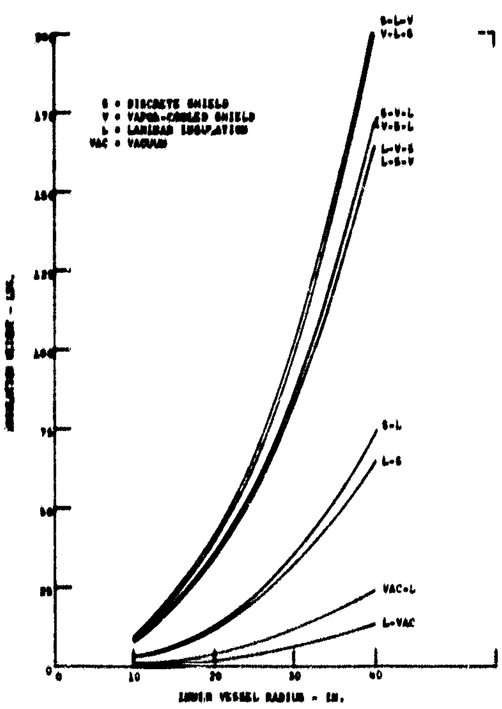


THERMAL TRANSFER THROUGH CAB-O-SIL H-5 POWDER INSULATION TO STORED OXYGEN AS A FUNCTION OF ENVIRONMENTAL TEMPERATURE

FIGURE 7-20

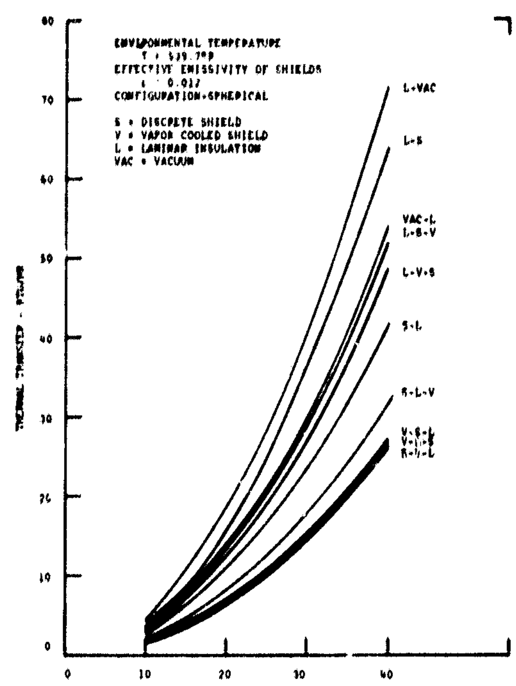
The data shown in the graphs is based upon the thermal transfer (BTU/hr) versus both the inner vessel radius and environmental temperature.

This thermal transfer data is limited to the various types of insulation. The interconnecting tubing and mounting systems were not taken into consideration, since the tubing would be similar regardless of the insulation used and due to the broad range of possible conductivities depending on the mount system used.



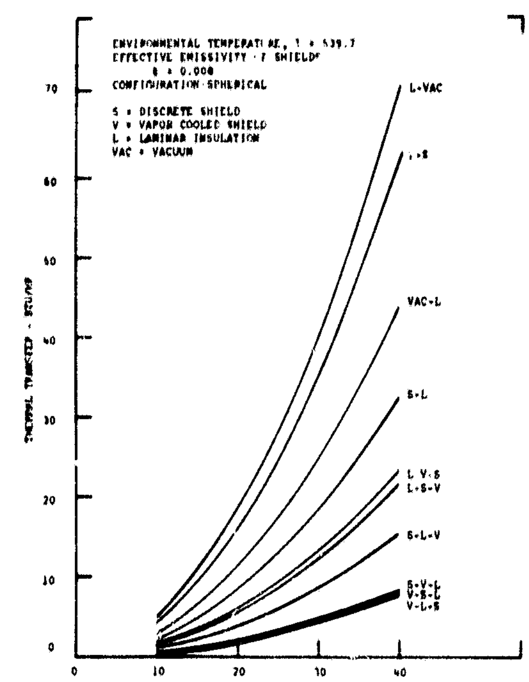
WEIGHT OF COMBINATIONS OF INSULATIONS AS A FUNCTION OF SPHERICAL RADIUS

FIGURE 7-21



THERMAL TRANSFER THROUGH COMBINATIONS OF INSULATIONS TO STORED OXYGEN

FIGURE 7-22



THERMAL TRANSFER THROUGH COMBINATIONS OF INSULATIONS TO STORED HYDROGEN

FIGURE 7-23

The laminar insulation effectiveness is shown with an insulation effectiveness factor of FTC = 5. This factor is considered to be within the present state-of-the-art.

The results shown for discrete radiation shield insulation are based upon two effective emissivity values. The higher value (ε = 0.014 for oxygen and ε = 0.008 for hydrogen) is that value being obtained in practice at this time. The low value (ε = 0.010 for oxygen and ε = 0.006 for hydrogen) are design goals which are considered obtainable with a reasonable amount of development of processes and procedures of metal surface finishing (polishing, plating, handling and protection). The same FTC factor is used for combinations of vapor cooled and discrete radiation shields.

Since powder insulation application is virtually free from artisan effects, one conductivity, the nominal one obtained in actual practice, is considered.

In addition to the graphs showing the thermal transfer through various insulations, graphs are also included to show thermal transfer through various combinations of insulation. The laminar insulation is, all examples, considered to be 0.500 inches thick and the conductivity is optimistically considered to be at an FTC = 3. Shield emissivities however, are in the obtainable range, with a value of ε = 0.008 for hydrogen and ε = 0.012 for oxygen being assumed.

In comparing laminar and shield insulations a 20 inch radius vessel with 1.5 inches of laminar insulation at an FTC of 5 was used. This corresponds with a 3 or 4 discrete shield system, depending on emissivity.

Examining the data for combinations of vapor cooled and discrete shields shows that, in general, vapor cooled shields are most effective if they are inside the discrete shields.

The data for the combinations of insulations indicates that the addition of laminar insulation to a shielded vessel is most effective if placed in the outside, warmer, regions.

THERMAL TRANSFER THROUGH COMBINATIONS OF VAPOR-COOLED AND DISCRETE RADIATION SHIELDS

CRYOGEN: OXYGEN TEMPERATURE: 519.7°R

S = DISCRETE SHIELD
V = VAPOR-COOLED SHIELD

INNER VESSEL RADIUS	10"		20"		30"		40"	
EFFECTIVE EMISSIVITY	.008	.012	.008	.012	.008	.012	.008	.012
CONDITION								
S	4.510	6.722	17.76	26.51	39.78	59.38	70.56	105.3
V	3.490	5.200	13.72	20.47	30.71	45.82	54.46	81.26
S-S	3.076	4.587	11.98	17.88	26.72	39.89	47.30	70.61
S-V	2.529	3.770	9.813	14.65	21.86	32.63	38.68	54.74
S-S-S	2.391	3.566	9.155	13.67	20.29	30.30	35.81	53.47
V-S	2.347	3.497	9.067	13.52	20.17	30.09	35.65	53.19
V-V	2.250	3.353	8.675	12.94	19.28	28.78	34.08	50.85
S-S-V	2.058	3.069	7.826	11.68	17.31	25.83	30.50	45.54
S-S-S-S	1.972	2.941	7.442	11.11	16.41	24.50	28.88	43.13
S-V-S	1.881	2.805	7.135	10.65	15.76	23.53	27.77	41.45
S-V-V	1.842	2.746	6.972	10.41	15.40	22.98	27.11	40.47
V-S-S	1.834	2.732	6.955	10.37	15.37	22.92	27.07	40.38
V-S-V	1.757	2.617	6.638	9.903	14.65	21.85	25.79	38.48
V-V-S	1.749	2.606	6.587	9.827	14.52	21.66	25.54	38.11
S-S-S-V	1.742	2.598	6.531	9.749	14.37	21.45	25.26	37.71
V-V-V	1.721	2.565	6.473	9.657	14.26	21.27	25.07	37.41
S-S-V-S	1.608	2.[illegible]98	5.998	8.953	13.17	19.66	23.13	34.53
S-S-V-V	1.588	2.367	5.912	8.825	12.98	19.37	22.78	34.01
V-S-S-S	1.526	2.272	5.704	8.508	12.54	18.70	22.03	32.85
S-V-S-S	1.525	2.273	5.693	8.494	12.50	18.66	21.96	32.78
S-V-S-V	1.488	2.218	5.540	8.267	12.16	18.15	21.34	31.85
S-V-V-S	1.491	2.223	5.535	8.261	12.13	18.11	21.28	31.77
S-V-V-V	1.477	2.202	5.474	8.169	11.99	17.90	21.03	31.39
V-S-S-V	1.465	2.186	5.455	8.136	11.97	17.86	21.02	31.36
V-V-S-S	1.451	2.162	5.375	8.018	11.77	17.57	20.65	30.80
V-S-V-S	1.441	2.147	5.344	7.972	11.71	17.47	20.54	30.65
V-S-V-V	1.428	2.128	5.290	7.892	11.59	17.29	20.32	30.32
V-V-V-S	1.427	2.127	5.259	7.847	11.50	17.15	20.13	30.35
V-V-S-V	1.423	2.120	5.258	7.844	11.50	17.17	20.16	30.07
V-V-V-V	1.416	2.110	5.210	7.733	11.38	16.98	19.93	29.74

Bendix Instruments & Life Support Division

THERMAL TRANSFER THROUGH COMBINATIONS OF VAPOR-COOLED AND DISCRETE RADIATION SHIELDS

CRYOGEN: HYDROGEN   TEMPERATURE: 519.7°R

S = DISCRETE SHIELD
V = VAPOR-COOLED SHIELD

INNER VESSEL RADIUS	10"		20"		30"		40"	
EFFECTIVE EMISSIVITY	.006	.010	.006	.010	.006	.010	.006	.010
CONDITION								
S	3.56	5.791	13.98	22.81	31.29	51.07	55.49	90.59
S-S	2.42	3.945	9.40	15.36	20.95	34.25	37.08	60.63
S-S-S	1.88	3.063	7.17	11.72	15.88	25.99	28.02	45.86
S-S-S-S	1.55	2.524	5.82	9.522	12.82	21.00	22.56	36.96
V	1.096	1.760	4.274	6.890	9.547	15.40	16.92	27.29
S-V	0.8784	1.425	3.371	5.483	7.486	12.18	13.22	21.52
S-S-V	0.7946	1.294	2.956	4.825	6.492	10.60	11.40	18.62
V-S	0.7099	1.131	2.722	4.352	6.047	9.672	10.69	17.09
S-S-S-V	0.7238	1.181	2.650	4.332	5.785	9.462	10.13	16.57
V-V	0.5800	0.9301	2.213	3.559	4.905	7.894	8.657	13.93
S-V-S	0.5911	0.9554	2.213	3.586	4.872	7.897	8.567	13.89
V-S-S	0.5613	0.8863	2.119	3.357	4.680	7.418	8.245	13.07
S-S-V-S	0.5392	0.8759	1.970	3.207	4.298	7.000	7.523	12.25
S-V-V	0.517	0.8395	1.924	3.129	4.223	6.872	7.417	12.07
S-S-V-V	0.4844	0.7953	1.771	2.891	3.855	6.294	6.739	11.00
V-S-S-S	0.4741	0.7457	1.767	2.789	3.886	6.135	6.830	10.79
V-S-V	0.466	0.7422	1.737	2.777	3.818	6.111	6.711	10.74
S-V-S-S	0.4630	0.7458	1.709	2.759	3.743	6.046	6.564	10.61
V-V-S	0.434	0.6956	1.619	2.601	3.559	5.721	6.254	10.05
V-V-V	0.4085	0.6562	1.514	2.440	3.320	5.354	5.827	9.399
S-V-S-V	0.4066	0.6574	1.487	2.401	3.245	5.263	5.682	9.217
V-S-S-V	0.3999	0.6343	1.471	2.342	3.218	5.126	5.641	8.988
S-V-V-S	0.3918	0.6349	1.429	2.322	3.116	5.064	5.454	8.863
S-V-V-V	0.3750	0.6083	1.360	2.213	2.961	4.818	5.175	8.422
V-S-V-S	0.3637	0.5800	1.331	2.129	2.905	4.652	5.087	8.147
V-V-S-S	0.3566	0.5701	1.310	2.101	2.865	4.576	5.021	8.056
V-S-V-V	0.3508	0.5606	1.277	2.048	2.783	4.467	4.870	7.817
V-V-S-V	0.3328	0.5337	1.213	1.952	2.645	4.258	4.627	7.451
V-V-V-S	0.3283	0.5273	1.193	1.923	2.598	4.189	4.543	7.326
V-V-V-V	0.3197	0.5197	1.157	1.867	2.515	4.061	4.394	7.096

THERMAL TRANSFER THROUGH COMBINATIONS OF VAPOR-COOLED AND DISCRETE RADIATION SHIELDS

CRYOGEN: OXYGEN RADIUS: 20" EMISSIVITY: .008

S = DISCRETE SHIELD
V = VAPOR-COOLED SHIELD

TEMPERATURE	399.7°F	459.7°R	519.7°R	579.7°F	639.7°F
CONDITION					
S	6.196	10.87	17.76	27.49	40.73
V	5.189	8.727	13.72	20.49	29.30
S-S	4.176	7.331	11.98	18.54	27.47
S-V	3.635		9.813		21.19
S-S-S	3.191	5.601	9.155	14.17	21.00
V-S	3.480		9.067		19.19
V-V	3.352	5.575	8.675	12.81	18.09
S-S-V	2.861		7.826		17.04
S-S-S-S	2.593	4.553	7.442	11.52	17.07
S-V-S	2.692		7.135		15.25
S-V-V	2.643		6.972		14.72
V-S-S	2.684		6.955		14.65
V-S-V	2.578		6.638		13.77
V-V-S	2.564		6.587		13.71
S-S-S-V	2.369		6.531		14.30
V-V-V	2.525	4.179	6.473	9.509	13.34
S-S-V-S	2.235		5.998		12.91
S-S-V-V	2.210		5.912		11.63
V-S-S-S	2.205		5.704		11.98
S-V-S-S	2.169		5.693		12.10
S-V-S-V	2.170		5.540		11.62
S-V-V-S	2.120		5.535		11.63
S-V-V-V	2.101		5.474		11.41
V-S-S-V	2.112		5.455		11.29
V-V-S-S	2.100		5.375		11.18
V-S-V-S	2.085		5.344		11.06
V-S-V-V	2.067		5.290		10.87
V-V-V-S	2.060		5.259		10.84
V-V-S-V	2.060		5.258		10.82
V-V-V-V	2.044	3.374	5.210	7.631	10.67

THERMAL TRANSFER THROUGH COMBINATIONS OF VAPOR-COOLED AND DISCRETE RADIATION SHIELDS

CRYOGEN: OXYGEN RADIUS: 20" EMISSIVITY: .012

S = DISCRETE SHIELD
V = VAPOR-COOLED SHIELD

TEMPERATURE	399.7°F	459.7°F	519.7°R	579.7°R	639.7°R
CONDITION					
S	9.199	16.19	26.51	41.07	60.91
V	7.701	12.99	20.47	30.60	43.81
S-S	6.203	10.92	17.88	27.70	41.09
S-V	5.398		14.65		31.69
S-S-S	4.741	8.345	13.67	21.18	31.41
V-S	5.164		13.52		28.69
V-V	4.976	8.302	12.94	19.14	27.05
S-S-V	4.250		11.68		25.48
S-S-S-S	3.853	6.783	11.11	17.21	25.53
S-V-S	3.998		10.65		22.81
S-V-V	3.925		10.41		22.01
V-S-S	3.982		10.37		21.90
V-S-V	3.827		9.903		20.58
V-V-S	3.806		9.827		20.50
S-S-S-V	3.519		9.749		21.40
V-V-V	3.749	6.224	9.657	14.20	19.95
S-S-V-S	3.321		8.953		19.30
S-S-V-V	3.284		8.825		18.83
V-S-S-S	3.272		8.508		17.91
S-V-S-S	3.221		8.494		18.10
S-V-S-V	3.149		8.267		17.37
S-V-V-S	3.149		8.261		17.40
S-V-V-V	3.120		8.169		17.07
V-S-S-V	3.150		8.136		16.88
V-V-S-S	3.117		8.018		16.72
V-S-V-S	3.096		7.972		16.53
V-S-V-V	3.070		7.892		16.25
V-V-V-S	3.059		7.847		16.21
V-V-S-V	3.058		7.844		16.17
V-V-V-V	3.035	5.024	7.733	11.40	15.96

THERMAL TRANSFER THROUGH COMBINATIONS OF INSULATIONS TO STORED OXYGEN

EFFECTIVE EMISSIVITY: .012 ENVIRONMENT TEMPERATURE: 539.7°R

L = 1/2" LAMINAR INSULATION
S = DISCRETE RADIATION SHIELD
V = VAPOR-COOLED SHIELD
VAC = VACUUM

RADIUS	10"	20"	30"	40"
CONDITION				
V-V-L	1.785	6.530	14.24	24.91
V-L-V	1.780	6.667	14.67	25.77
S-V-L	1.848	6.821	14.92	26.16
V-L-S	1.819	6.832	15.04	26.45
V-S-L	1.879	6.944	15.20	26.65
S-L-V	2.171	8.189	18.05	31.76
V-L	2.206	8.244	18.12	31.83
S-L-S	2.301	8.719	19.26	33.91
S-S-L	2.339	8.939	19.62	34.45
S-L	2.835	10.68	23.53	41.30
L-V-V	3.241	12.28	27.11	47.33
L-V-S	3.284	12.47	27.55	48.53
L-S-V	3.474	13.24	29.28	51.60
VAC-L	3.639	13.84	30.61	53.94
L-S-S	3.768	14.47	32.10	56.64
L-V	3.875	14.92	33.12	58.48
L-S	4.165	16.17	36.01	63.96
L-VAC	4.616	18.02	40.20	71.16

THERMAL TRANSFER THROUGH COMBINATIONS OF VAPOR-COOLED AND DISCRETE RADIATION SHIELDS

CRYOGEN: HYDROGEN RADIUS: 20" EMMISSIVITY: .008

S = DISCRETE SHIELD
V = VAPOR-COOLED SHIELD

TEMPERATURE	339.7°R	459.7°R	519.7°R	579.7°R	639.7°R
CONDITION					
S	6.730	11.46	18.40	28.17	41.45
S-S	4.516	7.699	12.38	18.96	27.93
S-S-S	3.462	5.872	9.445	14.48	21.33
S-S-S-S	2.789	4.764	7.671	11.76	17.33
V	2.559	3.844	5.582	7.820	10.63
S-V	1.943		4.427		8.615
S-S-V	1.670		3.891		7.688
V-S	1.665		3.537		6.635
S-S-S-V	1.475		3.491		6.972
V-V	1.360	2.028	2.886	3.975	5.343
S-V-S	1.315		2.899		5.549
V-S-S	1.288		2.738		5.050
S-S-V-S	1.142		2.589		5.014
S-V-V	1.158		2.527		4.785
S-S-V-V	1.043		2.331		4.472
V-S-S-S	1.069		2.278		4.159
V-S-V	1.063		2.257		4.139
S-V-S-S	1.031		2.234		4.239
V-V-S	1.001		2.110		3.857
V-V-V	.9362	1.390	1.977	2.713	3.620
S-V-S-V	.9048		1.944		3.670
V-S-S-V	.9105		1.906		3.498
S-V-V-S	.8730		1.876		3.512
S-V-V-V	.8328		1.787		3.345
V-S-V-S	.8179		1.730		3.155
V-V-S-S	.8149		1.706		3.103
V-S-V-V	.7854		1.663		3.041
V-V-S-V	.7562		1.583		2.890
V-V-V-S	.7439		1.558		2.846
V-V-V-V	.7213	1.065	1.512	2.075	2.766

THERMAL TRANSFER THROUGH COMBINATIONS OF VAPOR-COOLED AND DISCRETE RADIATION SHIELDS

CRYOGEN: HYDROGEN RADIUS: 20" EMISSIVITY: .006

S = DISCRETE SHIELD
V = VAPOR-COOLED SHIELD

TEMPERATURE	399.7°R	459.7°R	519.7°R	579.7°R	639.7°R
CONDITION					
S	5.185	8.751	13.98	21.33	31.32
S-S	3.472	5.875	9.40	14.35	21.09
S-S-S	2.641	4.476	7.17	10.95	16.10
S-S-S-S	2.139	3.630	5.82	8.895	13.08
V	1.997	2.965	4.274	5.958	8.073
S-V	1.500		3.371		6.519
S-S-V	1.284		2.956		5.809
V-S	1.307		2.722		5.054
S-S-S-V	1.132		2.650		5.265
V-V	1.060	1.565	2.213	3.029	4.056
S-V-S	1.020		2.213		4.205
V-S-S	1.015		2.119		3.857
S-S-V-S	0.8804		1.970		3.793
S-V-V	0.8948		1.924		3.620
S-S-V-V	0.8029		1.771		3.379
V-S-S-S	0.8454		1.767		3.184
V-S-V	0.8310		1.737		3.152
S-V-S-S	0.8014		1.709		3.217
V-V-S	0.7808		1.619		2.932
V-V-V	0.7283	1.071	1.514	2.069	2.749
S-V-S-V	0.7005		1.487		2.781
V-S-S-V	0.7330		1.471		2.656
S-V-V-S	0.6750		1.429		2.659
S-V-V-V	0.6426		1.360		2.531
V-S-V-S	0.6398		1.331		2.407
V-V-S-S	0.6384		1.310		2.364
V-S-V-V	0.6131		1.277		2.318
V-V-S-V	0.5901		1.213		2.198
V-V-V-S	0.5795		1.193		2.163
V-V-V-V	0.5611	0.8199	1.157	1.581	2.102

THERMAL TRANSFER THROUGH COMBINATION OF INSULATIONS TO STORED HYDROGEN

EFFECTIVE EMISSIVITY: .008 ENVIRONMENT TEMPERATURE: 539.7°R

L = 1/2" LAMINAR INSULATION
S = DISCRETE RADIATION SHIELD
V = VAPOR-COOLED SHIELD
VAC = VACUUM

RADIUS	10"	20"	30"	40"
CONDITION				
V-V-L	0.4246	1.555	3.396	5.947
V-L-V	0.5144	1.913	4.201	7.378
S-V-L	0.5495	2.024	4.429	7.763
V-S-L	0.5622	2.087	4.580	8.042
V-L-S	0.5645	2.120	4.674	8.225
V-L	0.6711	2.516	5.540	9.745
S-L-V	1.083	3.974	8.673	15.20
L-V-V	1.144	4.150	9.025	15.77
L-V-S	1.505	5.584	12.24	21.46
L-S-V	1.660	6.033	13.13	22.95
S-L-S	1.807	6.842	15.11	26.61
S-S-L	1.850	6.909	15.18	26.67
L-V	2.163	8.113	17.86	31.39
S-L	2.230	8.413	18.55	32.66
VAC-L	2.959	11.26	24.93	43.95
L-S-S	3.588	13.70	30.32	53.45
L-S	4.085	15.84	35.25	62.33
L-VAC	4.613	18.01	40.18	71.13

Insulation Strength Characteristics

The primary factor to consider when analyzing the strength capabilities of an insulation is its resistance to vibration and shock. Of secondary importance is its weight supporting ability.

