

# Hydraulic Accumulator Cylinder for Navy Submarines

## **Design Study Outline**

### Introduction

### Design for Performance

*Duplex Steel Approach*

*Alloy Selection*

### Design for Production

*Centrifugal Casting*

*Casting Orientation*

*Mold Preparation and Casting*

### Heat Treat and Machine

### Quality Assurance

### Lessons Learned and Summary



# **Start the Design Study !**

 [Next](#)

### **Acknowledgment --**

*The metalcasting design studies are a joint effort of the Steel Founders' Society of America and the American Foundry Society. Project funding was provided by the American Metalcasting Consortium Project, which is sponsored by the Defense Logistics Agency, Attn: DLSC-T, Ft. Belvoir, VA, 22060-6221*



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# Hydraulic Accumulator -- Application

U.S. Navy submarines use on-demand hydraulic pressure for system operations, using water as the working fluid.

- Hydraulic accumulators are used to contain and store the working fluid at full working pressures.
- The accumulators are cylindrical in shape with an enclosed movable piston which serves as the pressure transfer mechanism.



[Back](#) [Next](#)

2



[Return  
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Home  
Page](#)

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## Accumulator -- Function



The accumulators have to contain high hydraulic pressure without pressure loss or failure through numerous pressure cycles (>1/2 million cycles).

- The cylinder walls have to be resistant to both wear and corrosion to prevent pressure loss caused by seal damage, surface scoring and pitting, and wall cracking.
- Although fresh water is the standard working fluid, the system is designed to use seawater in emergency conditions and has to resist saline corrosion.



[Back](#) [Next](#)

3



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[Page 1](#)

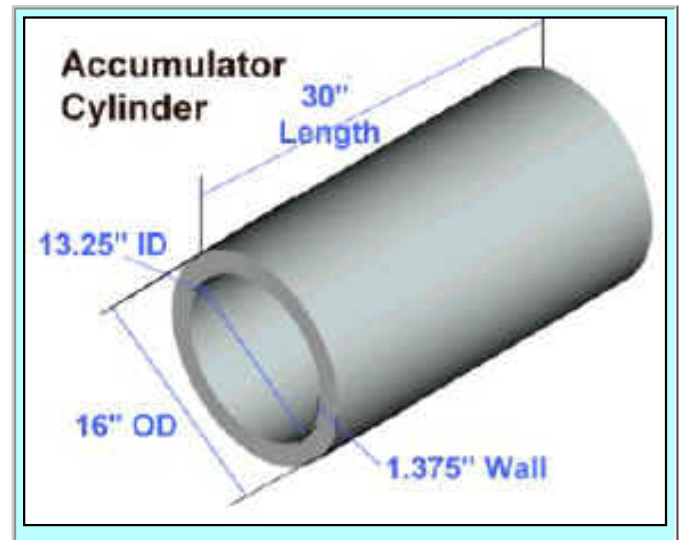
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## Accumulator Cylinder -- Description

Spuncast, Inc. of Watertown, Wisconsin manufactures the cylinder barrel for the accumulators in US Navy submarines.

- The cylinders are straight wall tubes with an outer diameter of 16 inches and a length of 30 inches .
- The wall thickness is a uniform 1.375 inches.
- The heat-treated and machined cylinders are assembled into finished assemblies with end plates, reinforcement rods, and the internal piston.



[Back](#) [Next](#)

4



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# Accumulator Cylinder -- Requirements

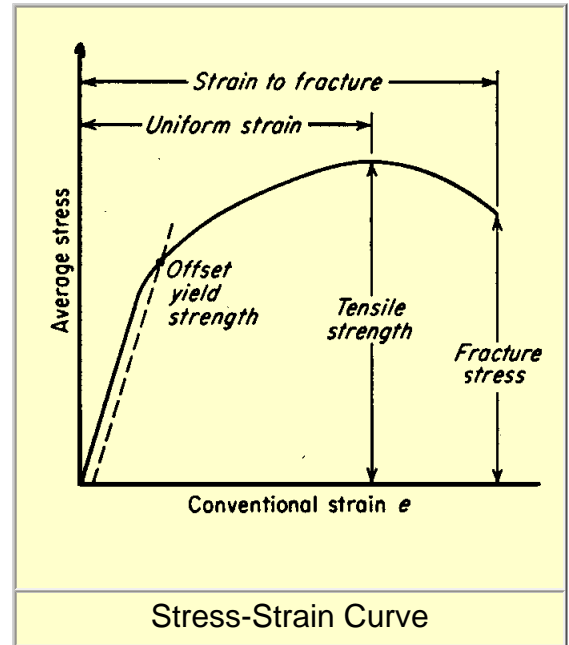
The performance requirements for the cylinder are:

## Mechanical Properties--

- Ultimate Tensile Strength = 110 KSI
- Yield Strength = 70 KSI
- Elongation/Strain to Fracture = 20%
- Fracture Toughness = 35 Ft. Lbs by Charpy Impact
- Hardness = 229-250 Brinell

As-cast Tolerances (OD, Length) =  $\pm 1/16$ "

The quality assurance process includes complete inspection of each casting per military specifications by liquid penetrant and radiographic testing.



[Back](#) [Next](#)



[Return to SFSA](#)  
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[Page](#)

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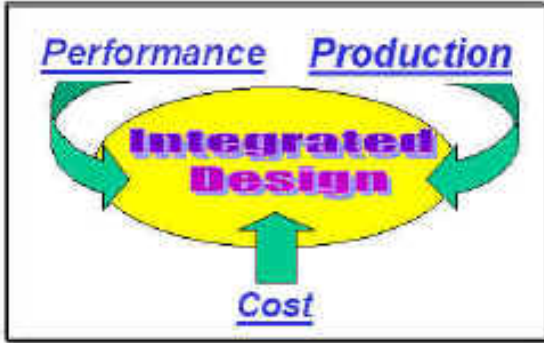


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# The Casting Design Issues



The casting design engineers at Spuncast of Watertown, WI focused on three imperatives

--

- *Design for Performance*
- *Design for Production*
- *Design for Cost*

**Critical Casting Design Issues** --The requirements for performance, casting production, and cost are closely interconnected. Four casting design issues played a major role in meeting the three design imperatives.

- Select a [steel alloy system](#) that meets the mechanical property and corrosion resistance requirements and reduces costs.
- Choose the [casting method](#) that rapidly produces flaw-free cast cylinders.
- Select a [casting orientation](#) that meets tolerances and minimizes machining
- Use a [heat treatment cycle](#) that optimizes the microstructure and properties.



[Back](#) [Next](#)

6



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# The Original Cylinder Design

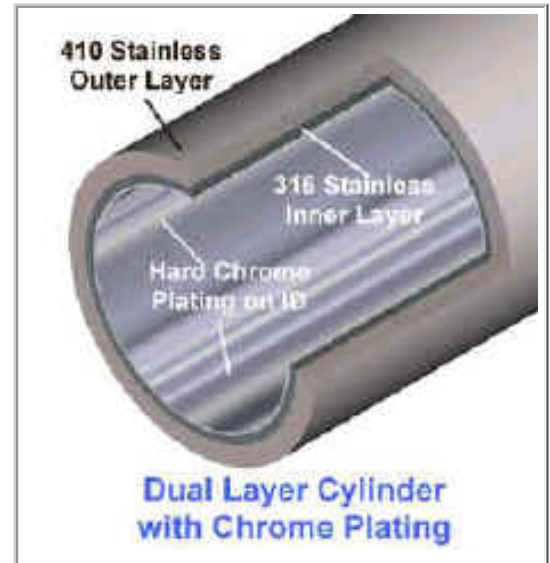
The historical design for the accumulator was a dual layer casting with chrome plating on the inner bore.

The dual layer design required two separate metal pours to cast the two layer wall.

-- The outer wall (1" thick) was a 410 stainless steel alloy and the inner wall (3/8" thick) was a 316 stainless steel alloy.