The weight-supporting capabilities of the insulation is not stressed, since the insulation is not intended to support the inner vessel. While not intended, it would be possible to use certain types of insulation for short durations with a retractable type mounting system. For example, acceleration in a weightless environment would produce an artifical gravity condition, and depending upon the length of the condition either powder or laminar insulation could support the inner vessel for short periods.

Insulation effectiveness is of major importance when dealing with the vibratory and shock loads that may be applied to the tankage system.

When laminar insulation is subjected to vibratory and shock loads, it presents particular problems that are extremely difficult to predict and prevent. Since the tankage systems being studied involve either spherical or compound curved surfaces, it is necessary that the laminar insulation be installed in small segments to obtain proper conformity to the inner vessel surface. Under vibration, the pieces may move slightly, causing them to compress in some areas or leave voids between the pieces of insulation. As a result, conductive heat shorts occur at the points of insulation buildup, and radiant heat shorts exist in the void areas. Prevention of these conditions is very difficult, and all degrade the effectiveness of the insulation.

The problems arising with powder insulation are similar to laminar insulation, but generally more serious. The powder will settle and pack in some areas, leaving insulation voids in other regions. Since powder insulations are composed of more than one substance, the varying size and density of the particles lead to separation of the powder with respect to grain size. This would lead to varying heat input characteristics during use.

While discrete shield insulation is also subject to several vibration and shock problems, these are more amenable to control or elimination through proper design. Since isothermal mounting of the shields is important to minimize heat input to the stored cyrogen, the number of mounting points must be minimal. For weight optimization, the shields must necessarily be fabricated from very thin material. However, when subjected to vibration, there is a possibility of obtaining large vibratory motions of the shields which could cause shield damage and possible conductive heat shorts due to physical contact between the shields and inner vessel and/or outer shell. These problems can be eliminated or reduced without sacrificing weight by being selective as to type of shield material and thickness, by properly locating shield mounting points and employing a technique to reinforce the shields.

Vapor-cooled shields are subject to the same factors as the discrete shields. However, although the vapor cooling coils will add more mass to the shields, they will also increase the rigidity of the shield which will prevent in part the flexing and bending of the shell.

Insulation Reliability Comparison

When applying the term "reliability" to insulation techniques, there are two distinct factors to consider. The first involves the ability to obtain identical heat-input characteristics when more than one system is produced, and the other involves the stability of these characteristics throughout the useful life of a system.

Laminar insulation is somewhat deficient for both factors, especially when used on spherical or other curved surfaces. Since it is produced in flat sections, it must be cut into smaller segments before it can be applied to curved surfaces. When fitting these segments to the curved surface, some bunching and wrinkling of the insulation occurs, and this results in variable "density" of the insulation. Thus, the variable "density" has an important degrading effect upon the effectiveness of the insulation, and severly restricts the duplicating of characteristics in multiple vessel production.

Since the area between the inner vessel and outer shell is made up of high vacuum for additional insulation, the material surface exposed to the vacuum is subject to outgassing of adsorbed gases. Due to its mode of fabrication, the insulation effectiveness of laminar insulation is adversely affected by its surface area, and this makes it increasingly difficult to maintain a stable vacuum throughout the life of the system. In addition, the segments of insulation may move slightly during motion of the system causing a change in the insulation density and a varying of the heat input during use.

Powder-type insulations are comparable to laminar insulation with respect to reliability, and the varying packing densities make repeatable results impossible to achieve. The large surface area of the powder causes serious outgassing problems which result in a rather unstable vacuum level. When the system is being used the motion can cause a separation of the powder by material and/or grain size. This can cause instability of heat leak characterisitcs.

The effectiveness of a discrete shield or vapor-cooled shield is dependent, to a large extent, upon obtaining a low emissivity surface on the vacuum exposed surfaces. To assure repeatable results, these surfaces must have consistent plating quality, and the handling of them must be restricted as much as possible to an inert gas atmosphere. Experience has demonstrated that this is not an extremely difficult condition to meet, and that the results are quite easily reproduced.

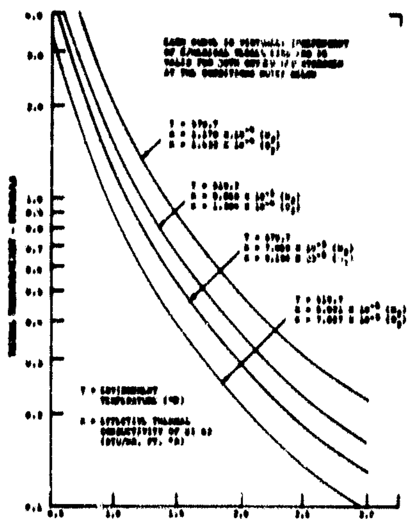
The use of shield-type insulation has produced desirable stability. Outgassing problems are minimized because the surface area exposed to the vacuum is relatively small. The vacuum protects the surfaces from emissivity degradation which enables the heat leak characteristics of the system to remain quite stable during its life. Normal motion experience during use has no effect on the effectiveness of the insulation. It would be necessary for the motion to be of such severity that the shields were materially damaged, resulting in conductive shorts.

Summary

Based on the data presented in this chapter, several conclusions can be made concerning the most advantageous insulating technique for present and future applications.

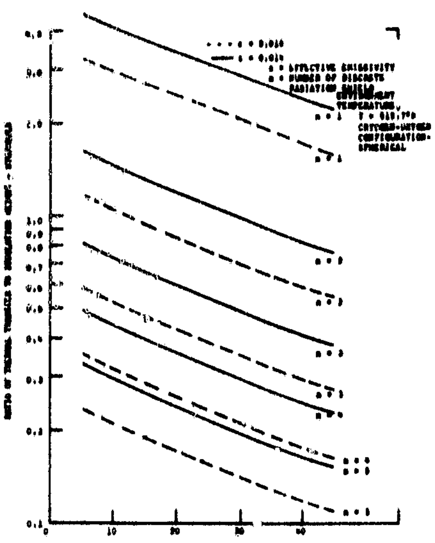
Powder insulation, for instance, possesses good thermal and weight characteristics. However, degradation of its thermal properties because of powder separation under vibration or extended handling tends to limit its capabilities for aerospace applications. As a result powder insulation has received limited usage and consideration.

Laminar insulation has received broad application and demonstrates several important advantages. Thermal



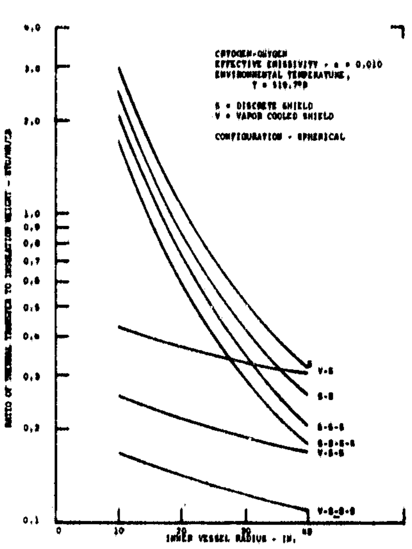
RATIO OF THERMAL TRANSFER TO WEIGHT AS A FUNCTION OF SI-62 LAMINAR INSULATION THICKNESS

Figure 7-24



RATIO OF THERMAL TRANSFER TO DISCRETE SHIELD INSULATION WEIGHT AS A FUNCTION OF INNER VESSEL RADIUS

Figure 7-25



RATIO OF THERMAL TRANSFER TO INSULATION WEIGHT AS A FUNCTION OF RADIUS FOR COMBINATIONS OF VAPOR COOLED AND DISCRETE RADIATION SHIELDS

Figure 7-26

and weight properties are adequate but fabrication and reliability are less certain due to the artisan techniques required during fabrication.

Both discrete and vapor cooled shields have been verified as being superior to laminar insulation in many respects. Artisan effects are much less important during fabrication. This results in a more defined system and a closer adherence to predicted results. This design has proven structurally sound and lends itself to weight optimization due to its reliability.

To evaluate the thermal capabilities of a particular insulation technique, a dewar possessing an inner vessel radius of 20 inches, and equipped with 2.5 inches of laminar insulation was used for comparison purposes. A conductivity of FTC = 5 is assumed since this represents the present state-of-the-art. An environmental temperature of 60°F is used. The three graphs in the column at left show the results of this comparative analysis.

The top figure shows that the 2.5 inches of laminar insulation results in a thermal transfer per unit weight of .25 BTU/hr/lb. for both oxygen and hydrogen.

The center figure shows that depending upon the emissivity, that four or five discrete radiation shields will provide the same ratio for oxygen.

It is also shown that five shields require 1.5 inches of annular space, resulting in an outer shell which is 2.00 inches smaller in diameter.

The lower figure demonstrates that one vapor cooled shield located within two discrete radiation shields will give equal performance for oxygen, and in addition will result in an outer shell diameter 2.50 inches less than the laminar insulation.

When considering powder insulation, more than 2.25 inches of Cab-O-SIL H-5 will give comparable results at the nominal conductivity value employed herein for oxygen.

Considering this same set of conditions with hydrogen storage gives approximately the same set of results. However, one less discrete shield is necessary in the case of both discrete shields alone, and vapor cooled and discrete shield combinations. In both cases, the outer shell diameter is reduced by an additional 0.50 inch.

In conclusion, it has been found that the increasingly sophisticated thermal requirements can be met by using combinations of laminar insulation, discrete and vapor cooled shields. This permits the combination of the most desirable aspects of each insulation technique.

To achieve the full effectiveness of these various combinations, certain design techniques have proven particularly advantageous. For instance, vapor cooled shields are generally most effective when placed next to the inner vessel. It has also been found more feasible to place laminar insulation on the outside of the shields, whether they are vapor cooled or discrete. This results in a low thermal transfer per unit weight and presents no serious fabrication problems.

CHAPTER VIII

Support Systems

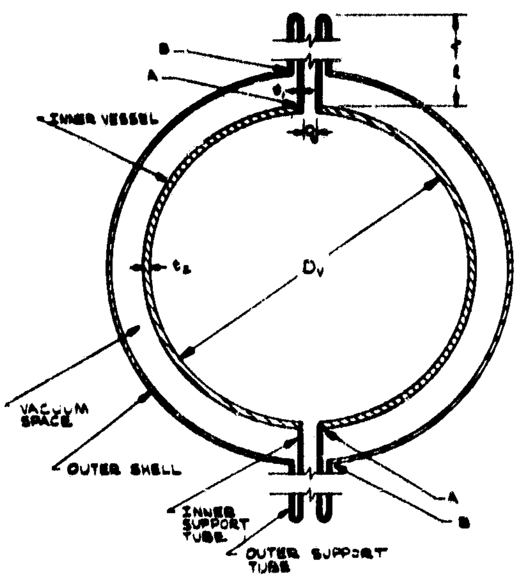
Every cryogenic storage system design must possess both inner and outer support systems that are compatible with the intended usage. Due to the diversity in their design, the outer support systems will be treated separately in Chapter IX.

There are four basic inner support system designs that have either had considerable past usage or lend themselves to practical application. Specifically, these designs are:

1. Neck Tube Design
2. Wire Suspension Design
3. Radial Bumpers Design
4. Post Type Design.

This chapter is designed to present a detailed discussion of each of these inner support systems, followed by a comparative analysis of their structural, thermal, and fabrication and assembly characteristics.

Neck Tube Design



BASIC NECK TUBE DESIGN
FIGURE 8-1

The neck tube design, as shown at left, supports the inner vessel with two tubes that are enclosed within concentric tubes running for some distance from the inner vessel. The space between the concentric tubes is subject to the same vacuum as the space between the inner and outer vessels, hence affording insulation to thermal conduction between the tubes.

In addition to providing support, these tubes can be utilized for filling, venting and withdrawal from the inner vessel.

This design concept provides a combination beam and column type of support depending upon the direction of acceleration to which the inner vessel is subjected. When the system is subjected to accelerations in the direction of the axes of the support tubes, the tubes will be subjected to compressive and tensile loads. If the direction of acceleration is perpendicular to the axes of the support tubes, they would be subjected to predominantly shear and buckling loads, which would be more critical than the tensile and compressive loads. Since the outer support tubes are not important factors in the heat path to the inner container, their size may be increased to add structural stability to the system without degrading the thermal characteristics of the storage system. The inner support tubes, however, must exhibit minimum cross-sectional areas for thermal conductivity reasons and may be expected to be susceptible to a buckling mode of failure.

When the system is subjected to accelerations in directions other than those parallel and perpendicular to the axes of the support tubes, the tube loading can be expected to be combinations of the conditions. Hence, it can be seen that the materials chosen for a support system of this type should have high tensile yield strengths in order to withstand force components in the axial direction accompanied by a high moduli of elasticity in order to resist buckling.

Vessel size variations will not appreciably effect the types of loads imposed on the components of this support system if the support tubes are located on the axis of symmetry of the inner vessel. The changes in load magnitudes due to vessel size variations will stem from two sources, namely increased inner vessel mass and increased inner vessel capacity. The masses of vessels having two of the most commonly used shapes may be calculated from the following equations.

Spherical Vessels

$$M = \pi/6 \left[\rho_v (D_v + 2t_2)^3 + D_v^3 (\rho_f - \rho_v)\right]$$

where:

D_v = Inside diameter of vessel

t_2 = Vessel wall thickness

ρv = Density of vessel material

ρ_f = Average density of vessel contents

Cylindrical Vessels with Hemispherical Heads

$$M = \pi/6 \left[\rho_v (D_v + 2t_2)^3 + D_v^3 (\rho_f - \rho_v)\right] + \pi L/4 \left[\rho_v (D_v + 4t_2)^2 + D_v^2(\rho_f - \rho_v)\right]$$

where:

L = Length of cylindrical section

Note: In this equation t_2 = thickness of the hemispherical ends and it has been assumed that the thickness of the cylindrical section is twice that of the hemispherical sections. This assumption is justified by the fact that it produces equal theoretical burst pressures for simple spheres and cylinders having the same inside diameter.

Thermal Characteristics

The conductive heat paths inherent in this system are easily defined and analyzed. They consist simply of the two support tubes connecting the inner vessel to the outer shell. In addition, the conduction through the gas or fluid in the support tubes will contribute slightly to the heat leak of the vessel. However, if the vessel plumbing is properly designed, the tubes will contain only gas or supercritical fluid depending upon the mode of operation of the particular storage system. Since these media display coefficients of thermal conductivity approximately 500 times smaller than most solids, this particular heat path may be neglected for the purposes of simplifing the preliminary analysis.

The conduction of the support tubes may be represented simply by the equation

$$C = \frac{A\,k}{\ell} \Delta T \qquad (1)$$

where:

- C = Thermal conduction
- A = Cross-sectional area of heat path
- k = Coefficient of thermal conductivity of the conducting material (average)
- ℓ = Length of heat path
- ΔT = Temperature differential across the conductor

The cross-sectional area of the neck tube shown previously is

$$A = \pi t_1 (D_t + t_1)$$

where:

- t_1 = tube wall thickness
- D_t = inside diameter of tube

Substituting into equation (1) the conductive heat transfer is

$$C = \frac{\pi t_1 (D_t + t_1) k \Delta T}{\ell} \qquad (2)$$

The effects of static and dynamic loading of the inner vessel on the thermal conductivity of this type of system are negligible. This is because the dimensions of the most significant heat paths (support tubes) are not altered by such loads. Nor are there any variations in contact areas of system components since the support tubes must be securely joined to the inner vessel and outer shell. These factors mean that the heat input to the contained fluid through the suspension structure is the same in a weightless environment as in an accelerating or gravitational one.

<u>Materials</u>

In view of the foregoing structural and thermal discussions, it is apparent that the tube material must exhibit high elastic modulus and tensile yield strength accompanied by low thermal conductivity. It must retain these properties at cryogenic temperatures.

Following an analysis of material candidates, Inconel "718" and titanium alloys display the most desirable characteristics, followed by maraging stainless steel (AM-362). While the titanium alloys met all the previously discussed material requirements, impact tests have shown them to be incompatible with liquid oxygen and possibly susceptible to Hydrogen embrittlement. Titanium alloys are thus questionable.

Aluminum and Kel-F were ruled out as material candidates since they showed degradation when subjected to the evacuation and bakeout process of the dewar annular space.

Fabrication and Processing

Aside from a long lead time, the parts making up the neck-tube design present no particularly difficult fabrication problems.

This type design offers a relatively simple means of supporting the inner vessel and associated components during the dewar assembly. However, this is offset by the disadvantages of the design.

In particular, this design requires a minimum of three structurally sound leak tight joints for each support tube. Welding has been shown to produce the best structural strengths and leak characteristics. This however, restricts the choice of neck tube material to the same or similar alloys as used for the inner vessel and outer shell, and this restricts the optimization of support system thermal conductivity.

In addition, this design permits contact of the stored fluid with the inner vessel support members. As was previously shown, this eliminates usage of such material as titanium, which otherwise displays the best strength and thermal characteristics.

Suspension System Heat Transfer

Through past experience, Bendix has accumulated experimental heat leak data involving various suspension techniques. The following table shows the heat leaks attributable to the support tubes for two one-cubic foot capacity dewars.

The data represents the heat transfer through both neck tubes. The information was obtained using liquid oxygen as the contained fluid with the exterior of the dewar exposed to ambinet room temperature and the system vented to atmospheric pressure.

NECK TUBE SUPPORT HEAT TRANSFER

	TUBE DIMENSIONS			HEAT LEAK THROUGH SUPPORT TUBES	
	LENGTH	OUTSIDE DIAMETER	WALL THICKNESS	ACTUAL	THEORETICAL
(A)	1.14"	0.875"	0.010	14.0 Btu/hr.	11.2 Btu/hr.
(B)	2.28"	0.875	0.005"	3.6 Btu/hr.	2.8 Btu/hr.

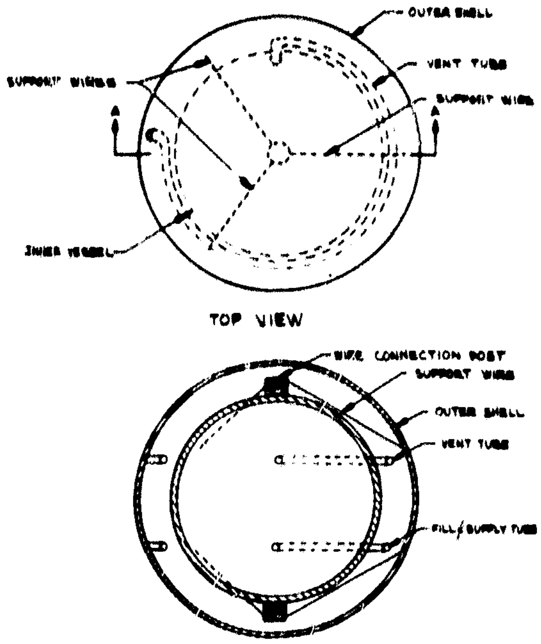
It can be seen that the theoretical values for the conduction of heat through the support tubes are somewhat less than the experimentally observed heat leaks. This is attributable to radiant heat absorbed by the support tubes, tolerances in tube wall thickness and diameter and changes in effective length of the tubes due to weld joints at the end.

It should be pointed out that data accumulated from tests on neck tube dewars indicates that case (b) above would be unable to pass the physical specifications (vibration, shock, etc.) for use in aircraft even with isolation mounting of the system. These support tubes suffer buckling failures when the system is subjected to accelerations in directions perpendicular to the axes of the tubes as a result of vibration.

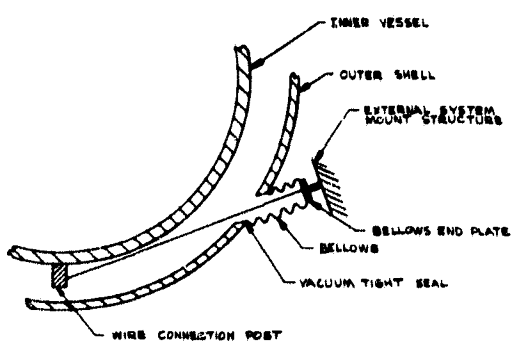
Wire Suspension Design

The wire suspension design is worthy of consideration since wires basically exhibit higher tensile strengths than normally attributed to the parent metal.

The following discussion is therefore, intended to highlight the design features of this system, and to point out the basic advantages and disadvantages that are most predominant.



BASIC WIRE SUPPORT DESIGN
FIGURE 8-2



BELLOW TYPE WIRE CONNECTION
FIGURE 8-3

Structural Characteristics

A detailed schematic of a basic wire suspension design is shown at left. As depicted, the inner vessel is solely supported by wires.

A minimum of six wires (3 at each end of the inner vessel) are required to make the system stable when subjected to forces (gravity and acceleration) in any arbitrary direction. From examination of the figure it is obvious that the tension in the support wires for any given condition of gravity and/or acceleration is dependent upon the angle which the wires make with the support post and with each other. In order for the system to be equally stable when subjected to forces of arbitrary direction the wires at each end must be distributed around the support post at equal intervals.

It is readily apparent that lateral loading of other system components by the inner vessel supports will result in bending moments at the points when the wire connection posts are attached. In the case of thin walled inner vessels which have been weight optimized, this condition will require the utilization of welded or integral reinforcement at the post-inner vessel junction. In addition and equally important is the fact that this type of system imposes rather concentrated bending loads on the outer container shell at the points of wire attachment. This is a very critical type of loading since any deformation of the outer shell tends to promote elastic instability or buckling of the shell which is externally pressurized. This factor again will require additional reinforcing hence necessitating weight sacrifices. It may be possible however, to alleviate these undesirable forces by connecting the end of the wire and the end plate of the bellow which is sealed to the outer shell and then connecting the external side of the end plate to the external system mount structure. The figure at left shows this design.

Vessel size variations will not effect the types (tensile, compressive, bending, etc.) of loads imposed on the components of this support system. It should be noted however, that some loads will increase with increasing vessel size not only because of increased vessel mass and capacity but also because of geometric reasons. As a result the length of the wire attachment posts must be increased as the vessel size increases. This increases the moment arm of the forces producing bending stresses in the inner vessel at the vessel-post joint and therefore, requires additional reinforcing over and above that necessitated normally by the load increases. This post extension is also unfeasible because the accompanying increase of the annular space would necessitate a disproportionate outer shell size and weight increases. Also if the post length problem is avoided by increasing the angle of the post beyond the optimum, the wire sizes must be increased by amounts over and above that necessitated simply by the increased load to be supported. This, of course, means an increased heat path cross-section and the accompanying degradation of the conductive insulation characteristics of the system.

Materials

To meet the structural and thermal requirements imposed on this type of design, the material used for the support wires must possess a high tensile yield strength accompanied by a low coefficient of thermal conductivity. In addition, fabrication, compatibility and availability problems must be considered. Any material selected must be able to retain its mechanical properties at cryogenic temperatures and not become excessively brittle.

The following table shows the readily available room temperature tensile and thermal conductivity properties of some wires exhibiting the necessary qualities.

18-8 STAINLESS STEEL

WIRE DIAMETER (Inches)	MINIMUM TENSILE YIELD STRENGTH (KSI)		COEFFICIENT OF THERMAL CONDUCTIVITY (Btu/Ft.Hr.°F)	T.Y.S./k (KSI/Btu/Ft.Hr.°F)	
	Annealed	Full Hard		Annealed	Full Hard
0.002-0.010	45	280	9.0	5.0	31.1
0.010-0.020	45	280	9.0	5.0	31.1
0.020-0.125	40	210	9.0	4.4	23.3
0.125-0.250	35	180	9.0	3.9	20.0

INCONEL "X-750"

WIRE DIAMETER (Inches)	MINIMUM TENSILE YIELD STRENGTH (KSI) Annealed	As Drawn*	COEFFICIENT OF THERMAL CONDUCTIVITY (Btu/Ft.Hr.°F)	T.Y.S./k (KSI/Btu/Ft.Hr.°F) Annealed	As Drawn*
0.020	51	233	6.9	7.4	33.8

* 65% Cold Reduction

As indicated by the table, any annealing of the support wires during assembly (due to operations such as welding or brazing) would have structurally deleterious effects unless the design utilizes the annealed strength of the wire. From the data in the table it can be seen that this would increase the thermal conductivity of the systems considerably due to the required increases in the wire cross-sections.

Fabrication and Processing

Assembly problems encountered with the wire suspension design result in several disadvantages. Initially, a rather elaborate technique is required to support the inner vessel during assembly of radiation shields and/or other types of insulation and associated equipment in the annular space. This support problem will also carry over to the outer shell fitup and welding operations. Likewise, if the system is designed to transmit the support wire tensions to the external system support structure the additional problem of supporting the system prior to assembly of the external mount structure would be present. Secondly, this design presents some difficult problems in the area of wire end connections. It will undoubtedly be necessary to provide a wire tension adjustment in order to equalize the tension in the support wires. If such an adjustment mechanism is external to the outer shell, a flexible leak tight joint must be provided between the wire and the outer shell such as the bellows shown previously. Otherwise, the system would have to be designed in such a manner as to have the wire adjustment mechanism within the annular space and provide access holes for tension adjustment which would subsequently be closed by welding, brazing or some other suitable means. In any event the problem of wire connection and adjustment can present fabrication complexities and additional possible leakage points.

If other than welding or brazing are used to attach the support wires to the inner vessel support posts, this design does have the advantage of uninhibited inner vessel material choice. Similarily, outer shell material choices are not inhibited if wire connection methods are limited to non-fusion type processes.

Suspension System Heat Leak

Since the conductive heat transfer of this suspension system is primarily through the support wires, a theoretical value for the conductive heat leak of an example dewar can be easily calculated with relative accuracy.

This can be accomplished by the following equation.

$$dQ/dt = k \frac{N \times A}{L} \Delta T$$

where:

dQ/dt = rate of heat flow through the suspension system

k = coefficient of thermal conductivity of the wires

N = number of wires

A = cross-sectional area of each wire

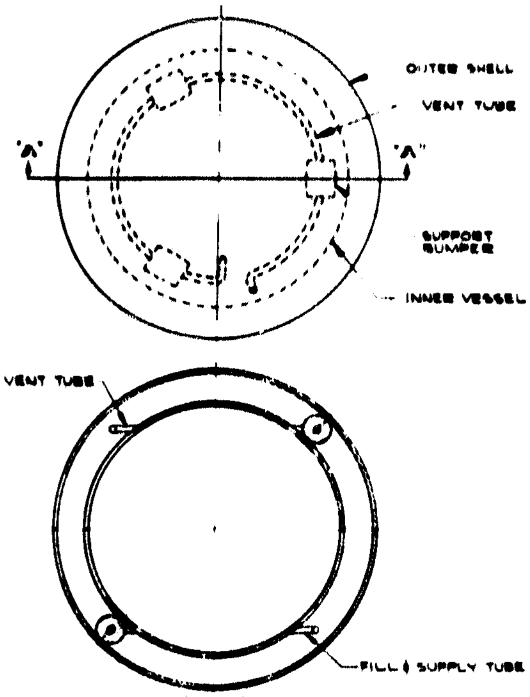
L = length of each wire

ΔT = temperature differential across wires

The following table is illustrative of the data generated in applying this equation to an example dewar.

SUSPENSION SYSTEM HEAT TRANSFER

INNER VESSEL DIAMETER (Inches)	HEAT TRANSFER-dQ/dt (Btu/Hr) ANNEALED WIRES	FULL HARD WIRES
14.90	4.81	0.80
20.00	16.02	2.76
30.00	50.16	9.87



BASIC RADIAL BUMPER DESIGN
FIGURE 8-4

BASIS:

Contained Fluid - Liquid Oxygen - 100% Full
Vacuum Space - 1"
Wire Tangent to Inner Vessel
Post Length - 3/4"

These results are based upon the following data:

(1) The coefficient of thermal conductivity for stainless steel of 9.0 Btu/ft. hr. °F.
(2) The use of 6 wires.
(3) A wire diameter of 0.0669 inches for the full hard wire and 0.164 inches for the annealed wire.
(4) A wire length of 7.41 inches or 0.618 ft. each.
(5) A temperature differential of 375°F, which represents the difference between room temperature of 78°F and the boiling temperature of oxygen at atmospheric pressure of -297°F.

Radial Bumper Design

The radial bumper design utilizes roller-type bumpers to support the inner vessel within the outer shell. This design exhibits good structural characteristics and is very adaptable for dewar fabrication and assembly.

Structural Characteristics

A schematic of the basic radial bumper design is shown at left. As shown, the inner vessel is supported by roller type bumpers which are located in two horizontal planes and utilize the vent, fill and supply tubes as axles.

The utilization of these annular tubes as bumper axles serves two purposes. First, they insure that the annular tubes do not contact the inner vessel or outer shell unnecessarily, which would result in shortened heat paths. Secondly, they positively position the bumpers at their desired location points.

A minimum of six bumpers are normally required to stabalize the system when it is subjected to forces (gravity and acceleration) in any arbitrary direction.

The support bumpers are located between two concentric spheres. All gravitational and/or acceleration loads imposed on the inner vessel will be transmitted to the outer shell as pure compressive loads on the bumpers and the direction of these load vectors will be through the center of gravity of the inner vessel. As shown, the load on the bumpers for any given condition of gravity and/or acceleration is dependent upon the location of the bumpers relative to the direction of the force and relative to one another. In order for the system to be equally stable when subjected to forces of arbitrary direction, each set of bumpers lying in the same plane must be equally distributed about the vertical axis of the inner vessel.

In the case of the example shown, wherein there are three bumpers in each plane, they must be located at 120° intervals.

As the size of the inner vessel increases, the number of support bumpers is correspondingly increased.

In actual practice, the inner vessel will be subjected to both membrane and shear stresses due to the compression of the bumpers. Where these stresses exceed the maximum allowable stress for a given inner vessel, they may be relieved by using stress distribution plates located between the bumper and the vessel. The values of the shear and membrane stresses may be calculated as follows.

<u>Shear Stress due to Bumpers</u>

$$\sigma_s = \frac{S \times F}{\pi d t}$$

where:

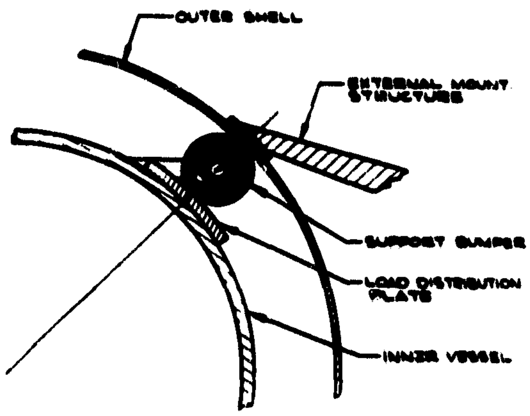
σ_s = shear stress

S = safety factor

F = maximum load on bumper due to gravity and acceleration

d = diameter of load distribution plate

t = vessel wall thickness



EXTERNAL SUPPORT OF INNER VESSEL

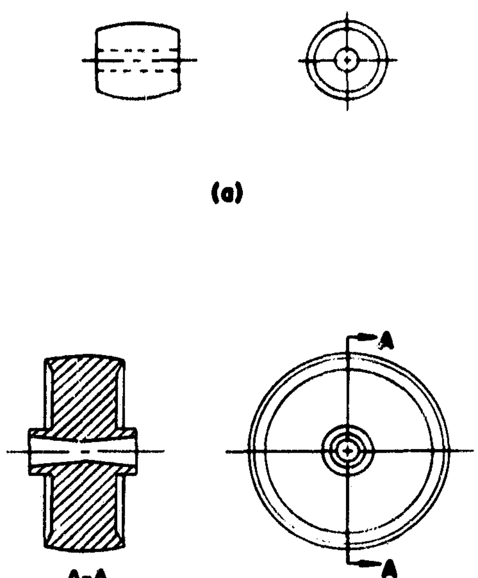
FIGURE 8-5

If σs is replaced by the maximum allowable shear stress for the material being utilized, then this equation can be solved for d. Hence, the size of the stress distribution plate required to reduce the shear stresses to a safe value can be determined.

The load distribution plate must be designed to produce safe levels of both shear and membrane stresses. Hence, the largest value of "d" must be utilized. If the diameter of the required plate does not exceed the area of contact provided by the bumper alone, however, the plate need not be used.

The same loads must be considered for the outer shell as were discussed above for the inner vessel if the outer shell is to support the loads imposed by other bumpers. However, it is possible to alleviate these loads on the outer shell by transmitting them directly to the external mount structure as shown at left.

Vessel size variations will not effect the types of loads (compressive, tensile, etc.) imposed on the components of this support system. The magnitudes of these loads will be a function of the supported mass, environmental conditions (gravity, acceleration) and the number of bumpers utilized.



(b)

TYPICAL SUPPORT BUMPER SHAPES

FIGURE 8-6

<u>Thermal Characteristics</u>

The predominant heat path inherent to this design is the conductive path through the support bumpers. Two typical bumper shapes are shown at left.

As shown, the shapes are basically cylindrical with an axial curvature.

This curvature is intended to reduce the area of contact of the bumper with the inner vessel and outer shell. In addition to this curvature, the bumper in the lower figure has a tapered center hole which limits the area of contact between the bumper and the tube which acts as its axle. It should also be noted that the radius of axial curvature is always greater than the radius of the bumper since this prevents the bumper from rolling in a sideward direction when in position between the inner vessel and outer shell.

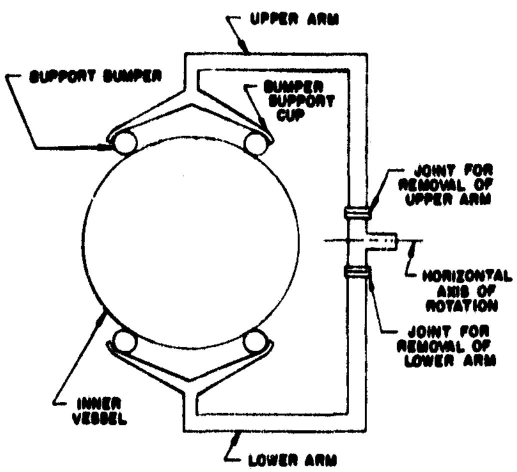
One parameter which must be considered when discussing the thermal characteristics of this design is cooling of the bumper during the vent and supply modes of the operation. It can be seen that some heat will be transferred from the bumpers to the affluent fluids since the vent and supply tubes act as the bumper axles. However, most bumper designs endeavor to minimize heat transfer between the bumper and axle tube since the tube may become an intermediate heat path from the inner vessel to the outer shell when no cooling fluid is passing through it.

As vessel sizes increase the conductive heat transfer to the inner vessel can be expected to increase due primarily to two factors. First the area of contact of the bumpers with the inner vessel and outer shell will increase due to the added load causing increased bumper distortion and contact pressure. Secondly, the greater number of bumpers required to support additional inner vessel and contained fluid mass will provide additional conductive heat paths. The nature of this increase in conductive heat transfer is extremely complex since the distortion and hence the contact area of a shape as complex as that of a bumper is difficult to predict.

Static and/or dynamic loading of the inner vessel can be expected to have considerable effect on the thermal conductivity of this type of suspension system. This stems from the fact that in a gravity of acceleration environment some of the support bumpers will be distorted to a greater extent than if these forces were not present. This distortion will result in increased areas of contact, and hence increased thermal conductivity of the system. This means that in a weightless environment this bumper distortion will decrease to a minimum and the suspension system thermal conductivity will be reduced accordingly.

Materials

Any material used for the support bumpers must have a very low coefficient of thermal conductivity. It must also have a reasonably high modulus of elasticity to prevent excessive distortion which would result in increasing the contact area between the bumper, inner vessel and outer shell.



SUPPORT STRUCTURE FOR ASSEMBLY

FIGURE 8-7

Metals are not considered as good bumper materials due to their high coefficients of conductivity. In addition, to utilize their high strength characteristics would require a minimal number of bumpers to support the inner vessel. To offset the accompanying high levels of stress concentrations would necessitate larger and heavier stress distribution pads.

Fluorocarbon plastics display appealing characteristics for use as bumper materials. Both "Teflon" and "Kel-F" have been utilized successfully. "Kel-F" has a higher strength and modulus of elasticity than "Teflon TFE." However, these properties degrade rapidly above 300°F. As a result, thermal-vacuum processing must be carried out at lower temperatures when "Kel-F" is used. Both of these materials are very stable and resist degradation when subjected to hard vacuum at temperatures below those mentioned above. The strength properties of "Teflon" can also be enhanced by adding a glass fiber filler, but this has an accompanying effect of increasing the coefficient of thermal conductivity.

Fabrication and Processing

Parts fabrication represent no particular problems since they can be fabricated by either machining from bar stock or casting.

The bumper suspension system affords an easy means of supporting the inner vessel during assembly of radiation shields and/or other types of insulation and associated equipment within the annular space. This is accomplished by supporting the system by the bumpers within a yoke as shown at left. The yoke is made such that the upper and lower arms may be removed. The vessel may be oriented in either the upright or upside down positions, with the upper arm being removable to allow assembly of equipment. Outer shell fitup can be accomplished in the same manner by using support rings on the yoke arms instead of bumper support cups.

This design allows unlimited flexibility in material choice for components, since the bumpers are not physically fastened to either the inner vessel or outer shell.

Suspension System Heat Transfer

The curves shown in the figure at the bottom of this page are the result of calorimeter tests showing the conductive heat transfer of several support bumpers of different sizes, shapes and types of construction.

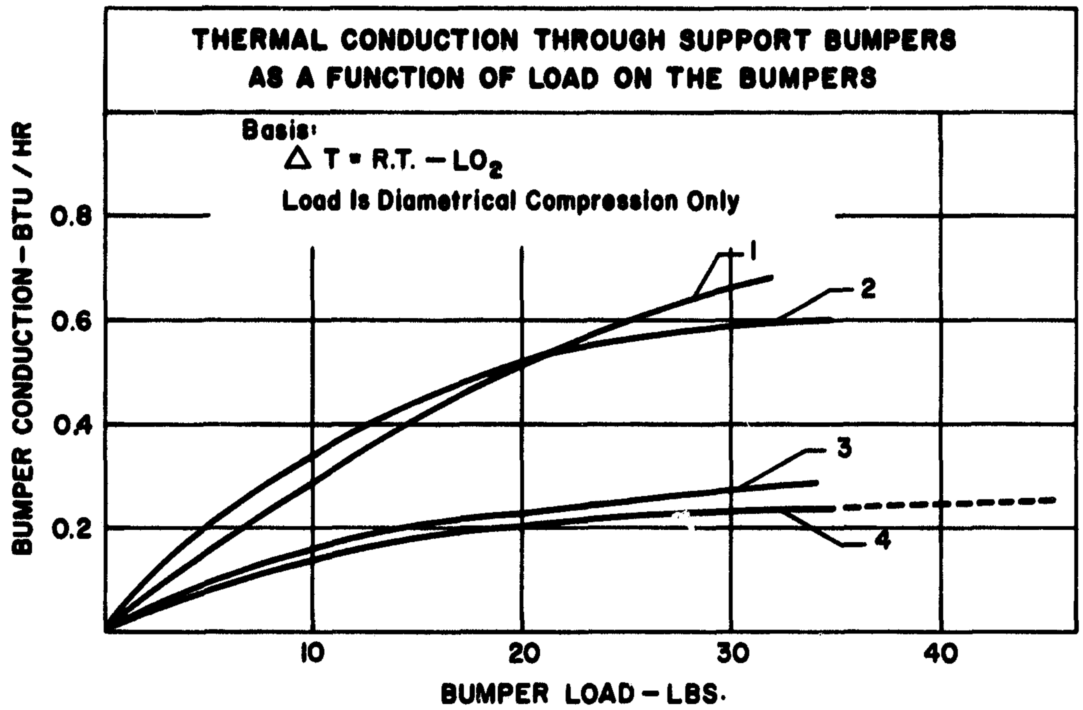


FIGURE 8-8

The calorimeter was assembled with three test bumpers in place between the inner vessel and outer shell. The annular space was then evacuated and the inner vessel was filled with liquid oxygen. The draw bolt was first adjusted such that the inner vessel did not contact the support bumpers and the flow rate of the boil-off gas was determined by means of a wet test meter. Next, the inner vessel was lowered until it contacted the bumpers and a load was applied by means of compressing the springs on the draw bolts. In this manner various loads were applied to the bumpers and the magnitudes of these loads were determined by measuring the compression of the springs and weighing the calorimeter to determine the weight of the contained fluid. By knowing the heat of vaporization of liquid oxygen, the flow rates were converted to the heat transfer rate of the dewar. The changes in this rate after the inner vessel had made contact with the support bumpers were due to bumper conduction. In this manner, bumper conduction values were determined for different loading conditions.

The bumpers were of the following materials and construction.

Curve #1 - A segmented bumper having eight 25% glass-filled Teflon bumper segments and a 1.75" outside diameter.

Curve #2 - A segmented bumper having six 25% glass-filled Teflon bumper segments and 1.14" outside diameter.

Curve #3 - A solid bumper made of Kel-F and having an outside diameter of 2.00".

Curve #4 - A solid bumper made of Kel-F and having an outside diameter of 1.125".

The tests showed that segmented bumpers did not possess the low thermal characteristics obtained from the solid construction type. This may be due to the fact that the segmented type of construction requires the use of several metal parts such as the spindle and segment retaining cups. These parts have higher conductivity and may cause a significant increase in the overall conductivity of the bumper. In addition, it should be noted that the solid bumpers tested were fabricated from Kel-F while the segmented bumpers were fabricated from 25% glass-filled Teflon which has a coefficient of thermal conductivity 1.7 times that of Kel-F. However, taking this factor into consideration it does not appear that segmented bumpers of the types tested will display conductivities lower than those of similar sized bumpers of solid construction. Another disadvantage is that the load bearing capabilities of the segmented bumpers is considerably less than that of the solid type.

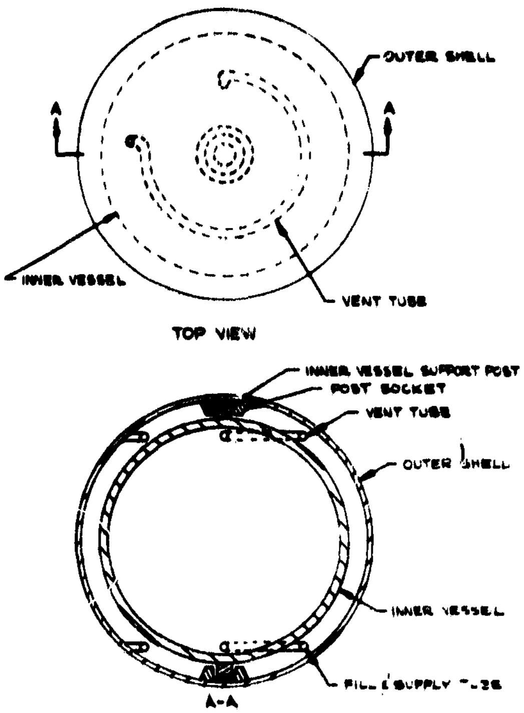
The important thing to note about these curves is that the slope decreases with increasing load on the bumper. That is the thermal conduction of the bumper is less than linear with supported mass. This is the only support system thus far investigated which has displayed this appealing characteristic. This characteristic can probably be attributed to the relationship between load and contact area of the bumper and vessel.

It can also be seen from these curves that as the bumper load increases, the thermal conduction through the support bumpers becomes nearly constant. Hence, it can be expected that conduction will increase only slightly with increasing mass to be supported up to the point where the bumpers are loaded to their maximum at which time additional bumpers must be added increasing the conduction of the system proportionally.

The conductive heat transfer of the bumper suspension system of a one cubic foot spherical vessel containing liquid oxygen was analyzed with good results. The example dewar utilizes the bumpers represented by curve #4. A 0.30" thick stainless steel inner vessel was used. The combined weight of the vessel and its contents when full is then 77.9 pounds. Since the heat leak of this system is somewhat dependent on position, the sample dewar is considered as being positioned vertically with the inner vessel supported by three bumpers in a 1g field. Since in this position the weight of the inner vessel is compressing the lower bumpers it can be expected that the three upper bumpers are making only slight, if any, contact with the inner vessel and that they will introduce negligible heat to the system.

A load on each of the three supporting bumpers has been determined to be 45.3 pounds. Even though curve #4 does extend to this load level, the slope of the curve at the upper end indicates that the heat transfer rate at that level will not exceed 0.23 Btu/hr. for each bumper. The total heat transfer through the bumpers can therefore be expected to be 3 x 0.23 = 0.69 Btu/hr. Adding to this the heat leak through the annular tubing which is 0.12 Btu/hr. for this size vessel, the total support system heat transfer will be 0.8. Btu/hr.

In addition to producing a very desirable heat leak, the bumper design provides a worthy inner vessel support concept for dewars of almost any size.



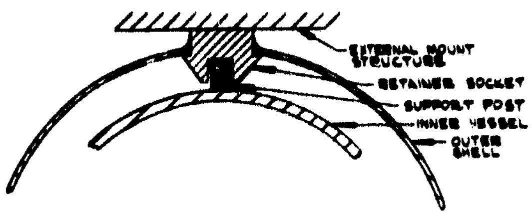
BASIC POST SUPPORT SYSTEM
FIGURE 8-9

Post Support Design

The post support design utilized post type protrusions from the inner vessel for support and positioning of the vessel. These posts fit into sockets secured to the outer shell. The basic schematic of this design is shown at left.