-- The 316 stainless provided the corrosion resistance on the inner wall, while the 410 stainless gave the cylinder high mechanical strength (110 ksi tensile)

After finish machining, the inner wall of the cylinder was then hard chrome electroplated (15-20 mils) for the required wear resistance.



[Back](#) [Next](#)



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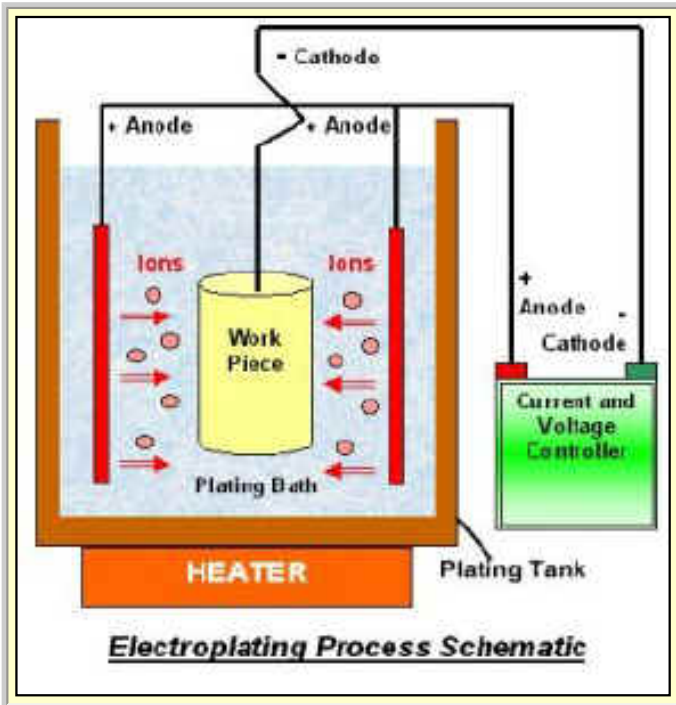
[Page 1](#)

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## Original Process Shortcomings

The dual layer casting with the chrome plating on the ID had three significant process shortcomings.



1. The dual layer casting process requires very tight control of casting conditions ( *melt temperatures, cooling rates, and pour timing* ) to produce a clean, sound metallurgical bond between the two alloy layers.
2. Two alloys requires two melt units with the added operational cost.
3. Chrome electroplating has undesirable environmental costs and risks and is under tight EPA regulation. The Department of Defense policy calls for the replacement / reduction of hard chrome electroplating in military components, whenever suitable alternative technology is available.

**Duplex steel alloys offered a solution that provided both strength and corrosion resistance in a single alloy casting without the need for chrome plating.**

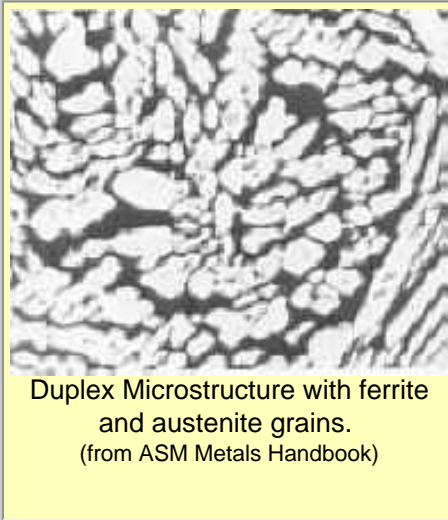
← →  
[Back](#) [Next](#)





## Duplex Stainless Steel

**Duplex stainless steels have a balanced microstructure mixture of ferrite and austenite phases in the solution annealed condition.**



Chromium and nickel are the principal alloying elements in duplex steels, but nitrogen, molybdenum, copper, silicon, and tungsten are often used to control structural balance, mechanical properties and corrosion-resistance characteristics.

**Corrosion Resistance** -- The low carbon content and high chromium content make the duplex alloys relatively immune to intergranular corrosion.

- The high chromium and molybdenum content also provide a high degree of resistance to pitting and crevice corrosion, while the duplex microstructure resists stress corrosion cracking.