Structural Characterstics

As the schematic shows, the inner vessel is solely supported by the support posts. These posts are subjected to predominantly two types of loads when the system is subjected to forces (gravity and/or



EXTERNAL SUPPORT OF INNER VESSEL
FIGURE 8-10

acceleration) in any arbitrary direction. Components of such forces in the direction of the axes of the support posts will cause compression of the post located in the direction of that component. Force components in the direction perpendicular to the axis of the support posts will cause shear loads on the posts if the postsocket fit is relatively close.

As with all systems in which the supporting members are physically attached to the inner and/or outer shell, the imposition of inner vessel loadings can cause bending forces to be imposed on the inner vessel and outer shell necessitating welded or integral reinforcement. These bending forces may be alleviated from the outer shell by connecting the post retainer socket directly to the external system mount structure such as shown at lower left.

Thermal Characteristics

The heat paths inherent in this system consist of the support posts, retaining cups and the post-cup interfaces. The interface is the most favorable location for the utilization of limited contact area and/or laminated type connections in order to minimize heat flow. Since the forces in the interface region are compressive in nature, it is possible to utilize low thermal conductivity non-metallic materials. Due to structural and space limitations, it is necessary to limit the support post length, and for these reasons it is necessary to depend primarily on designing the interface for the greater part of the thermal resistance to heat flow.

Since the tubing used for the fill, vent and supply lines is not required to support structural loads, this design increases the heat path by allowing the tubing to run for a greater distance in the annular space.

As the vessel size is varied, it is expected that the cross-section area of contact at the post-cup interface will vary linearly with the supported mass for any given set of environmental requirements (shock, vibration, acceleration). Therefore, for any given application the heat input through the support system is expected to vary linearly with the combined mass of the inner vessel and contained fluid.

The effects of static and dynamic loading of the inner vessel on the effective thermal conductivity of this type of suspension system is dependent on the degree of loading. This is because there is a significant variation in heat path area and the variation in conduction will stem from changes in the interfacial contact pressures. This means, of course, that the effective thermal conductivity of the system is quite different in a weightless environment than in a gravitational field.

Materials

Materials used for the post-cup interface region must have high compressive yield strength combined with low thermal conductivity. More specifically, they should display a large ratio of compressive yield strength to thermal conductivity. For ease of fabrication and welding compatibility, the actual post and retainer cup should be made of materials similar to those used for the inner vessel and outer shell.

The prime material selection rests with the inserts or laminations which fit between the retainer cup and support post to provide maximum conductive insulation. Titanium alloys and Inconel 718 display the most desirable characteristics. Kel-F and Teflon TFE also have good strength to conductivity ratios.

Fabrication and Processing

Aside from obtaining close tolerances on the components, fabrication presents no forseeable problems. Close component tolerance is necessary to eliminate lateral play when the system is subjected to dynamic loading.

One particular advantage of this design is that dissimilar materials can be used in the post-cup interface area. This eliminates the need for structually sound transition joints since all interfacial forces would be primarily compressive in nature and any inserts or laminations are held in place by these forces. Thus, materials with more desirable thermal properties than those used for the inner vessel and outer shell can be used for the retainer cup and support posts.

With this design, the support posts provide a ready means of supporting the inner vessel during the installation of thermal radiation shields and other associated insulation and components in the annular space.

As would be expected, there are also disadvantages associated with this design. First, there is no acceptable point of structural support for positioning the radiation shields and/or other types of insulation. This is because the support posts are almost completely enclosed within the retainer cups.

Secondly, this method of support will probably require a retainer cup adjustment mechanism, especially for large vessels, in order that the post cup fit may be adjusted after final outer shell welding has been completed. This requirement would necessitate the design of a moving vacuum tight joint or the welding of the retainer cup to the outer shell after final adjustments have been accomplished.

Overall Comparison Inner Vessel Support Systems

When comparing the various inner vessel support systems discussed in this chapter, it is necessary to evaluate their relative desirability for spacecraft cryogenic storage system usage. From this standpoint, there are three basic areas of evaluation.

1. Structural Characteristics
2. Thermal Characteristics
3. Fabrication and Assembly Characteristics

The first two factors bear directly on system performance, while the third factor controls scheduling, cost and system reliability.

Based upon the investigations and data collected throughout this study, the radial bumper design was found to be most desirable in all three areas of evaluation. The designs under consideration are shown in their decreasing order of desirability.

1. Radial Bumper Design
2. Post Support Design
3. Neck Tube Design
4. Wire Suspension Design

Structurally, every inner vessel support system design must be based on minimizing thermal conduction to the stored cryogen and reducing system weight. Thus, structural integrity cannot be evaluated without including the equivalent thermal conduction characteristics.

To justify the above order of rating, it should be pointed out that the radial bumper design has shown through experience to be superior when subjected to both dynamic and static loadings of the type which would be expected in spacecraft applications. In addition, the thermal conduction of this type of system is very appealing as can be seen by comparing the conductive heat input of a one cubic foot liquid oxygen tank using this type of support with similar tanks using the other types of support. This information is given in the discussions of the respective support designs. The wire suspension design is rated lowest because it appears to be dangerously susceptible to destructive resonant frequencies when subjected to vibratory loads. Also, though it provides a low thermal conduction in the one cubic foot example tank, the thermal conduction of this system increases very rapidly as the tank size increases. The other two types of support systems fall between these two extremes.

The fabrication and assembly of an inner vessel support system must take into consideration more than the relative difficulties involved in the fabrication and assembly of the components making up just the support mechanism. Consideration must also be given as to the effect this design has on other components in the areas of fabrication techniques, material choices, component configuration and order of processing.

The radial bumper has been rated ahead of the others studied since it provides ease of assembly accompanied by a minimum number of constraints on the design of other system components such as inner vessel and outer shell. The neck tube and post type designs display similar advantages and disadvantages from a fabrication and assembly point of view. The neck tube design, however, has been rated the better of the two due primarily to its greater simplicity. The wire suspension system was rated last due to the assembly difficulties exhibited by this design.

CHAPTER IX

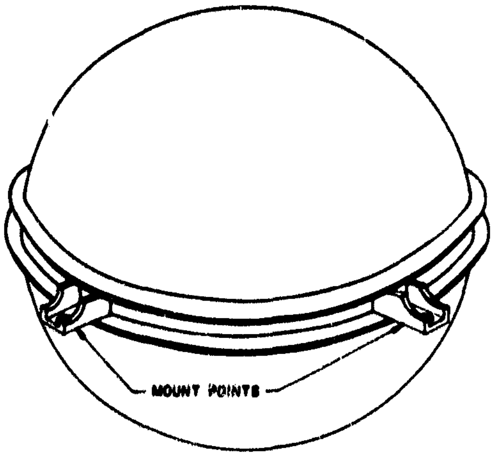
EXTERNAL SUPPORT STRUCTURES

Before the design of a cryogenic storage system can be considered as complete, the design must include a means of transporting the system as well as mounting it to the space vehicle. The mounting as referred to herein is termed the "external support structure" and is an integral part of the system. In addition, means must be provided for vehicular attachment to the space vehicle. While the external support structure must be compatible to the vehicular attachment, for discussion purposes vehicular attachments will be treated separately in Chapter X.

Within this chapter three different external support structures are discussed and evaluated. Where possible a general comparison of the three structures will be given at the end of the chapter.

Chronologically the three structures to be discussed are:

1. Center Plane Type External Support
2. Trunion Type External Support
3. Cradle Type External Support



BASIC CENTER PLANE MOUNT

FIGURE 9-1

CENTER PLANE TYPE EXTERNAL SUPPORT

Basically, the center plane type support structure consists of a mounting ring that encircles the girth of the tank. It is equipped with a number of mounting points as shown in the sketch at left.

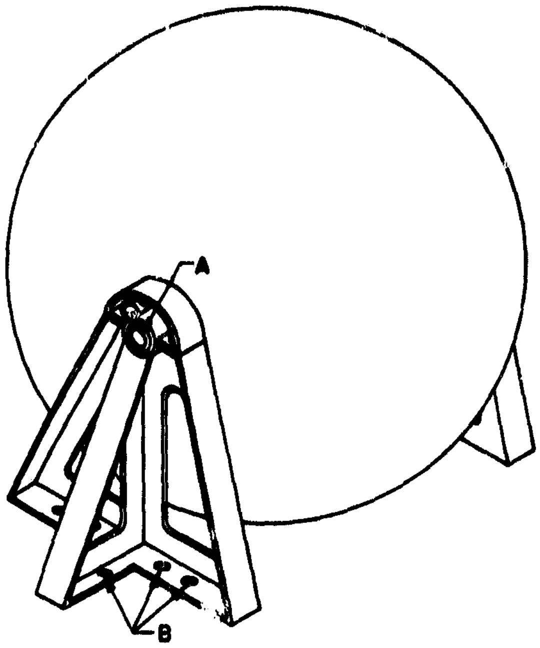
The mount ring may be of an arbitrary cross sectional shape. The one shown at left is a channel shaped mount ring. This particular design is intended for mounting with the mount ring in a horizontal plane. However, the center plane type can be utilized in a design which would orient the mount ring in a vertical plane.

From a structural standpoint, this design requires that loads necessary to support the inner vessel must be transmitted through the outer shell to the external mounting points. Otherwise, the inner vessel support members must be located between the mount ring and inner vessel, or the outer shell must be designed to withstand these loads.

To merely increase shell thickness to withstand these loads would impose a considerable weight penalty on the system since the inner vessel support members apply the load to the outer shell at discrete areas and hence produce stresses which are not uniformly distributed throughout the shell. A more nearly optimum system may be produced, however, by utilizing a thin outer shell which is reinforced in the regions which undergo the above mentioned stresses. This reinforcement may be provided in two ways. It may be made integral with the outer shell by etching, machining, or other suitable means. Or, the reinforcement ribs may be welded to the outer shell which is normally a less costly manner of providing these elements than the methods mentioned above. Despite the method used, this design imposes material choice constraints and complicates outer shell fabrication.

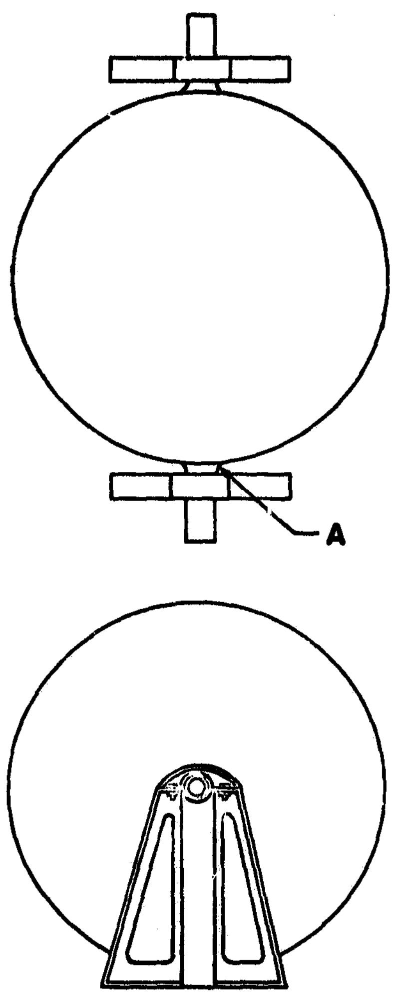
This system has the inherent disadvantage of requiring that the mounting ring be physically attached to the outer shell. If welding is used for this purpose, then certain constraints are placed on material choices for the outer shell and mounting ring. In addition, the sequence of heat treat operations would be somewhat controlled by the necessity of performing this welding operation. Other means of attachment often require through-holes which increase the probability of leakage.

In conclusion, it must be said that this design appears less flexible and less weight efficient than the cradle design to be discussed later.



BASIC TRUNION DESIGN

FIGURE 9-2



TOP & FRONT VIEWS OF BASIC TRUNION DESIGN

FIGURE 9-3

TRUNION TYPE EXTERNAL SUPPORT

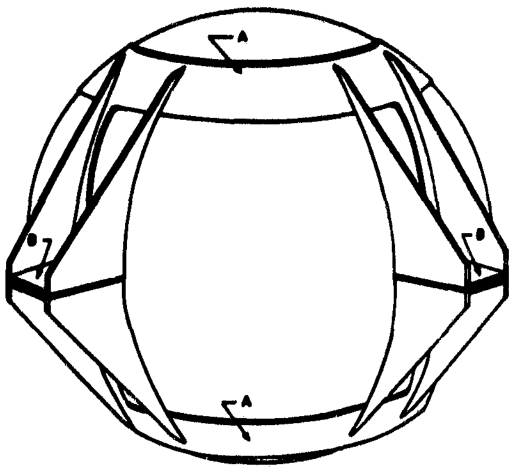
The basic trunion type support structure is shown at left. As shown, the tank is supported by tabular supports designated "A" which extend perpendicular to the outer shell wall. The loads imposed on these support tubes are transferred by the support structure to the mounting points designated as "B". Although the system shown in the figures utilizes only two support tubes, it is possible that some tanks may utilize more depending on factors such as the mass to be supported, the type and configuration of the inner vessel support structure, etc. In addition, even though the figures indicate that the tank is being supported by a member located below the tank, this same concept can easily be utilized to transmit the support stresses to adjacent vertical members or to horizontal members located above the tank.

As with most other support designs, the trunion concept is more desirable for use with some inner vessel support system than with others. It can be seen that the trunion is particularly suitable for use with tanks in which the inner vessel is supported at a few locations about a single diameter. In this case, the support tubes may be located opposite each inner vessel support thus eliminating all inner vessel support stresses from the outer shell. This, of course, allows the use of an outer shell of the simplest geometry and lighest weight since the structural considerations which must be included in its design are minimal. In addition, this allows increased flexibility and ease in the fabrication of the outer shell since welded and/or integral reinforcements of the outer shell is not necessary.

This method of external support is probably best suited for use with tanks which utilize the post or neck tube type inner vessel support systems. In these cases the post or neck tube can in effect be extended through the outer shell and the inner vessel and its contents can thus be supported directly.

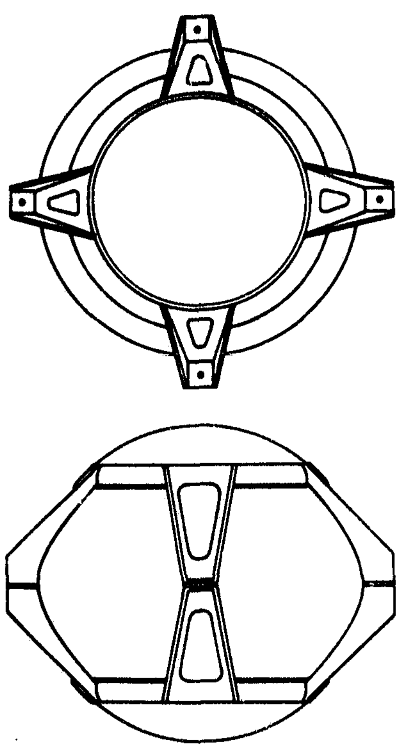
Physical attachment, usually by welding, to the outer shell is one of the requirements of this external support design. Imposition of this welding requirement not only adds fabrication complications, but also reduces outer shell fabrication and process flexibility, and imposes material selection constraints.

CRADLE TYPE EXTERNAL SUPPORT



BASIC CRADLE DESIGN

FIGURE 9-4



TOP & FRONT VIEWS OF BASIC CRADLE DESIGN

FIGURE 9-5

The basic cradle type support structure is shown at left. As shown, the tank is supported by two parallel rings designated as "A" and the loads imposed on these rings are transferred by the gusseted support structure to the mounting points designated as "B". The number and/or size of these gusseted load supporting members depends upon the mass of the storage tank, its contents, and the particular mission characteristics for which the system is designed.

This system provides structural support to the tank without requiring physical attachment of the structure to the outer vessel. This of course, eliminates the need for welding, and permits utilization of outer shell and support structure materials which are dissimilar. Also, this system eliminates other types of attachment, many of which would necessitate the need for leak tight joints to insure the vacuum integrity of the storage tank.

This design is especially adaptable to inner vessel support systems such as the radial bumper type discussed earlier. With the radial bumper design, support members primarily support only compressive loads. Thus when these members are located on the opposite side of the outer shell from the supporting rings (A) of the cradle type external mounting structure, then the loads required to support the inner vessel are transmitted directly to the external mounting structure without imposing stresses in the outer vessel other than compressive stresses across the thickness of the material. This technique allows the use of an outer shell of the simplest possible geometry since the structural considerations which must be included in its design are minimal. This concept also minimizes outer shell weight for the same reasons.

If used with other inner vessel support designs (neck tube, post, etc.), the system would require additional outer shell reinforcement in order to withstand the stresses imposed by inner vessel loading. This is due to the fact that these designs impose bending moments on their structural members. This type of load cannot be alleviated by a cradle type support which is not mechanically attached to the storage tank. Hence the outer shell would be required to support these bending loads, or the system would have to be designed as integral with or welded to the outer shell. In this manner it could be made to support the above mentioned bending loads which are associated with some inner vessel support designs.

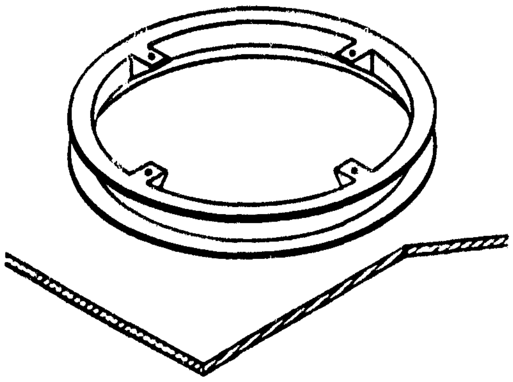
EXTERNAL SUPPORT STRUCTURE COMPARISON

It is virtually impossible to make an overall comparison of the external support structures described previously.

It was generally pointed out during the description of each design that the optimum external support for a cyrogenic storage system is heavily dependent on the construction of a particular system. Thus, the type of internal structure used, as well as the materials and configuration of the outer shell all have a bearing on the design of the external support system.

Since the design of both the vehicle and the cryogenic storage tank are generally governed by more important criteria than the interfacing of the two, the external support design must be considered as a logical area of compromise.

CHAPTER X



MOUNT RING
FIGURE 10-1

Vehicular Attachment

Before the design of a cryogenic storage system can be considered complete, it is necessary that consideration be given to the method of attaching it to the space vehicle. Since the area available and configuration of the space vehicle will ultimately dictate the type of vehicular attachment to be used, no general design can be considered all-encompassing.

Thus, this chapter is intended only to describe several possible vehicular attachments. Some of these methods are presently in use, while others remain only as alternatives.

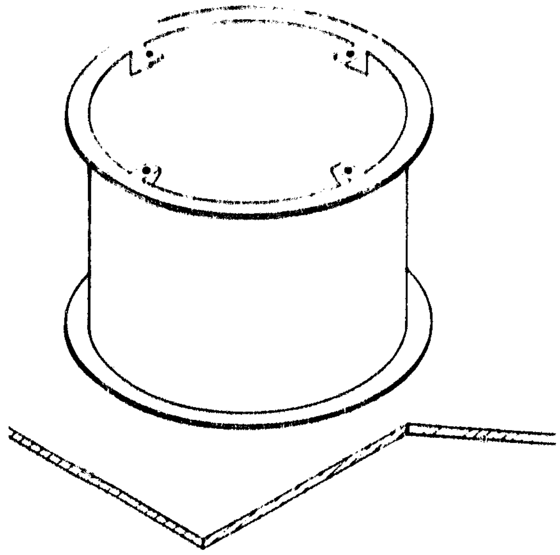
MOUNTING TO HORIZONTAL BULKHEADS

Ring Mount

One configuration of a mount ring for mounting a cryogenic tank to a horizontal spacecraft bulkhead is shown at upper left.

This particular configuration is well suited for mounting a tank which is equipped with the cradle type support structure. With this design, the mount ring distributes the load from four discrete mount points over a circular area of the bulkhead. In the case of a honeycomb sandwich bulkhead, this distribution of load is very desirable since discrete loading tends to deform this type of structure. When this type of vehicular attachment is utilized a large hole is required in the bulkhead in order to allow the tank to protrude into the space below. This configuration locates the tank center of gravity in very nearly the same plane as the bulkhead to which it is mounted. This has the effect of minimizing bending loads and supporting lateral forces by predominately shear stresses.

Even though the mount ring as shown was specifically designed for a cradle type tank support, a ring may just as easily be designed which would accept a trunion type support or most any other type of tank support structure. It should be pointed out however, that the center plane type tank support discussed in Chapter IX is basically a mount ring in itself and would need no additional attachment equipment in order to utilize this type of vehicular attamchment.



MOUNT SKIRT
FIGURE 10-2

Skirt Mount

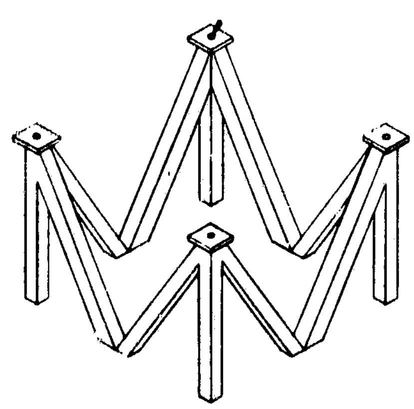
One configuration of a skirt type mount is shown at lower left. This particular configuration is also well suited for mounting a tank that is equipped with the cradle type support structure having four discrete mounting points. The basic design is adaptable however, to other types of tank support structures.

This type of attachment has an advantage in that it does not require a large hole in the bulkhead to which it is mounted as does the ring type. Structurally this configuration is similar to the ring type mount, but it does support the tank some distance above the bulkhead and therefore, is not as efficient at supporting lateral loads since such loads impose considerable bending stresses on the system which tend to buckle the cylindrical skirt.

Cradle Type Support Mount

The cradle-type support mount shown at left is specifically designed for tankage equipped with a cradle-type external support.

This type of structure can easily be fabricated from aluminum tubing of either circular or square cross-section and can be attached to the bulkhead by welding or bolting. Although this type of structure provides good support for loads of any direction, unfortunately it exerts discrete loads on the bulkhead. This situation is undesirable in many cases where honeycomb sandwich bulkheads are utilized and steps would have to be taken to distribute these loads.



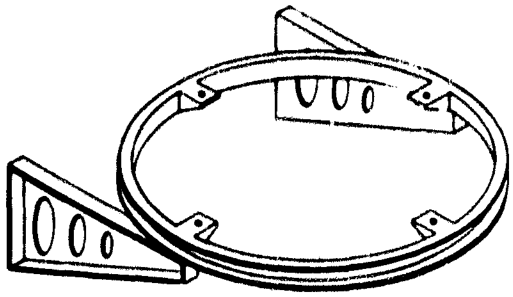
MOUNT FOR CRADLE TYPE SUPPORT
FIGURE 10-3

Vertical Bulkhead Mounting

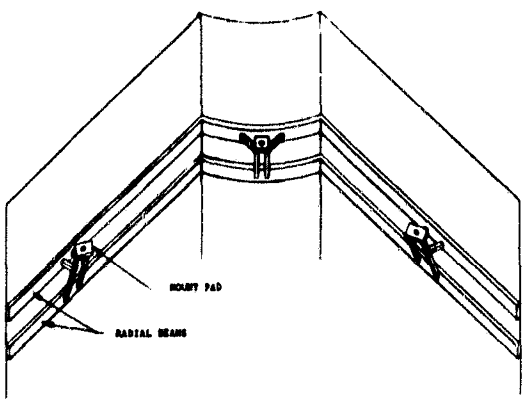
While some of the mounting techniques discussed for horizontal mounting would be applicable to vertical mounting as well, other designs would have to be taken into consideration. Following is a discussion of some of these designs.

Ring Mount

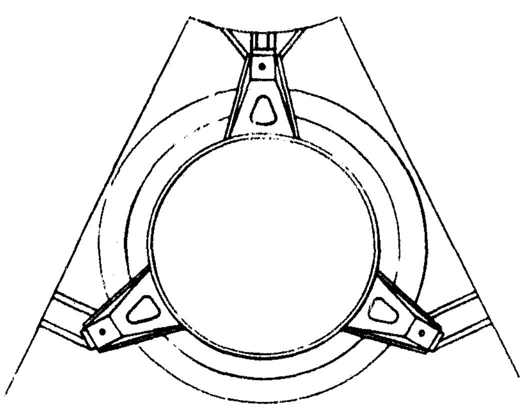
A mount ring type of attachment similar to that shown previously could easily be adapted to use as a vertical bulkhead mounting device. This type of attachment does have an advantage in that it produces a minimum of bending loads in the bulkhead.



CANTILEVER MOUNT
FIGURE 10-4



THREE POINT SECTOR BAY MOUNTING
FIGURE 10-5



THREE POINT SECTOR BAY MOUNTING
TOP VIEW (WITH TANK IN POSITION)
FIGURE 10-6

Skirt Mount

The skirt mount will not be considered for vertical bulkhead mounting since this would cause vertical forces to load the skirt in the least desirable direction, and therefore this type of mount would not be weight efficient.

Cantilever Mount

A cantilever type mount is shown at upper left. The particular design shown is a combination of the ring mount and a cantilever and is specifically suited for use with a tank equipped with a cradle type external mount structure having four mount points. This, of course, is only one of a large number of variations of this concept which could be chosen. The cantilever mount can also be adapted to tanks equipped with trunion or center plane external support structures which are described in Chapter IX.

The greatest disadvantage of this design is that it imposes high loads on the bulkhead to which is attached. Vertical forces are transmitted to the bulkhead in the form of bending loads which are undesirable in a flat plate. These bending loads could, however, be alleviated by locating equivalent sized tanks on opposite sides of the same bulkhead, thus cancelling the bending moments. Since the severe vertical forces generally occur during launch when all tanks are full, this would appear to be a practical approach for some missions.

MOUNTING IN CYLINDRICAL VEHICLES

The middle and lower drawings shown at left represent a specific design for mounting cryogenic tanks in a sector bay of a cylindrical space vehicle. A three-point concept is used.

The tank is equipped with a cradle type external mount structure having three equally spaced attachment points. As shown, the three vehicular mounting pads are attached to radial beams on the sector bay bulkheads which provide the required support.

Bendix Instruments & Life Support Division

ARDE, Inc. 7657

7657

Thirty-nine Inch Cylinder

for

Bendix Corporation

Instruments and Life Support

Systems Division

Inspection & Test Plan

Dated 23 February 1967

Prepared in accordance with

Purchase Order No. 26-53287

Approved by:

F. Warth
Program Manager

A. Giordano
Project Engineer

G. Basile
Quality Assurance Manager

Prepared by:

G. Roberts
Quality Assurance Engineer

Inspection & Test Plan

Table of Contents

Inspection & Test Plan

1.0 SCOPE

This inspection and test plan covers the mechanical inspection and physical non-destructive testing of the Bendix 39 inch cylindrical hydrogen vessels.

2.0 APPLICABLE DOCUMENTS

The following documents form part of this plan to the extent specified:

- Purchase Order No. 26-52387
- Bendix drawing 6477-4
- AES 253 Cleaning of Ardeform Components
- AES 251 Process Operating Instructions on Cold Pickling
- AES 254 Process Operating Instructions for Passivation
- AES 351 Process Operating Instructions for Annealing
- AES 450 Process Operating Instructions for X-ray

AES 451 Inspection of Fusion Welded Joints

2.1 If any of the publications which form a part of this plan are superceded by a later specification, revision, or amendment during the life of the Purchase Contract of which this plan is a part; the later specification revision or amendment may be issued.

ARDE, Inc.

3.0 PERFORMANCE REQUIREMENTS

The 39 inch vessels will be subject to the performance testing as presented in the body of this plan.

3.1 TESTS & TESTING SEQUENCE

a) Mechanical Inspection

b) Dye Penetrant

c) X-Ray

d) Weight

e) Volume

f) Helium Leak Test

g) Proof Pressure

h) Volume

i) Burst (Prototype/Development only)

The sequence of testing shall be that which appears above.

4.0 INSPECTION & TESTS

It is the mutual understanding between Arde and the Instruments and Life Support Division that Bendix personnel shall have the option of observing certain manufacturing steps. Thus, it is in keeping with this understanding that Arde shall notify Bendix forty-eight (48) hours in advance of the execution of the following manufacturing milestones:

a) Vessel assembly postform machining, Drawing J3498, IMS Sheet 76575 Items 8 through 10 inclusive and Item 26.

b) Vessel assembly preform weldment, Drawing J3497, IMS Sheet 76574 Items 8 through 11 inclusive.

It is further understood that if Bendix personnel are not available, or wish to exercise their option, the said tests and milestones shall be accomplished without interruption.

4.1 MECHANICAL INSPECTION

All details which make up the assembly, J3498, shall be inspected 100 per cent as described on their individual Inspection Method Sheets (I.M.S.). See Appendix for inspection sheets.

4.2 DYE PENETRANT

All accessible welds shall be subject to dye penetrant inspection immediately after welding and again after stretch forming.

4.3 X-RAY

Inspection of welded joints shall be performed after welding of details and subassemblies.

4.4 LEAKAGE TEST

The assembly shall be leak tested with a helium mass spectrometer. There will be no evidence of leakage through vessel walls or welds when using the helium mass spectrometer. Sensitivity of the instrument shall be such that a helium leak rate of 5×10^{-9} cc/sec STP is definitely distinguishable above the background. Pressure in the leak detector during calibration shall not exceed .05 microns.

4.5 BURST

The prototype/development units shall be pressure tested hydrostatically to burst.

4.5.1 BURST STRENGTH

The burst test consists of positioning the empty cylinder in a burst strength tester and subjecting it to an internal hydrostatic pressure until burst. The burst strength design objective is 600 psig. The data obtained from this test shall be recorded and authenticated on I.M.S. 76575.

4.6 PROOF PRESSURE TEST

Each assembly shall be subject to a hydrostatic proof pressure test of not less than 440±10 psig at 80°F. This test shall be conducted with demineralized oxygenated water, full pressure for three (3) minutes with no sign of permanent deformation. Certification of Compliance with this requirement will be entered on I.M.S. 76575.

4.7 WEIGHT - ASSEMBLY

Each deliverable assembly shall be weighed. Weight per assembly shall not exceed 111.5 pounds. Actual weight shall be recorded on I.M.S.

4.8 VOLUME

The absolute volume of the 39 inch cylindrical tank shall be a minimum of 58,000 cubic inches at STP.

5.0 PREPARATION FOR DELIVERY

5.1 IDENTIFICATION AND MARKING

There shall be no marking or other identification on the exterior surface of each specimen cylinder.

5.2 PRESERVATION/PACKAGING

Each burst specimen shall be purged with clean, dry nitrogen, bagged and sealed in 3 mil polyethylene.

5.3 PACKAGING

The two (2) cylinders shall be boxed for shipment in wooden containers with sufficient packing such as to preclude transportation handling damage.

5.4 MARKING

Each shipping container shall be exteriorly marked as follows:

The Bendix Corporation
Instruments & Life Support
Systems Division
Davenport, Iowa 52808

5.4.1 PACKING SHEET DATA

The shipping container shall include a packing sheet in two (2) boxes which shall bear the following information:

Purchase Order No. 26-52387
Item No. 1
Quantity: 2 each
Description: 39" cylinder
Arde Part No.: J3498
Bendix P/N: 6477-4

5.4.2 ACCEPTANCE DATA PACKAGE

The following data shall accompany vessels shipped to Instrument & Life Support, Systems Division, Bendix Corporation:

a) Certificate of Conformance
b) Test Reports
c) Inspection records of the top assembly
d) Drawing and manufactured configuration certification of each vessel.

5.5 SHIPMENT

The thirty-nine (39) inch cylinders shall be shipped:

"FOB Shipping Point" - Routing to be determined by customer.

APPENDIX

Bendix Instruments & Life Support Division

EXHIBIT A

BENDIX 39" VESSEL

QUALITY ASSURANCE

BLOCK DIAGRAM

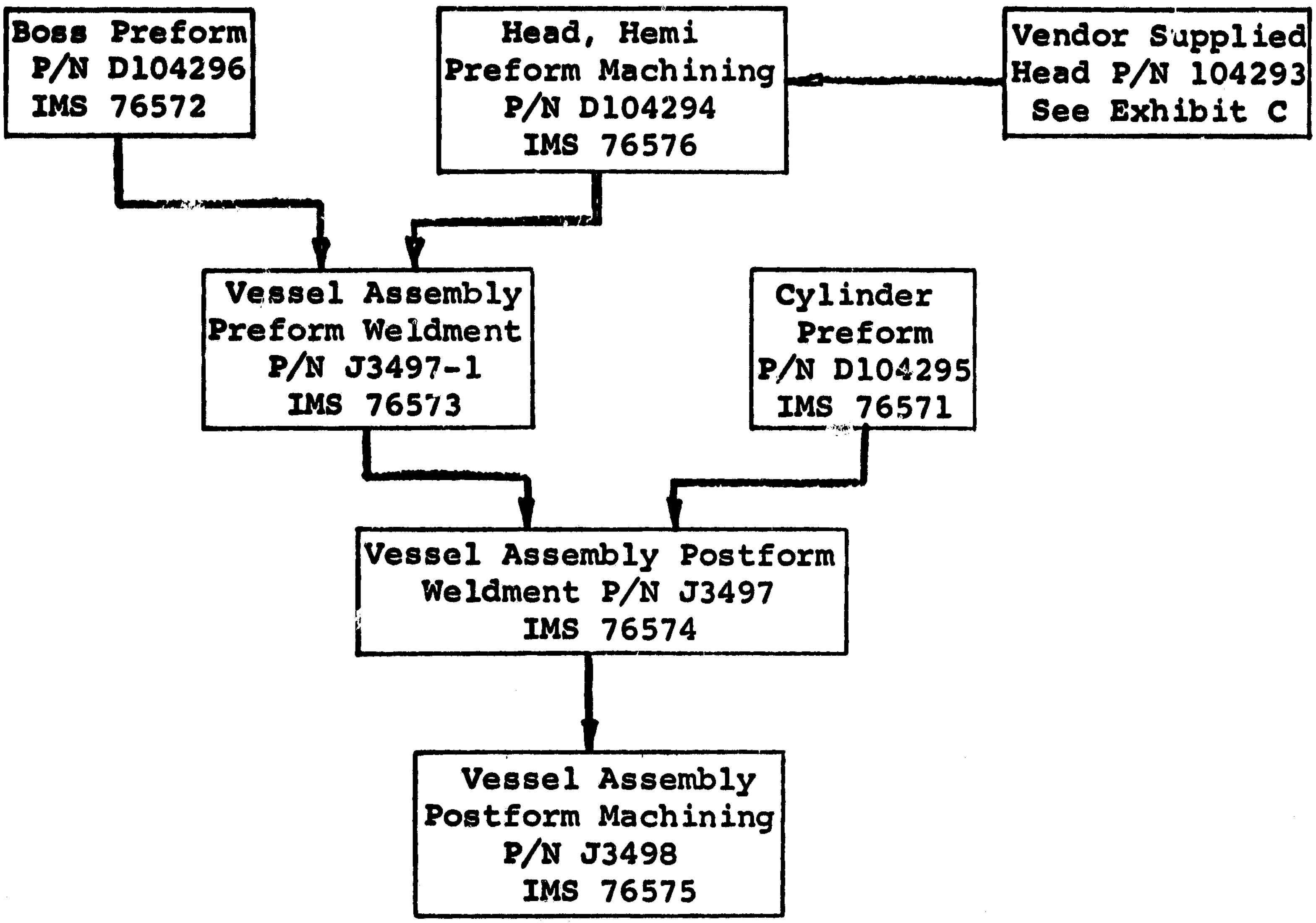


EXHIBIT B - QUALITY ASSURANCE PROCESS PLAN

BOSS PREFORM
P/N D104296
IMS 76572

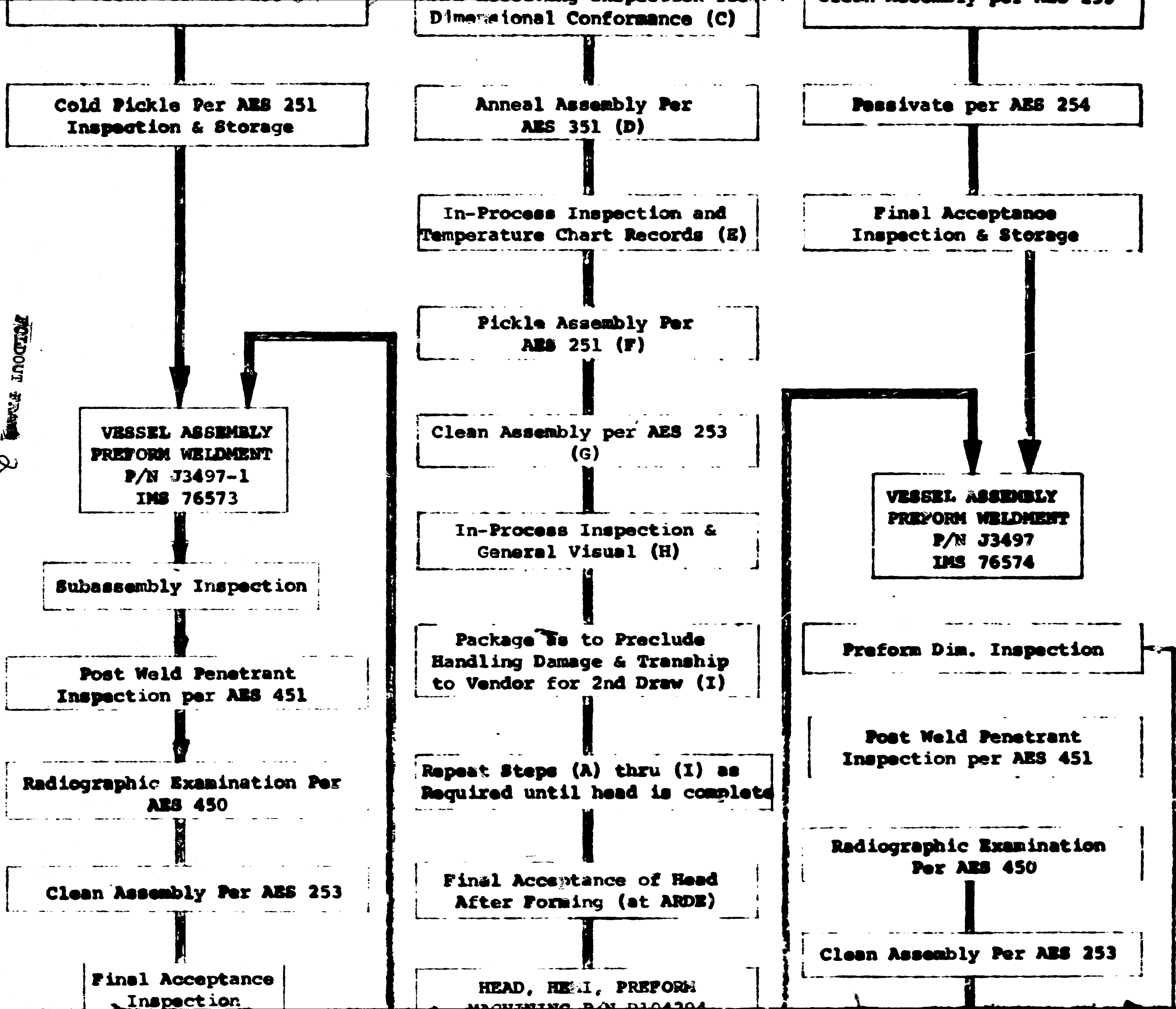
- Material Blanks, Inspect Certification, Serialization.
- Inspection Preparation for Vendor Transhipment
- Receiving & Dimensional Inspection After Machining
- Penetrant Inspection Per AES 451
- Radiograph Examination per AES 450
- Clean Per AES 253

DEEP DRAW & MACHINING VENDOR OPERATIONS

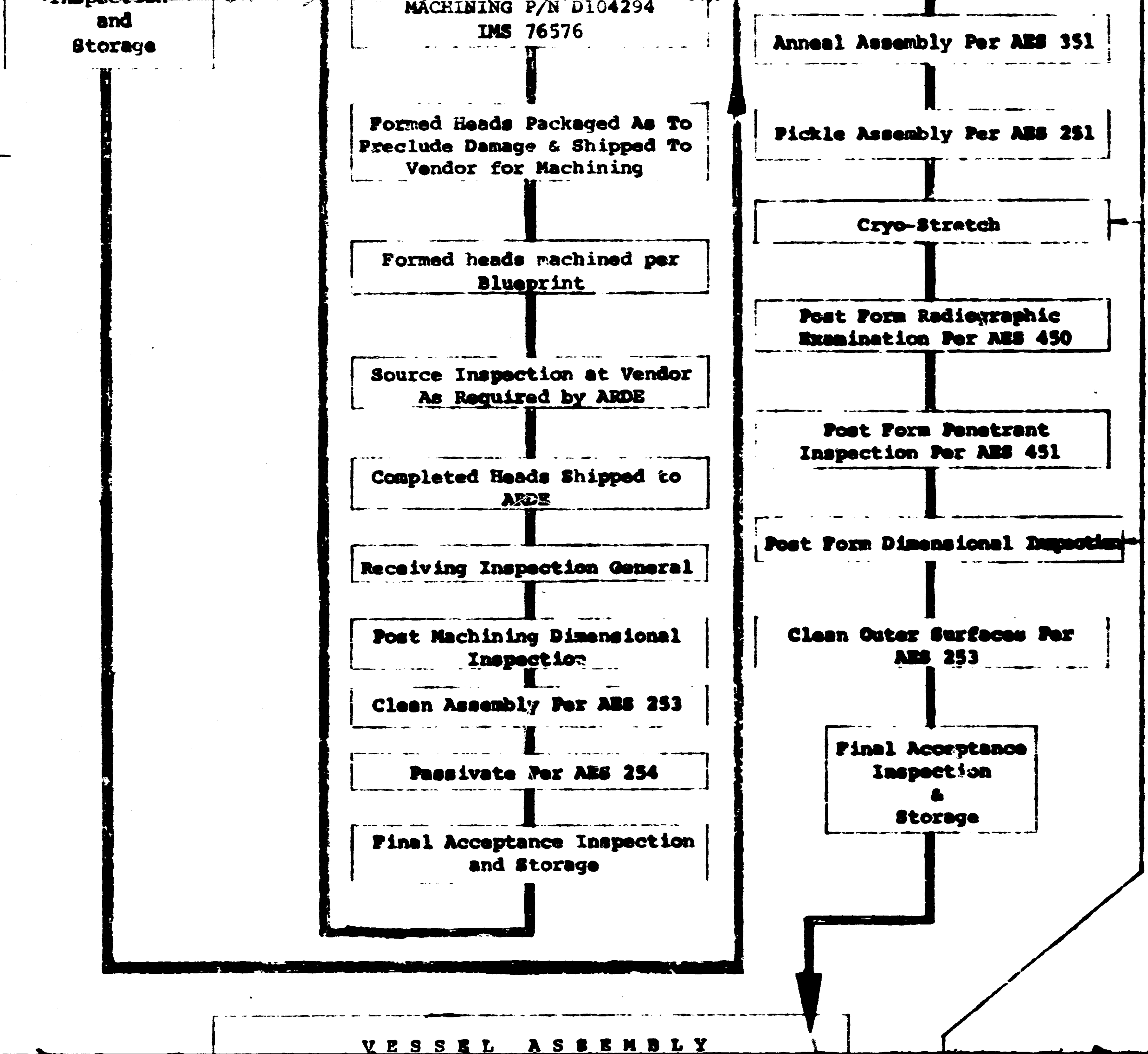
- Material Blanks, Source Inspection Certification & Serialization at ARDE
- Tranship to Deep Draw Vendor for Forming (H.J.Hubbert Co.)
- Vendor Receiving Inspection & Bonded Area Security of Mat'l.
- 1st Draw Accomplished & Heads Shipped to ARDE (A)
- Source Inspection of 1st Draw by ARDE (B)
- ARDE Receiving Inspection for Dimensional Conformance (C)