**The duplex stainless steels have higher tensile and yield strengths than austenitic alloys with a fracture toughness between that of austenitic and ferritic alloys.**



[Back](#) [Next](#)

9



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## Duplex Alloy Selection

**The duplex stainless steel alloy of choice for this casting is ASTM A-890, which is available in seven different grades.**

Given the mechanical property requirements for the accumulator, consider the nominal properties of three A-890 grades in the table below and choose the grade that best meets the mechanical requirements.

ASTM A-890-Grades =>	Minimum Requirement	Choose Grade 1A	Choose Grade 4A	Choose Grade 1B Modified
Ultimate Tensile Strength	110 ksi	100	90	110
Yield Strength	70 ksi	70	60	70
% Elongation	20%	16%	25%	30%

 Choose an alloy grade above  
[Back](#)

10



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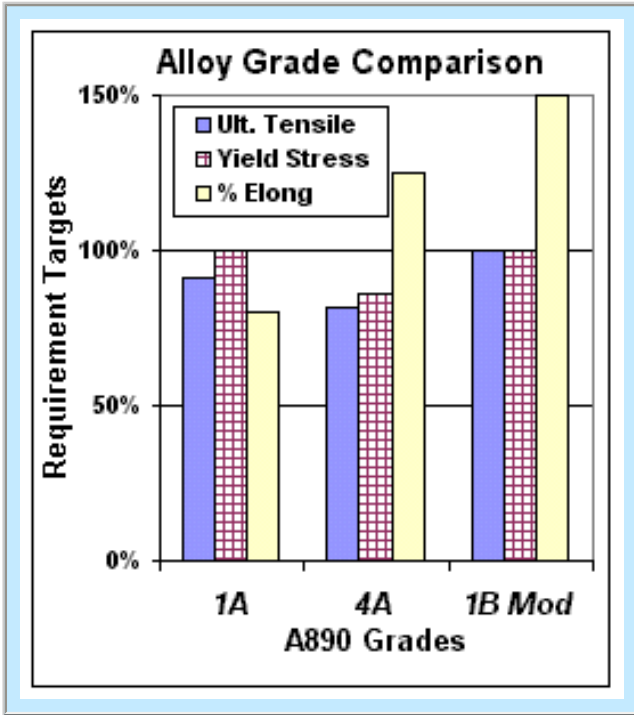


[Page 1](#)

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# A-890 Grade 1A



The ASTM A-890 Grade 1A is a duplex stainless steel cast alloy with the following composition

C - 0.04 max, Cr - 24.5-26.5, Ni - 4.75-6.00 max,  
 Cu - 2.75-3.25, Mo - 1.75-2.25, Mn - 1.00 Max,  
 P - .040 max, S - 0.040 max, Si = 1.00 max

The 1A grade has sufficient yield strength, but doesn't meet the requirements for ultimate tensile strength or % elongation.

***The Grade 1A is not the best alloy choice.  
 Go Back for Another Choice!***



[Back](#)



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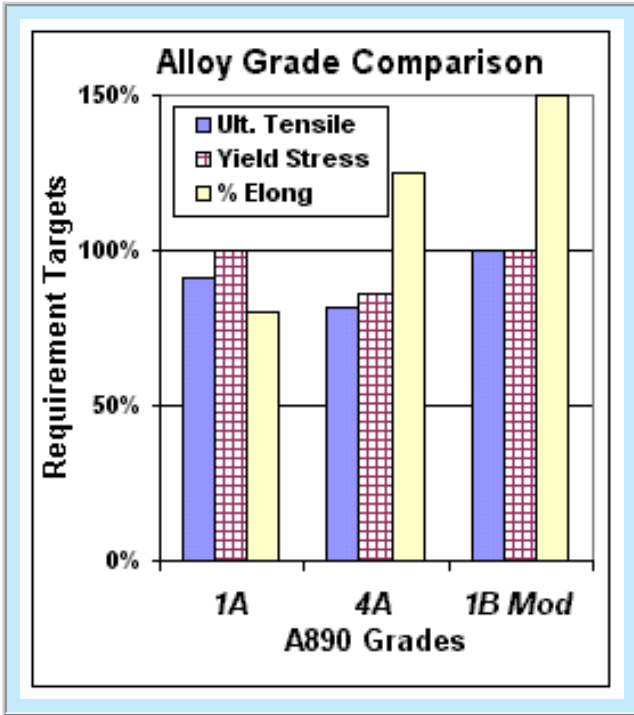