CYLINDER PREFORM
P/N D104295
IMS 76571

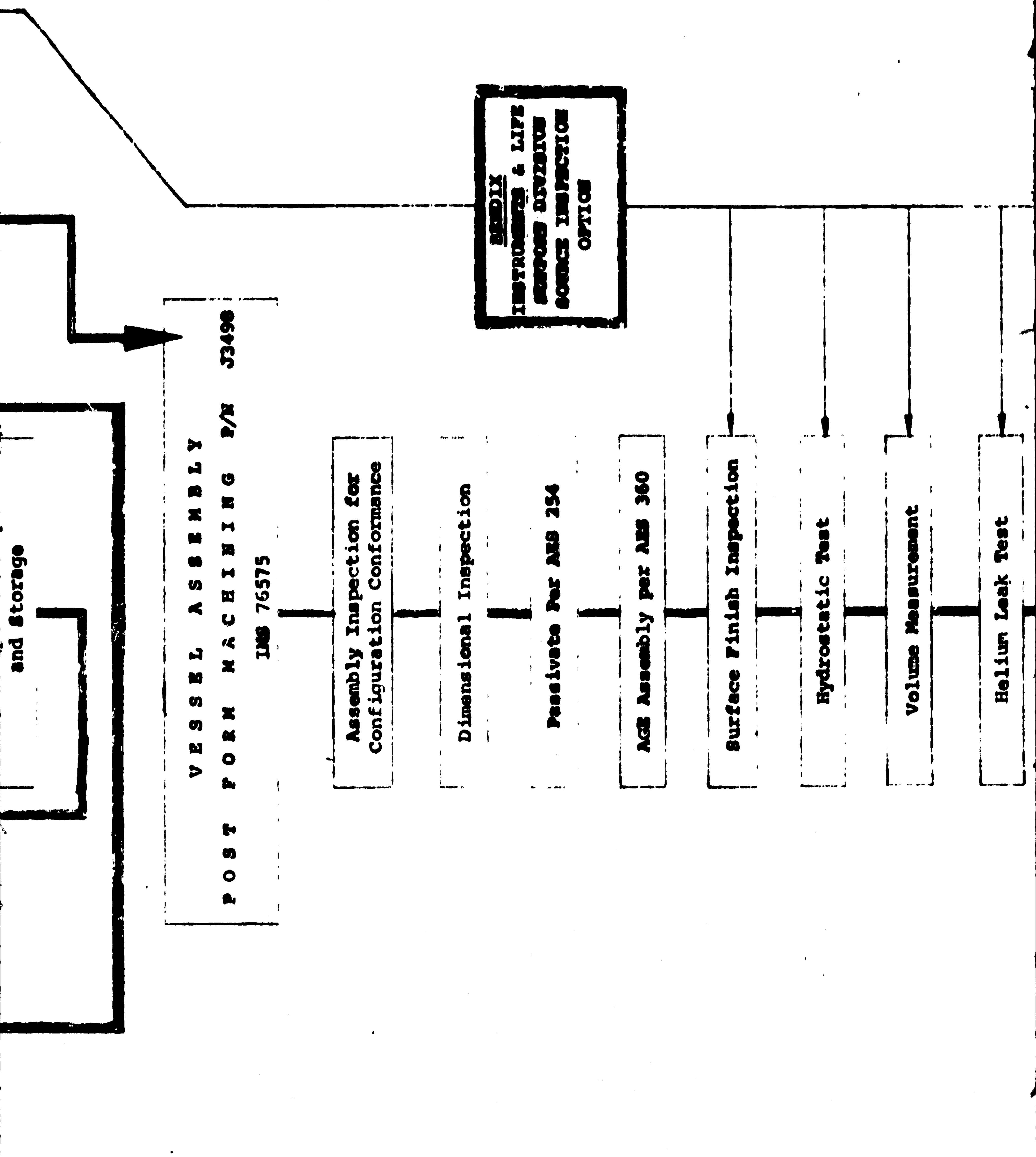
- Material Blanks, Inspected Certification & Serialization
- Clean Cylinder per AES 253
- Post Weld Penetrant Inspection per AES 451
- Radiographic Examination of Weld per AES 450
- Post Machining Dimensional Inspection
- Clean Assembly per AES 253



FOLDOUT FRAME 2

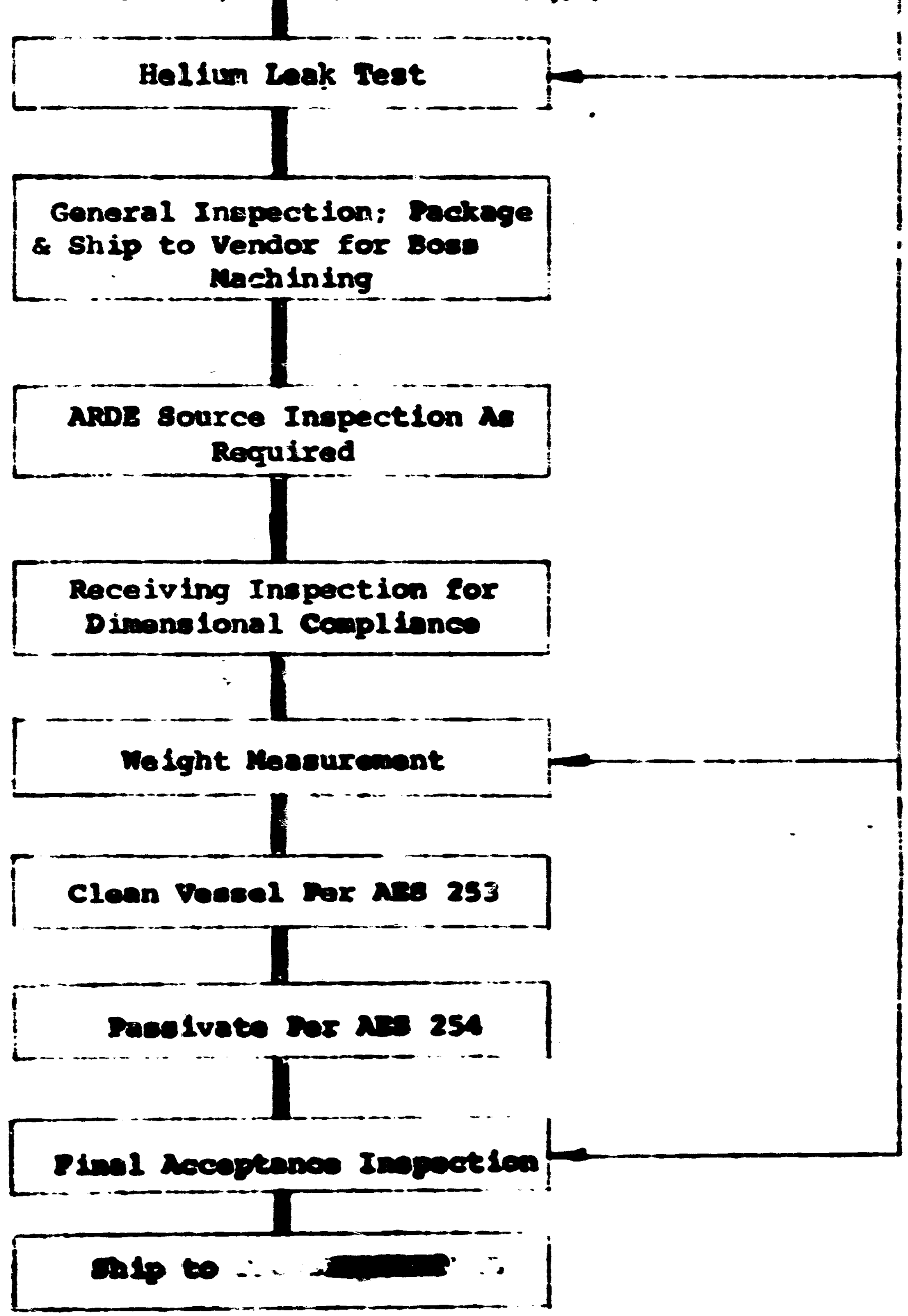


and
Storage
MACHINING P/N D104294
IMS 76576
Formed Heads Packaged As To Preclude Damage & Shipped To Vendor for Machining
Formed heads machined per Blueprint
Source Inspection at Vendor As Required by ARDE
Completed Heads Shipped to ARDE
Receiving Inspection General
Post Machining Dimensional Inspection
Clean Assembly Per ABS 253
Passivate Per ABS 254
Final Acceptance Inspection and Storage
Anneal Assembly Per ABS 351
Pickle Assembly Per ABS 251
Cryo-Stretch
Post Form Radiographic Examination Per ABS 450
Post Form Penetrant Inspection Per ABS 451
Post Form Dimensional Inspection
Clean Outer Surfaces Per ABS 253
Final Acceptance Inspection & Storage
V E S S E L A S S E M B L Y



FOLDOUT FRAME

FOLDOUT FRAME 4



FOLDOUT FRAME 5

Inspection Method Sheets

IMS NO.	P/N	
76571	D104295	Cylinder, Preform
76572	D104296	Boss, Preform
76573	J3497-1	Vessel Assembly Preform Weldment
76574	J3497	Vessel Assembly Preform Weldment
76575	J3498	Vessel Assembly Postform Machining
76576	D104294	Head Hemispherical Preform Machining
76577	D104293	Head Hemispherical Preform

Bendix Instruments & Life Support Division

Configuration Control Sheet   Job 7657   Dated 2/23/67   Issue No. 2

Process Drawing No	Revision Letter	IMS Number	Revision Letter	Date Issued	Process Drawing No	Revision Letter	IMS Number	Revision Letter	Date Issued
D104295	N/C	76571		12/22/66					
D104296	N/C	76572		12/22/66					
J3497-1	N/C	76573		12/22/66					
J3497	N/C	76574		12/22/66					
J3498	N/C	76575		12/22/66					
D104294	N/C	76576		12/22/66					
D104293	N/C	76577	A	2/22/66					
J3499	not required								

ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76571

PART NO. D104295	REV. LET. N/C	JOB NO. 7657	
PART NAME Cylinder Preform	MODEL	DATE REC'D	
LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY
REVISION		REVISION	

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY G. Roberts	DATE 12/23/66	SHEET 1 OF 2

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
1	Serialize, material certification, record heat number. and material serial numbers	Verify			
2	Grain direction per drawing D104295	Verify			
3	Clean blanks per AES 253	Verify			
4	Penetrant inspection of complete seam weld per AES 451, record	Verify			
5	Radiographic inspection of weld per AES 450	Verify			
6	Cylinder height 26.00 ± .01	Vernier			
7	Outer diameter of cylinder 36.86 ± .01 in restrained position	Pi tape			
8	Wall thickness of cylinder .055/.049	O.D. Micrometer & Set up			
9	TIR cylinder end Side A .005	Indicator & Set up			
10	Flatness Side A .005	Set up & Indicator			
11	TIR cylinder end Side B .005	Set up & Indicator			
12	Flatness Side B .005	Set up & Indicator			
13	Clean cylinder per AES 253	Verify			

ARDE INC.

INSPECTION METHOD SHEET NUMBER 76571

PART NO. D104295	REV. LET. N/C	JOB NO. 7657	
PART NAME Cylinder Preform	MODEL	DATE REC'D	
LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY
REVISION		REVISION	

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY G. Roberts	DATE 12/23/66	SHEET 2 OF 2

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
14	Passivate per AES 254 Solution A, 5 to 10 minutes only, record actual time	Verify			
15	Inspect for general quality in workmanship	Verify			
16	Identify, bag & seal in 3 mil polyethylene	Verify			
17	Package as to preclude handling damage	Verify			
18	Transfer to stores				

ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76572

PART NO. D104296	REV. LET. N/C	JOB NO. 7657
PART NAME Boss Preform	MODEL	DATE REC'D

LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY

		REVISION			REVISION

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY	DATE	SHEET 1 OF 3
	G. Roberts	12/23/66	

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
1	Serialize, material certification, record heat and material serial number	Verify, record			
2	Rolling plane of stock blanks in accordance with Note 6, dwg. D104296	Verify			
3	Package to preclude handling damage, ship to vendor	Verify			
4	Receiving inspection for general quality in workmanship	Verify			
5	Overall diameter 4.499/4.497	O.D. Micrometer			
6	Thread 3/4 NPT	Thread gage			
7	O.D. at induction end 2.460 ± .005	O.D. Micrometer			
8	TIR at induction end .005	Indicator & Set up			
9	I.D. 1.840 ± .005	Plug gage			
10	O.D. 1.50 ± 01	O.D. Micrometer			
11	Thickness of boss from recorded gage point ℄ induction end on 2.460 diameter 1.264 ± .005	O.D. Micrometer			

Bendix Instruments & Life Support Division

ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76572

PART NO. D104296	REV. LET. N/C	JOB NO. 7657
PART NAME Boss Preform	MODEL	DATE REC'D

LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY	DATE	SHEET 2 OF 3	REVISION	REVISION
	G. Roberts	12/23/66			

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
12	Slope on outer surface of boss 9°	Vernier/Protractor			
13	Thickness of weld end lip within .020 of edge .053/.049	O.D. Micrometer			
14	Slope on inner surface of weld end lip 2°	Vernier/Protractor			
15	Thickness of section inside boss 0.75±.01	O.D. Micrometer			
16	Thickness of section inside boss .31 ± .01	O.D. Micrometer			
17	Radius on outside of boss .25 blend R	Radius gage			
18	Radius of inner lip of boss .12 blend R	Radius gage			
19	Radius of inner section .09R	Radius gage			
20	Radius at bottom of inner annular ring .17R	Radius gage			
21	Inspect all finished surfaces: 63	Standard Comparison			
22	Penetrant inspection of assembly per AES 451, record	Verify			
23	Radiographic inspection of assembly per AES 450 as required by AES 452	Verify			

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INSPECTION METHOD SHEET
NUMBER 76572

PART NO. D104296	REV. LET. N/C	JOB NO. 7657
PART NAME Boss Preform	MODEL	DATE REC'D

LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY

		REVISION			REVISION

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY	DATE	SHEET 3 OF 3
	G. Roberts	12/23/66	

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
24	Clean assembly per AES 253	Verify			
25	Cold pickle assembly per AES 251	Verify			
26	Inspect for general quality in workmanship	Verify			
27	Bag & seal in 3 mil polyethylene, identify	Verify			
28	Package as to preclude handling damage	Verify			
29	Transfer to stores				

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INSPECTION METHOD SHEET
NUMBER 76573

PART NO.	J3497-1
REV. LET.	N/C
JOB NO.	765
PART NAME	Vessel Assy Preform Weldment
MODEL	
DATE REC'D	
LOT NO.	
SERIAL NO.	
REC. SLIP NO.	
QTY	
REVISION	
REVISION	

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY	DATE	SHEET 1 OF 1
	G. Roberts	12/23/66	

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
1	Serialize and record serial numbers for subassemblies D104294 & D104296, record heat and material serial numbers	Verify, record			
2	Inspect records, certificates of compliance for completion	Verify			
3	Penetrant inspection of weld per AES 451, record	Verify, record			
4	Radiographic examination of weld per AES 450	Verify			
5	Clean assembly per AES 253	Verify			
6	Inspect for general quality in workmanship	Verify, Visual			
7	Bag and seal in 3 mil polyethylene, identify	Verify			
8	Package as to preclude handling damage	Verify			
9	Transfer to stores				

ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76574

PART NO. J3497	REV. LET. N/C	JOB NO. 7657	
PART NAME Vessel Assy Preform Weldment	MODEL	DATE REC'D	
LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY
REVISION		REVISION	

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY G. Roberts	DATE 12/23/66	SHEET 1 OF 2

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
1	Serialize part numbers J3497-1 & D104295 subassemblies. Material certifications, identify record heat and material serial numbers	Verify, record			
2	Penetrant inspection of all girth welds per AES 451, record	Verify, record			
3	Radiographic examination of girth welds per AES 450	Verify			
4	Clean assembly per AES 253	Verify			
5	Solution anneal per AES 351 argon purge throughout cycle, 1950°F 25°F for 25 minutes	Verify			
6	Pickle assembly per AES 251	Verify			
7	General visual for quality of workmanship Check w/Proj Engineer, record stretch pressure	Visual, Verify			
8	Cryogenic stretch - pressure. Record goal ______ psig actual ______ psig	Heist gage & Speedomax reader			
9	Penetrant inspection of welds per AES 451, record	Verify			

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ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76574

PART NO. J3497	REV. LET. N/C	JOB NO. 7657	
PART NAME Vessel Assy Preform Weldment	MODEL	DATE REC'D	
LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY	DATE	SHEET 2 OF 2
	G. Roberts	12/23/66	

REVISION	REVISION

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
9	Post form inspection A ___ B ___	Pi tape			
10	Clean outer surface only per AES 253	Verify			
11	Inspect for general quality of workmanship	Visual			
12	Identify, bag in polyethylene & seal	Verify			
13	Crate or package as to preclude handling damage	Verify			
14	Transfer to stores				

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ARDE INC.

INSPECTION METHOD SHEET NUMBER 76575

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY G. Roberts	DATE 12/22/66	SHEET 1 OF 4

PART NO. J3498	REV. LET. N/C		JOB NO. 765
PART NAME Vessel Assy Post Form Machining	MODEL		DATE REC'D
LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY
REVISION		REVISION	

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
1	Serialize assemblies J3497, material certification, inspect records	Verify			
2	Passivate vessel per AES 254 Solution A for 10 minutes, bag in polyethylene and heat seal	Verify			
3	Inspect for general quality of workmanship	Visual			
4	Age vessel per AES 360 Argon purge throughout 790°F±10°F for 20 hours ± 30 minutes	Verify			
5	Record wight of vessel __________	Scale			
6	Surface finish 16, except on welds	Verify			
7	Record weight of vessel __________	Scale			
8	Passivate vessel per AES 254 Solution A for 15 to 25 minutes	Verify			
9	Hydrostatic test 440±10 psig minimum at 70°F, demineralized oxygenated water, full pressure for three (3) minutes	Verify, record			
10	Minimum Volume 58,000 cubic inches at 70°F record	Verify, record			

ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76575

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY: G. Roberts	DATE: 12/22/66	SHEET 2 OF 4

PART NO. J3498	REV. LET. N/C	JOB NO. 7657	
PART NAME Vessel Assy. Post Form Machining	MODEL	DATE REC'D	
LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY.
REVISION		REVISION	

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
11	Helium Leak check per drawing J3498 note 2 requirements	Verify, Record			
12	Inspect for general quality of workmanship, Visual	Verify			
13	Identify, bag in polyethylene & seal	Verify			
14	Crate or Package to preclude handling & shipment damage	Verify			
15	Ship to Ven dor for further processing	Verify			
16	Receiving inspection, general visual	Visual Record			
17	Overall diameter of Boss side A - 2.275 ± .005	O. D. Micrometer			
18	Inner diameter of Boss side A - 2.027/2.023	Plug gage			
19	Depth of Chamfer .078 ± .005 Side A	Depth micrometer			

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ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76565

PART NO. J 3498	REV. LET. N/C
JOB NO. 7657	
PART NAME Vessel Assy. Post Form Machining	MODEL
DATE REC'D	
LOT NO.	SERIAL NO.
REC. SLIP NO.	QTY

REVISION	REVISION

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY	DATE	SHEET 3 OF 4
	G. Roberts	12/22/66	

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
20	Side A Radius inner & outer .14R TYP blended smoothly into boss contour	Radius gage			
21	Side A - Chamfer .078 x 45°	Vernier, protracter			
22	Overall diameter of Boss Side B- 2.275 ± .005	O.D. Micrometer			
23	Inner Diameter of Boss Side B - 2.027/2.023	Plug gage			
24	Side B - depth of Chamfer .078 ± .005	Depth micrometer			
25	Side B - Radius inner & outer .14R TYP Blended smoothly into boss contour	Radius Gage			
26	Side B Chamfer .078 x 45°	Vernier, protractor			
27	Weight of Vessel - max. 111.5 lbs.	Scale, Record			
28	Clean vessel per AES - 253	Verify			

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ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76575

PART NO. J3498	REV. LET.	JOB NO. 7657	
PART NAME Vessel Assy. Post Form Machining	MODEL	DATE REC'D	
LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY.
	REVISION		REVISION

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY	DATE	
	G. Roberts	12/22/66	SHEET 4 OF 4

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
29	Passivate per AES 254 solution"A" for 25 minutes	Verify			
30	Inspect for general quality of workmanship	Verify			
31	Re-identify finished vessel to P/N J-3499	Verify			
32	Bag & seal in 10 mil polyethylene	Verify			
33	Package or crate to preclude handling damage	Verify			
34	Transfer to Stores				

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ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76576

PART NO. D104294	REV. LET. N/C	JOB NO. 7657	
PART NAME Head, Hemi Preform Machining	MODEL	DATE REC'D	
LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY

REVISION	REVISION

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY G. Roberts	DATE 12/23/66	SHEET 1 OF 2

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
1	Serialize; material certification, recrod heat and material serial number of P/N D104293	Verify			
2	Package as to preclude handling damage and and ship to vendor for processing	Verify			
3	Receiving inspection for general quality of workmanship	Visual			
4	Inspect on machine I.D. 36.76 ± .01	I.D. Micrometer/Pi tage			
5	Flatness on weld end face .005	Indicator			
6	Inspect on machine hole 4.502/4.500	Plug gage			
7	Inspect on machine perpendicularity at hole .005	Indicator & Set up			
8	Inspect on machine TIR at hole .005	Indicator & Set up			
9	Inspect on machine centerline of hole must equal centerline of head	Verify			
10	Clean assembly per AES 253	Verify			
11	Passivate component per AES 254 Solution A for 5-10 minutes only. Record time.	Verify			

ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76576

☐ FUNCTIONAL ☐ DIMENSIONAL	WRITTEN BY G. Roberts	DATE 12/23/66	SHEET 2 OF 2

PART NO. D104294		REV. LET. N/C	JOB NO. 7657
PART NAME Head, Hemi Preform Machining		MODEL	DATE REC'D
LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY
REVISION		REVISION	

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
12	Inspect for general quality of workmanship	Verify			
13	Identify, bag and seal in 3 mil polyethylene	Verify			
14	Package as to preclude handling damage	Verify			
15	Transfer to stores				

Bendix Instruments & Life Support Division

ARDE INC.

INSPECTION METHOD SHEET
NUMBER 76577

PART NO. D104293	REV. LET. N/C	JOB NO. 7657
PART NAME Head, Hemi Preform	MODEL	DATE REC'D

LOT NO.	SERIAL NO.	REC. SLIP NO.	QTY

		REVISION			REVISION
A	2/22	Added note			

☐ FUNCTIONAL ☒ DIMENSIONAL	WRITTEN BY	DATE	SHEET 1 OF 1
	G. Roberts	12/22/66	

ALL CHARACTERISTICS TO BE INSPECTED 100%, UNLESS OTHERWISE SPECIFIED

INDEX	SPECIFICATION	INSPECTION METHOD/GAGES	INSPECT A	INSPECT B	RECORD
1	Serialize, material certification, record heat and material serial number.	Verify			
2	Visual inspection of blank surface Record ______	Verify			
3	Package as to preclude handling damage and transship to forming vendor for processing	Verify			
4	Receiving inspection for general quality of workmanship	Verify			
5	Spherical radius 18.38R	Radius template			
6	Thickness of head within spherical radius .049/.055	Thickness gage & Set up			
	NOTES: Wrinkling on periphery of formed heads may not because for immediate rejection, but shall be individually evaluated.				
7	Identify, bag and seal in polyethylene	Verify			
8	Package as to preclude handling damage	Verify			
9	Transfer to stores				

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ARDE, INC.

HYDRO BURST TEST

of

39" CYLINDRICAL VESSEL

S/N 1

Prepared by S. Osborn
S. Osborn

Approved by F. Mollo
F. Mollo

11 December 1967

ARDE, INC.

OBJECT:

Determine the burst stress of 39" cylindrical vessel, Serial Number 1.

VESSEL HISTORY:

A cylindrical vessel (P/N J3498, S/N 1) 39 inches in diameter and 65 inches long was fabricated using the Ardeform process.

Heads for this vessel were formed by a mechanical deep draw process. The cylindrical section of the vessel was rolled from sheet stock. Both heads and cylinder were fabricated from heat 96269, a low silicon material. Components were T.I.G. welded together using argon gas backup. The preform vessel was solution annealed while in an air atmosphere. Argon gas flow was maintained on the vessel interior to inhibit annealing oxides. The outside and inside of the vessel was subsequently pickled to remove annealing oxides. Preform dimensions were recorded, see Figure 1.

The vessel was cryogenically stretched in an open ended cylindrical die to 745 psi. Postform dimensions were recorded, see Figure 1. Volume was measured at 58,622 cu.in. vessel weighed 118 pounds. All postform dimensions were within blue-print tolerances except for slight excess in weight.

The vessel was aged for 20 hours at 790F, and the outside of the vessel was polished to a 16 rms micro-inch finish.

Bendix Instruments & Life Support Division

ARDE ASSOCIATES

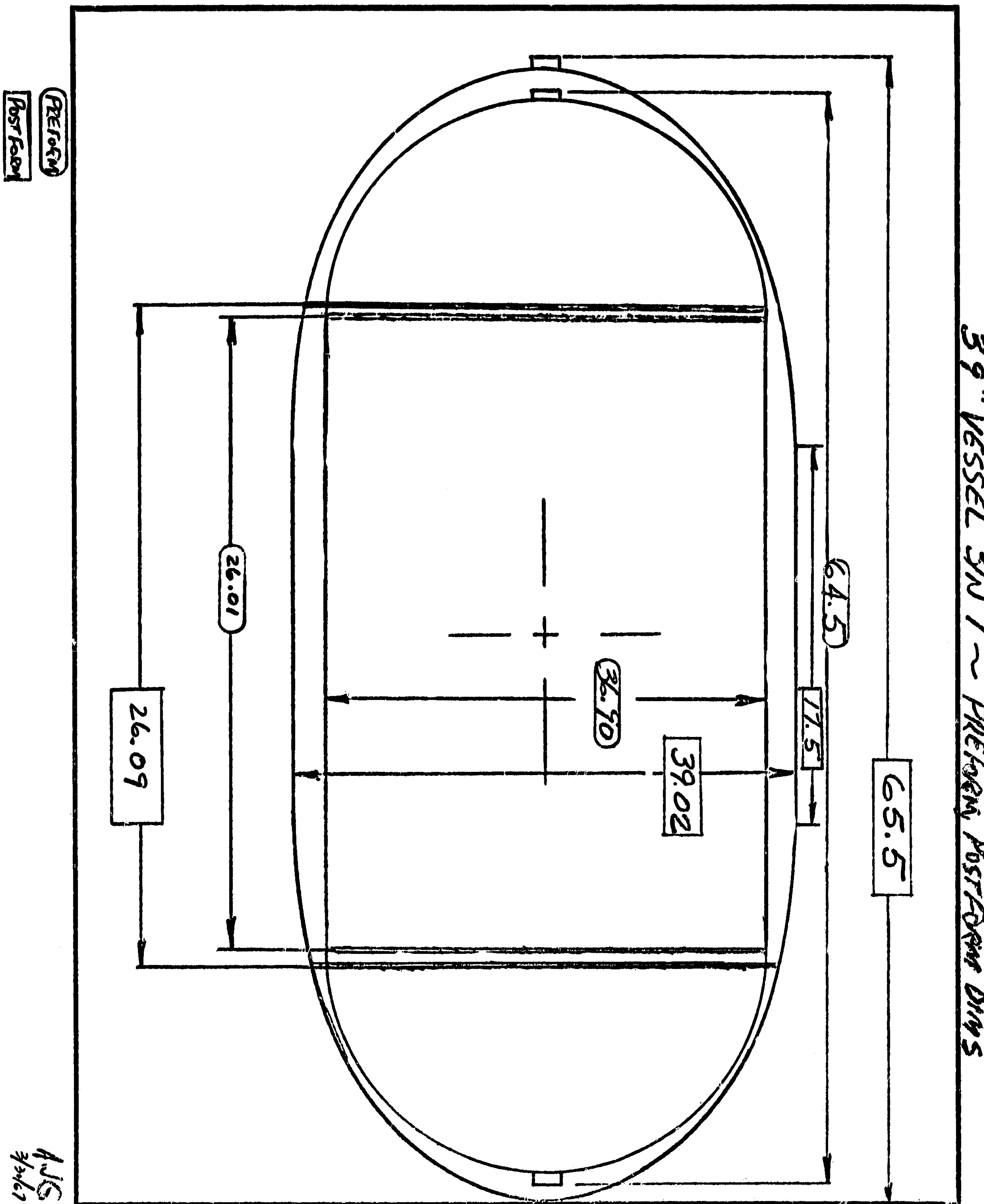
PAGE 2

REPORT NO. ______

JOB NO. ______

PREPARED BY ______

DATE ______



FIG

A helium leak check was run on the vessel. During this procedure a slight vacuum was created in the vessel and it buckled. The vessel was hydropressurized to its original shape.

Vidigage thickness measurements were taken over the cylindrical surface of the vessel, see Figure 2, and minimum thickness was recorded. Eight strain gages were affixed to the cylindrical portion of the vessel. These gages were placed in pairs, one in the hoop and one in the longitudinal direction, at four areas of the vessel where the thickness was minimum.

Vessel was hydrostatically pressurized to burst while incremental strain gage readings were taken. The .17%* offset yield and burst pressure were established as 623 psi and 645 psi respectively. These pressures are equivalent to stress levels of 238 ksi and 247 ksi respectively.

* .17% offset is equivalent to .2% offset for uniaxial test

ARDE ASSOCIATES

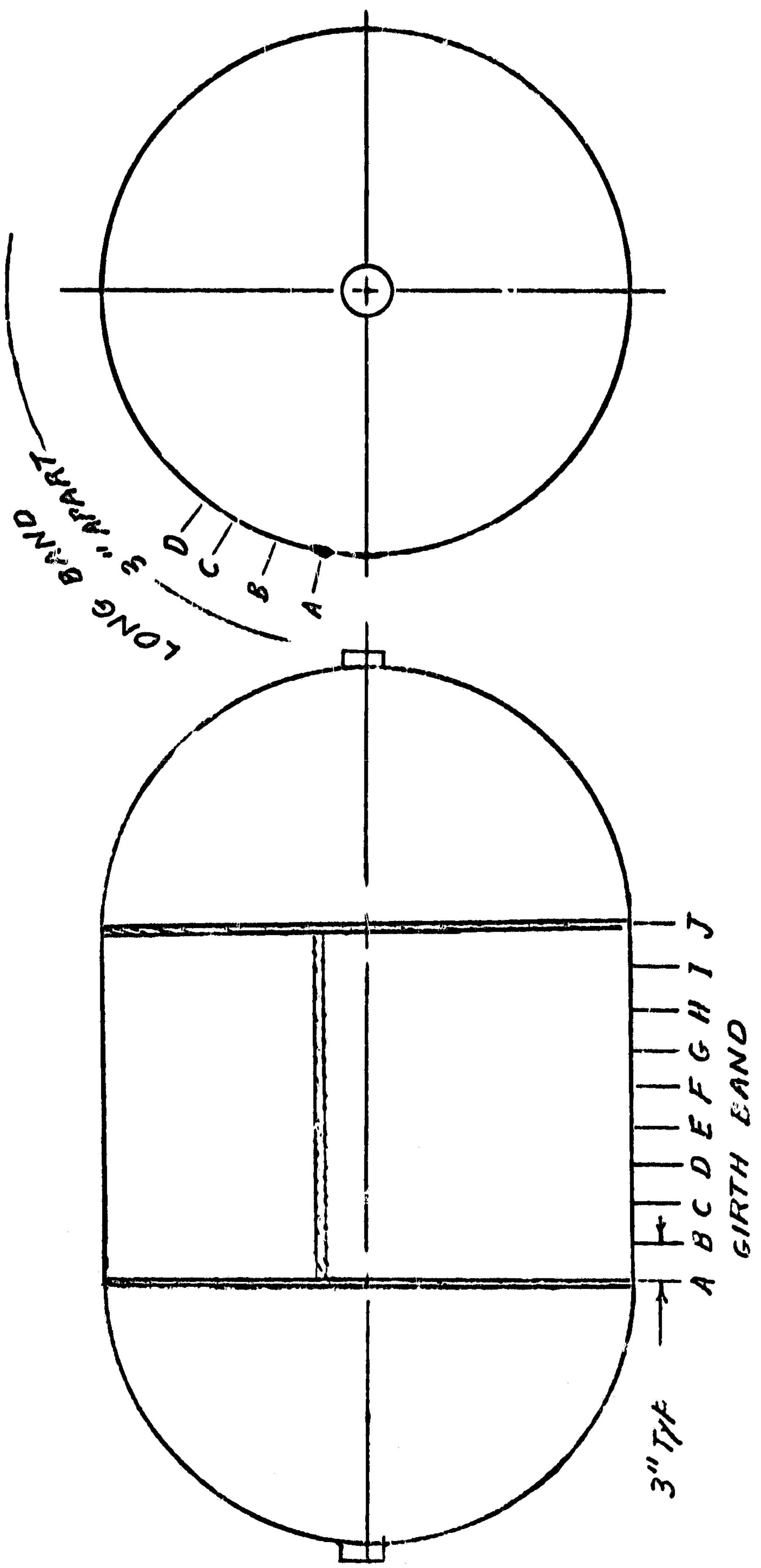
PAGE 4

REPORT NO.

JOB NO.

PREPARED BY

DATE



STRAIN GAGE NUMBER	LOCATION GIRTH BAND	LOCATION LONG BAND	CYL. THICKNESS
1	I	A	.051
2	E	H	.052
3	H	N	.051
4	G	G	.053

FIG # 2

AMR #250

FAILURE ANALYSIS

39" BENDIX CASE

Prepared by: R. Alper
R. Alper

13 November 1967

FAILURE ANALYSIS 39" BENDIX CASE

INTRODUCTION

A series of four (4) vessels, P/N J3499, were fabricated from heat 96269 and stretched at-320F in the sequence shown with the following results:

S/N	Stretch Pressure	Type of Die	Result
1	745 psi	Stove Pipe	Stretched successfully
4	710 "	Closed Die	Burst
2	590 "	Stove Pipe	Burst
3	660 "	Stove Pipe	Stretched successfully

The failures of S/N 4 and S/N 2 vessels were analyzed in order to determine the causes. S/N 2 failed at a low stress level indicating a defect as the cause of failure. However, S/N 4 had reached a high enough stress level to make it necessary to consider the possibility of over-stressing as a cause of failure.

The failure analysis consisted of examination of the fracture surfaces of both vessels, testing of tensile specimens from both vessels and extensive microsectioning of regions near the fracture edges. A description and discussion of the findings are presented below.

DESCRIPTION OF THE FRACTURE

The fracture path on S/N 2 and S/N 4 were strikingly similar. The fracture ran along the edge of the longitudinal weld, in both cases, at the weld-base metal interface.

At many locations on the fracture face, roughly textured, dark areas were noted. These contrasted with the more reflective surfaces generally noted on the fracture face. The reflective surfaces of the fracture face lay in a plane making an angle with the surface of the sheet stock which is usually associated with ductile shear. The roughly textured surfaces were more nearly normal to the sheet surfaces. It should be noted, however, that classification of a fracture mode as "ductile" or "brittle" from the angle the fracture surface makes with the sheet surface is not reliable when the fracture occurs at a weld-base metal interface in thin sheet. The plane of the fracture surface tends to be directed more by the shape of the weld-base metal interface and by variations in metallurgical characteristics in the vicinity of the interface than by the mode of fracture. The roughly textured fracture surface was noted in particular where the fractures approached within approximately 1/8" of girth welds, indicating that some heat effect from the girth welds played a part in these areas. The reason for the rough textured surface is discussed in the next section.

In vessel Serial #4, a bulge about 1" long and 1/2" wide was noted in the fracture path adjacent to the girth weld at that end of the cylindrical portion of the vessel which had been placed upward in the die. This appeared as the most likely place for the fracture origin.

Vessel Serial #2 showed no such distinct bulge. However, the fracture crosses from one side of the weld to the other on Serial #2. At those locations where the fracture crossed the weld it was noted that sometimes splitting of the weld-base interface on the I.D. of the vessel occurred. From further examination of the locations on Serial #2 where the fracture crossed the weld, it was possible to establish the direction in which the fracture ran. As the fracture first crossed from one side of the weld to the other, a continuation of the fracture in its original path direction was noted. Upon recrossing the weld, no continuation of the original fracture path was noted, thus, the direction from which the fracture came could be established. From these observations the failure origin on Serial #2 was isolated to that half of the cylinder which had been placed downward in the stretch die. Unfortunately, there were many areas in this half of the cylinder which appeared as possible fracture origins from simple examination of the fracture face. Microsections were, therefore, made along the length of the fracture in several suspicious areas of both vessels and these are discussed below.

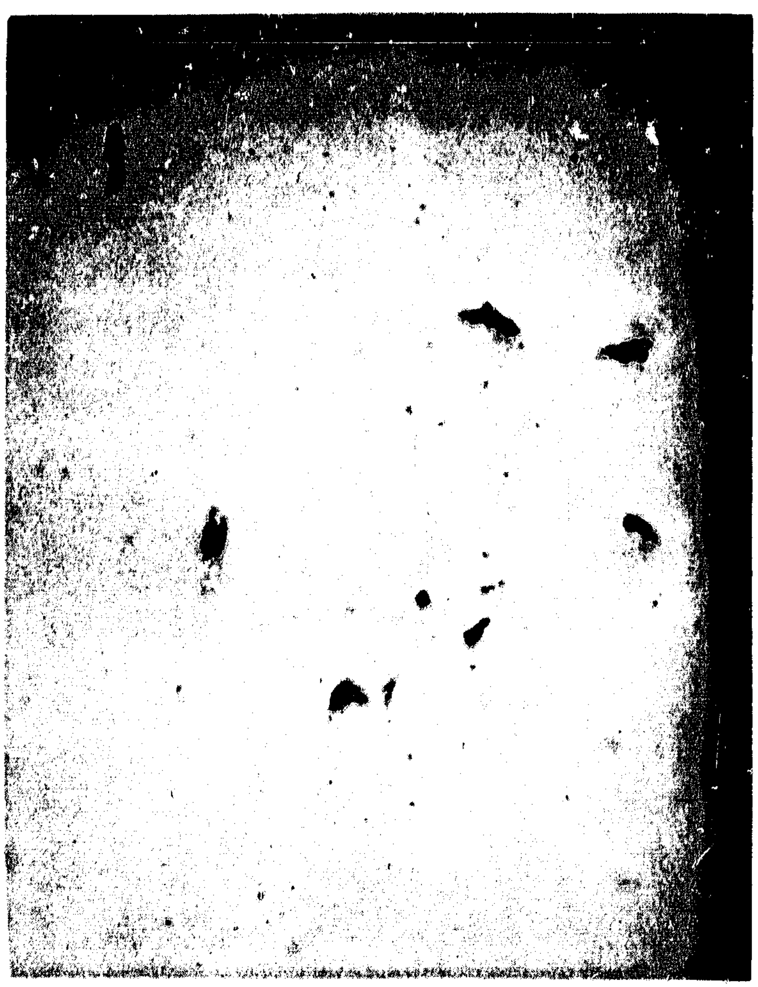
MICROSECTIONS

The microsections made from both vessels showed unusually large numbers of inclusions for this type of material. A section made from vessel Serial #2 near the girth weld is shown at two different magnifications in Figure 1 and 2. These inclusions were noted not only in base-metal but also in the weld as shown in Figure 3. The section in Figure 3 is taken near the suspected fracture origin. The presence of so many inclusions in the weld is unusual. The photomicrograph shown in Figure 4 indicates the occurrence of these inclusions near the fracture edge and shows a relationship between cracking parallel to fracture face and some of these inclusions.

Distribution of Inclusions in base-metal adjacent to fracture in S/N 2 vessel. Section near girth weld - longitudinal weld intersection.

Mag 100X Unetched

FIGURE 1



Inclusions shown in Figure 1 except at higher magnification

Mag 500X Unetched

FIGURE 2

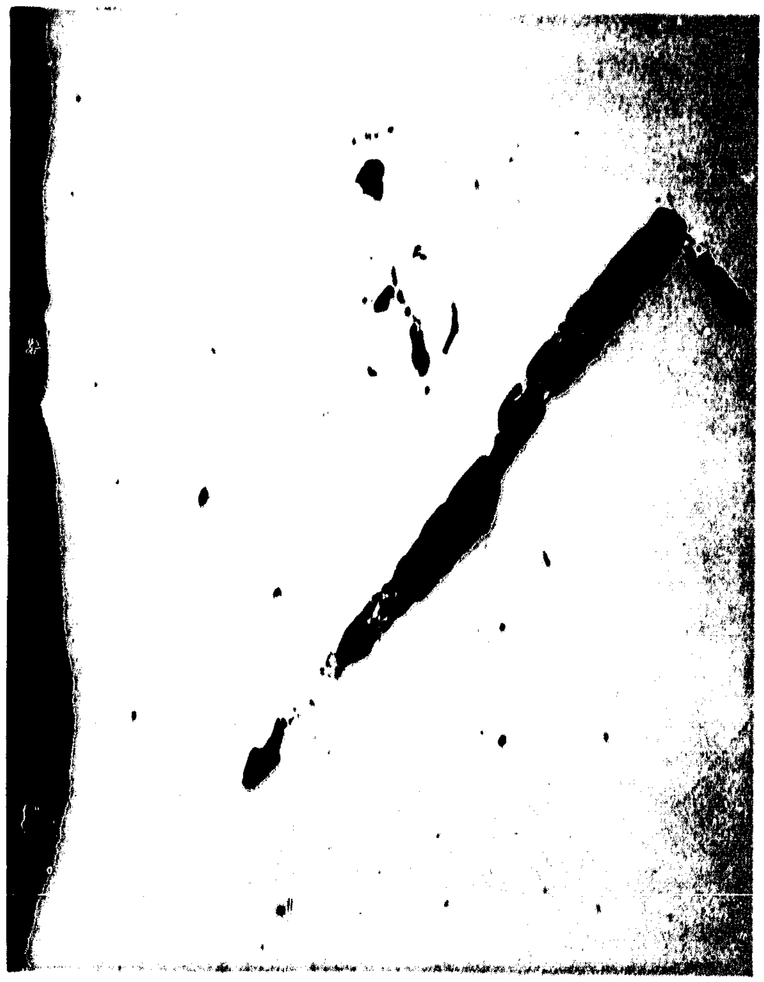
AMR #250

FIGURE 3

Distribution of Inclusions in Weld and Base Metal from S/N 2. View shows Fracture Edge.

Mag 25X Unetched

ARDE Photo Numbers: 102767-2
102767-3
102767-4
102767-5



Cracking near fracture edge of S/N2, on base metal side of fracture. Note inclusions within and near the crack.

Mag 200X Unetched

FIGURE 4

In sections taken from Serial #4, an additional type of inclusion was noted. These appear as a string of smaller inclusions as shown in Figure 5. This particular type of inclusion has been noted before in material melted at Eastern Stainless Steel using their vacuum induction furnace. It is believed that these non-metallic inclusions originate either from their furnace lining or pouring box. Because of the large number of possible fracture origins on both vessels, it was not possible to find a precise origin of failure. Nevertheless, sufficient evidence was noted to indicate that the probable cause of failure was these inclusions. For reference, compare the inclusions noted in Figure 5 with a section taken from a 22" diameter spherical vessel manufactured from a different heat (97058) made in the same furnace and which failed during cryostretch. The microsection shown in Figure 6 was taken from a definitely established fracture origin on the spherical vessel. Note the similarity of this type of stringer to that noted in Figure 5. It has been shown that this stringer type of inclusion does not occur with great frequency in a given sheet of material. Furthermore, the properties of the material are not unduly affected except when a weld passes directly over such an inclusion. A good deal of the material in the stringer may then be lifted up into the weld but does not seem to flow freely to the surface of the weld. Figure 7 shows what happens when such inclusions are passed over by a weld. This photograph is taken at a higher magnification in the weld above the inclusion shown in Figure 6. Compare Figure 6 from the sphere with Figure 4 from S/N 2. In addition, a further comparison of the inclusions in the cracks adjacent to the fracture path is shown at 1000 X in

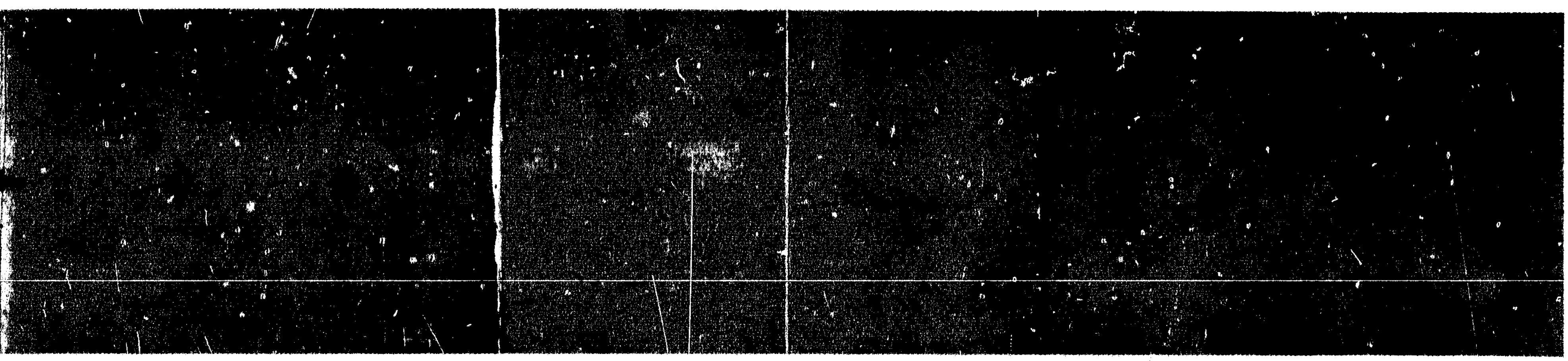
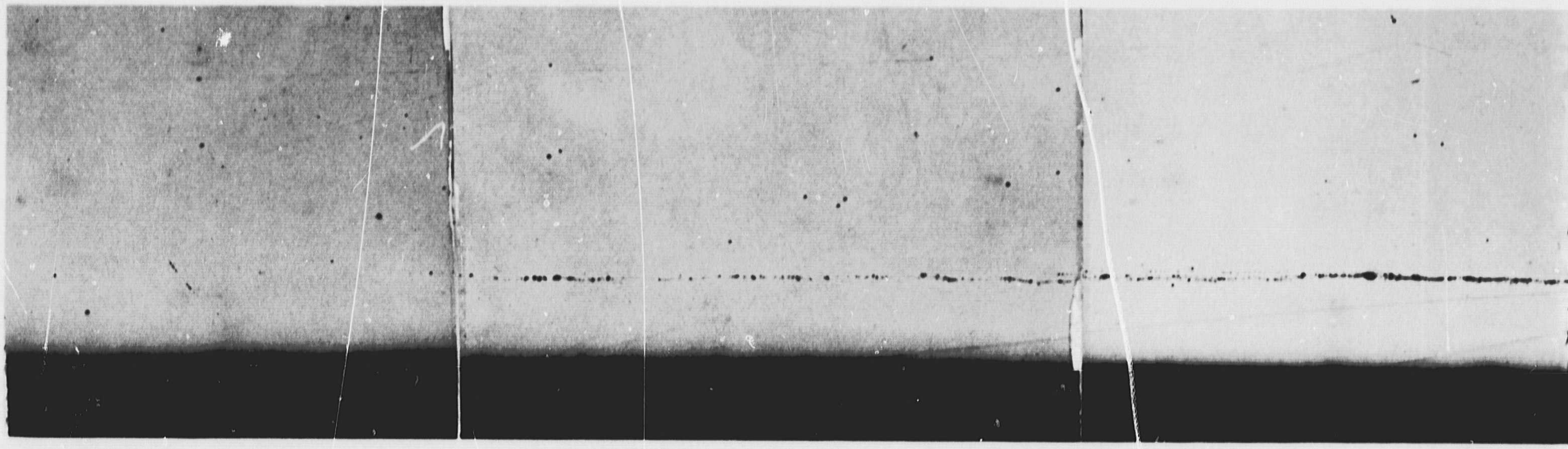


FIGURE 5

String of Inclusions in base metal near longitudinal weld; from S/N 4.

Mag 500X Unetched

ARDE Photo Numbers: 11367-1
11367-2
11367-3
11367-4
11367-5
11367-6



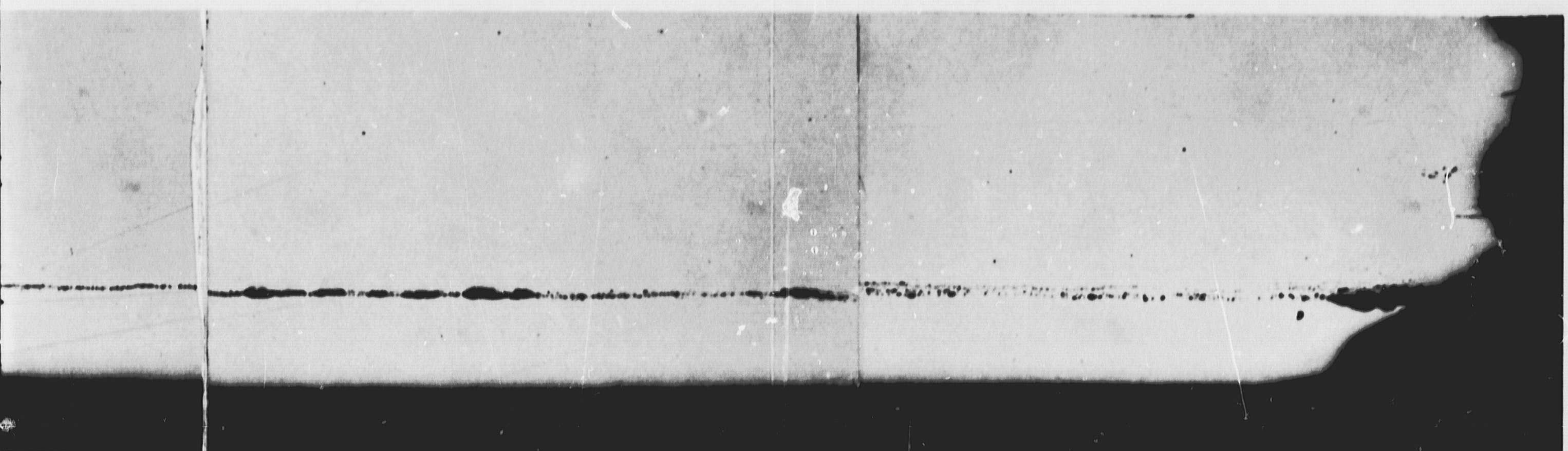
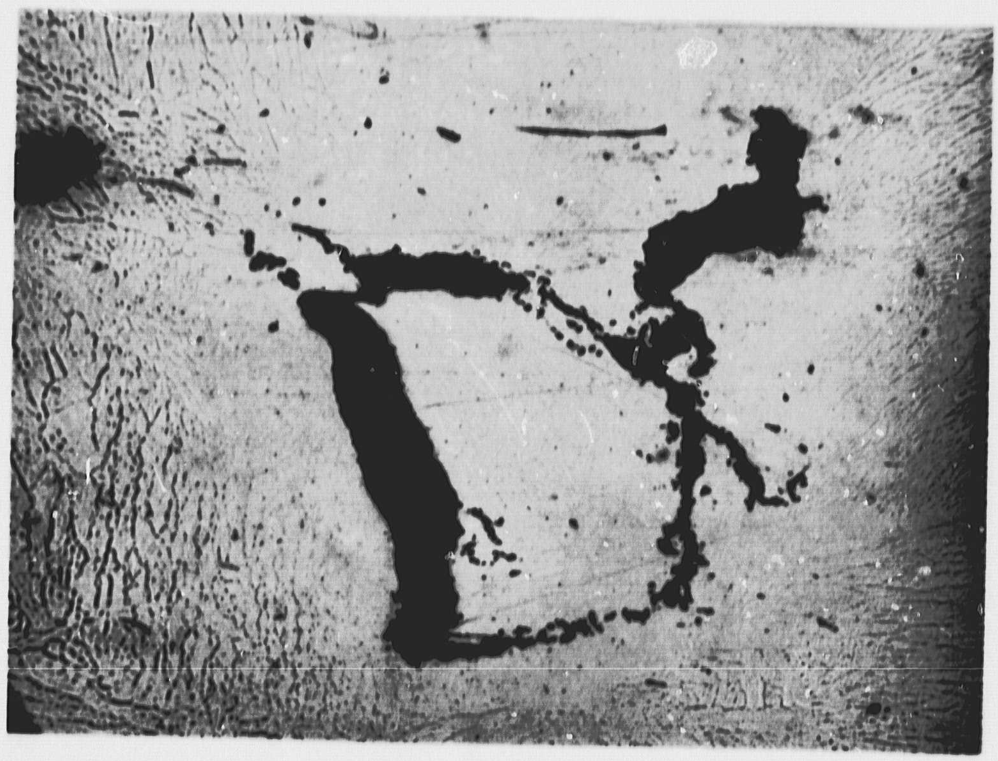


FIGURE 6

Laminar Slag Inclusion from a 22" Diameter Spherical Vessel

Mag 100X Unetched.

ARDE Photo Numbers: 71267-2
71267-3
71267-4
71267-5
71267-6



Effect of Laminar Slag Inclusion in Weld.
Section from Failed 22" Sphere.

Mag.

10% Oxalic Acid Electrolytic Etch.

FIGURE 7

Figures 8 and 9. Figure 8 is from S/N 2 and Figure 9 is from the failed sphere. Based on these observations, the presence of definite stringer type inclusion in Serial #4, and the large amount of inclusions in Serial #2 near the fracture edge, indicates that material was the primary cause of failure for both of these vessels. Although inclusions of globular oxides are often noted in reasonably large quantities in our air melted material, these float out of the weld and unless they are extremely large never appear in the weld on microsection. The microsections gave an explanation for the occurrence of the rough textured fracture surface. These areas could be associated with the passage of the fracture through a region between the actual fusion zone of the weld and the base-metal in which horizontal bands of delta ferrite were observed. When the fracture passed through this heat affected zone, the fracture face appeared rough in texture probably due to the differences in structure between the delta ferrite and the surrounding transformed martensite. The occurrence of this heat affected zone could not be tied to the cause of failure. This type of heat affected zone has been noted before in pressure vessels successfully fabricated from low silicon material. In vessels Serial #2 and #4, in some cases, the fracture passed right through the middle of this zone. The zone is shown in Figure 10. A section through a split noted at the point where the fracture path crosses the weld shows that splitting originated not in the middle of this heat affected zone, but actually in the weld metal at the interface between the weld and this delta ferrite region. This is shown in Figure 11.

In summary, then, the micro-examination of the fracture region of both vessels indicated the presence of large amounts

Nature of cracking adjacent to fracture path. From vessel S/N 2

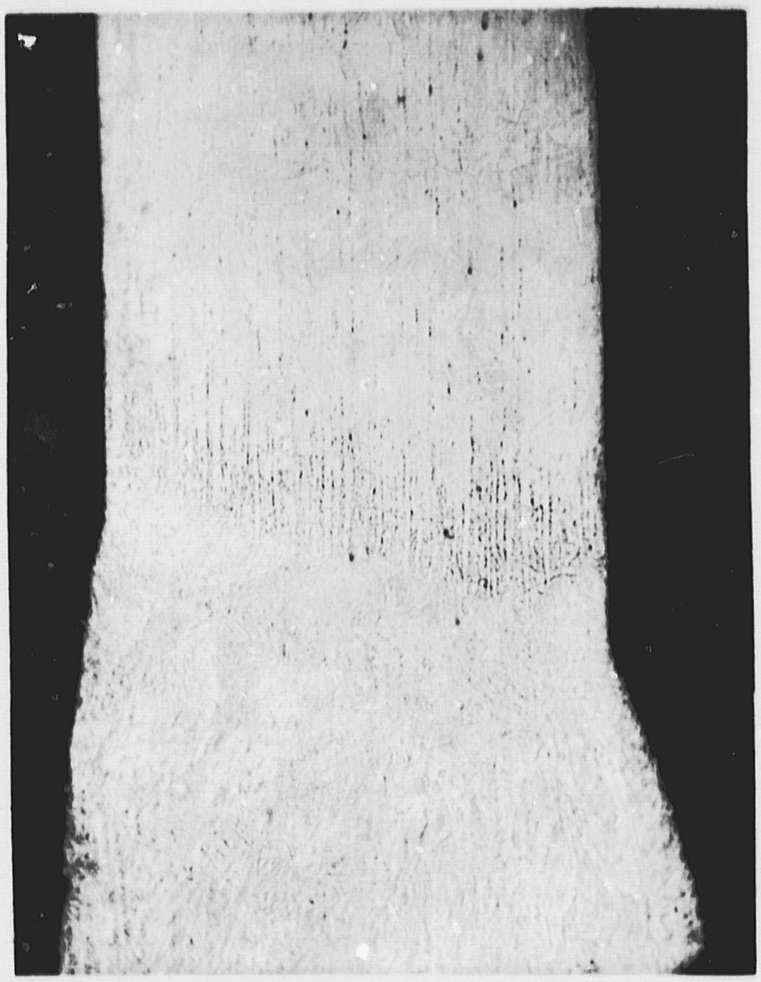
1000X Unetched

FIGURE 8

Nature of cracking adjacent to fracture path. From 22" dia. spherical pressure vessel.

1000X Unetched

FIGURE 9



Horizontal bands are delta ferrite in the heat affected zone adjacent to the weld.

Mag 50X 60% oxalic acid electrolytic etch.

FIGURE 10

Splitting starting at I.D. of vessel, outside zone of delta ferrite bands.

Mag 100X 10% oxalic acid electrolytic etch.

FIGURE 11

of inclusions. In particular, the inclusions were of a type which had previously been associated with a cryogenic stretch failure on another vessel fabricated from heat 97058, a material produced in a similar fashion to heat 96269. The fracture path and a roughly textured surface was noted to be associated with a heat affected zone adjacent to the weld consisting of bands of delta ferrite parallel to the sheet surface. However, previous experience with this type of heat affected zone does not indicate that its presence is necessarily a cause for premature failure. Finally, the existence of a large number of areas of similar appearance on the fracture surface which might have indicated a fracture origin did not permit a precise origin to be located on either vessel. Instead, cause of failure was deduced from the presence of extraordinary amounts of non-metallic inclusions at each of the suspicious areas examined.

TENSILE TESTING

As was stated previously, the low stress level at which Serial #2 vessel failed was a clear indication that a defect had been the cause of failure. Serial #4 vessel, however, stretched out to the die and a considerable region of the cylinder had apparently contacted the die. Therefore, since the possibility of over stressing of Serial #4 existed, tensile specimens were cut from both Serial #2 and Serial #4 and aged. These specimens were then tested at room temperature. By this means, it is possible to determine the amount of cryogenic straining which the material had undergone during the stretching process. Figure 12 and Figure 13 show the location and room temperature strength levels

Fig. 12

Room Temperature Tensile Test Results

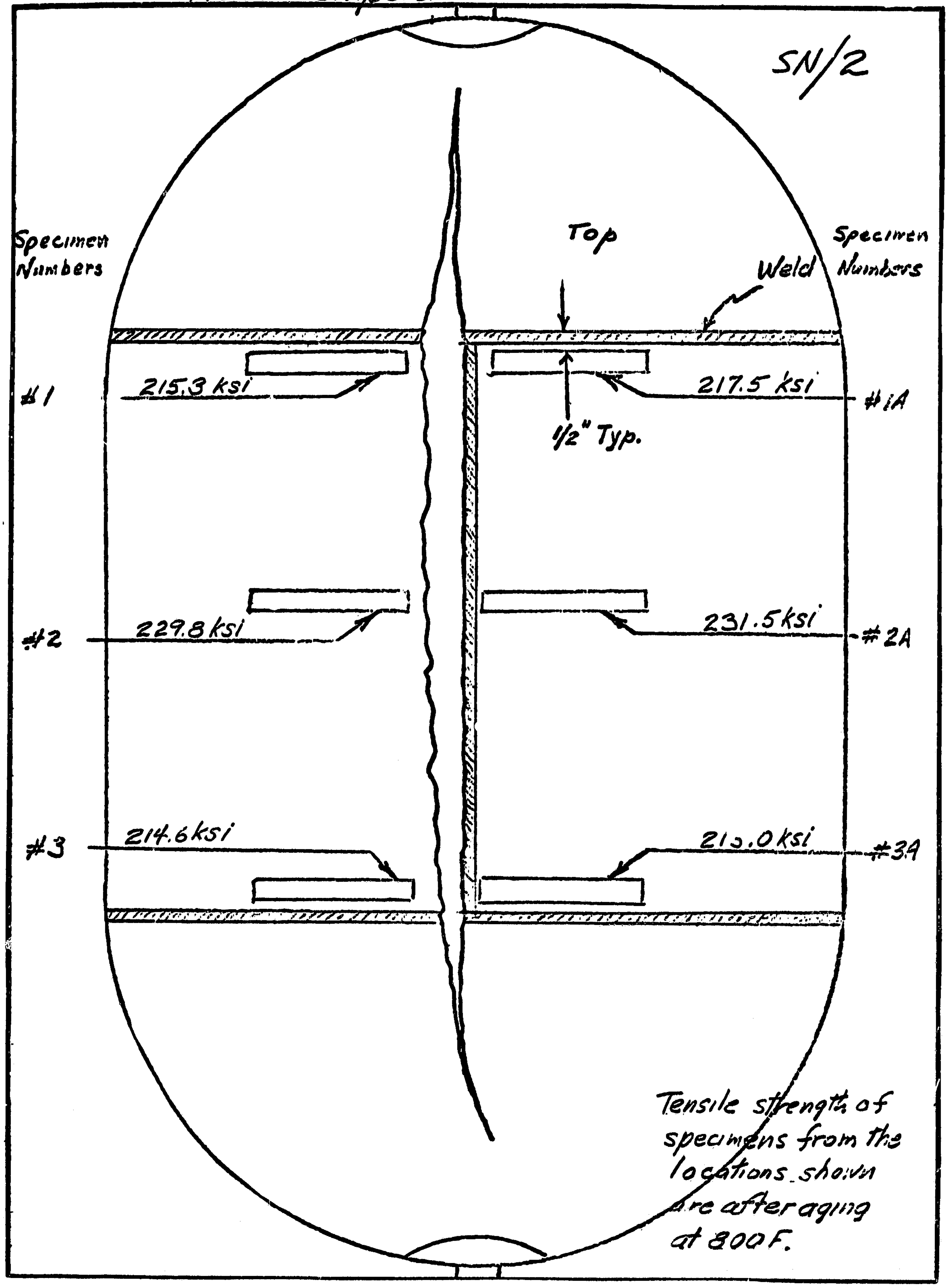
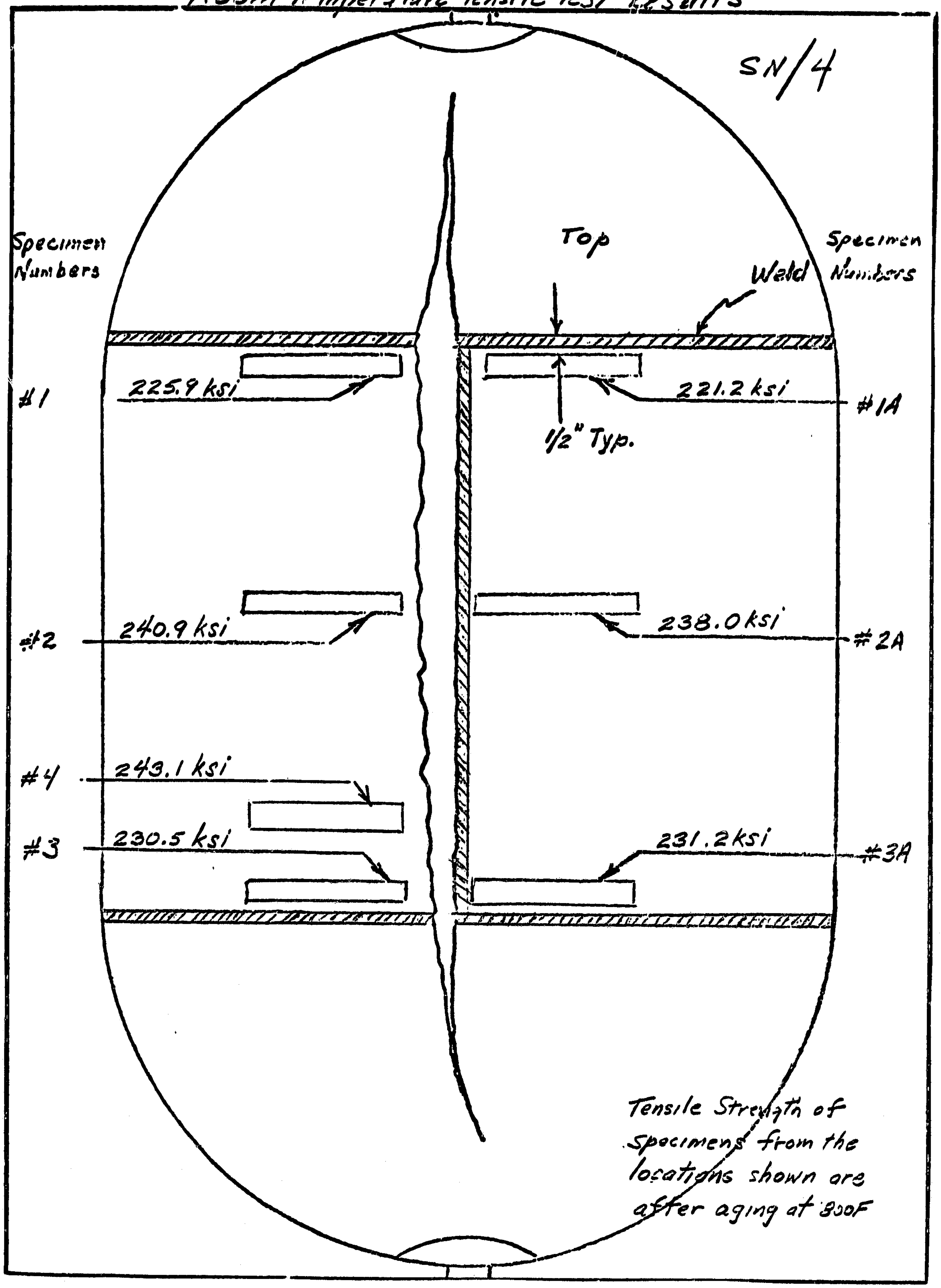


Fig. 13

Room Temperature Tensile Test Results



of the tensile specimens cut from both vessels. The room temperature strength of the tensile specimens from Serial #2 were noted to be considerably lower than that of the specimens from Serial #4 which was stretched to a higher stress level. The strongest uniaxial tensile specimen from Serial #4 was that specimen taken from one end of the cylindrical region close to the last point of contact between the vessel and the die. This specimen was approximately 4 3/4" from a girth weld. The strength level of 242 ksi was well below the strength level which could be obtained with a uniaxially stretched tensile specimen from this heat. Tensile specimens from this heat have been stretched to room temperature strength levels of 268 to 270 ksi. Furthermore, a material evaluation sphere from this same heat had been stretched to a level which produced a room temperature hoop strength of 256 ksi. Since, in a sphere, there is no increase in biaxial hoop strength over uniaxial strength, this 256 ksi hoop strength level implies a 256 ksi uniaxial strength.

In summary then, the tensile data indicates that neither of the cylinders were stretched to too high a stress level, inasmuch as the room temperature strength of tensile specimens cut from both cylinders were well below the strength level which the material was demonstrably capable of achieving.

In addition to the tensile testing described above, tensile specimens were fabricated from sheet stock from the same heat which was available from the stockroom. One specimen was also cut from each of the tanks and annealed. These four specimens were then pulled in a cryostat at -320F and their stress-strain curves examined. The stress-strain curves were identical to those which had formed the basis for the design and which had been pulled as part of the material evaluation procedure for his heat several months ago. The purpose of this testing was to determine if an accidental error had been made in the use of the wrong material. This cryogenic tensile testing, however, indicated that no such problem existed.

CONCLUSIONS

Testing of tensile specimens from the two vessels indicated that they were indeed not overstrained and that both vessels had failed due to a defect somewhere in the fracture path. Because of the nature of the fracture path it was not possible to determine precisely the origin of the failure in either vessel. However, the presence of inclusions in a quantity and of a type known to have caused failures when these are encountered during welding, leads to the conclusion that the cause of failure of both of the vessels, was the occurrence of non-metallic inclusions in the weld path.

RECOMMENDATIONS

The type of inclusion noted in this material and in additional heats poured at the same source has been found to be rather sparsely distributed in clumps throughout a given piece of wrought material. Detection by X-ray has not been found feasible because of the small thickness of the defect. ARDE has some experience in detection of this type of inclusion using ultrasonics. Detection, however, was accomplished in a thicker material with somewhat thicker stringer type inclusions than those noted in heat 96269 and then only after extensive experimentation with different ultrasonic techniques on a specific part. Sample microsections of the material at random location is not a satisfactory method for detection because of the sparse distribution of these areas of defects. For example, in a 20" diameter head made from heat 97058, only one such inclusion was found after scanning the entire surface.

It is, therefore, recommended that the best approach is to utilize material in which the inclusions are more finely and widely distributed. This can be accomplished by vacuum consumable electrode remelting of clean vacuum induction heats. Heat 96269 was vacuum induction melted but not vacuum remelted.