[Page 1](#)

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# A-890 Grade 4A



The ASTM A-890 Grade 4A (CD3MN) is a duplex stainless steel cast alloy with the following composition

C - 0.03 max, Cr - 21.0- 23.5, Ni 4.5-6.5 max,  
 Cu - 1.0 max N - 0.10-N-025, Mn - 1.50 max,  
 P - .040 max, S - 0.020 max, Si = 1.0 max,  
 N - 0.10-0.30

The 4A grade exceeds the % elongation requirement, but doesn't meet the requirements for ultimate tensile strength or yield strength.

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[Back](#)



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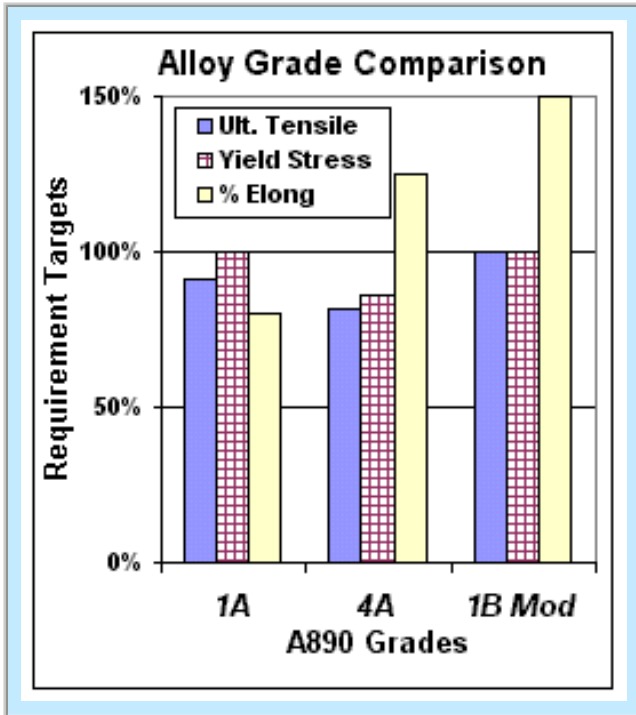


[Page 1](#)

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## A-890 Grade 1B Modified



The ASTM A-890 Grade 1B (CD4MCuN) is a duplex stainless steel alloy that is similar to the Grade 1A, but has a controlled nitrogen level

C - 0.04 max, Cr - 24.5-26.5, Ni - 4.75-6.00,  
 Cu - 2.75-3.25, Mo - 1.7-2.3, N - 0.10-0.25,  
 Mn - 1.00 max, P - .040 max, S - 0.040 max,  
 Si - 1.00 max

Controlled nitrogen in the 1B increases the fracture toughness of the alloy. But the ultimate tensile strength and yield strength of the baseline grade 1B are too low.

Spunecast engineers modified the 1B alloy with a proprietary composition change which increased the ultimate strength, yield strength, and % elongation, so that all the mechanical requirements were met.

**The modified 1B alloy meets all the mechanical requirements.**  
 Go to the [Next Design Issue](#)



[Back](#) [Next](#)



## Centrifugal Casting

Spuncast, Inc. specializes in centrifugal casting where molten metal is cast into a mold which is rapidly spinning during the pouring and cooling steps.

- Molds for centrifugal casting are commonly permanent steel molds, shaped as hollow tubes with partially capped ends.  
*Expendable sand molds are sometimes used for very large and/or single run castings.*
- No cores are needed or used in the centrifugal casting of tubes and hollow cylinders.  
*Centrifugal force holds the metal against the mold wall and forms the interior bore.*



Metal Pour into a Horizontal Centrifugal Mold

**Centrifugal casting is particularly suited for the production of cylindrical shapes and can be done in a vertical or horizontal orientation.**



[Back](#) [Next](#)

14



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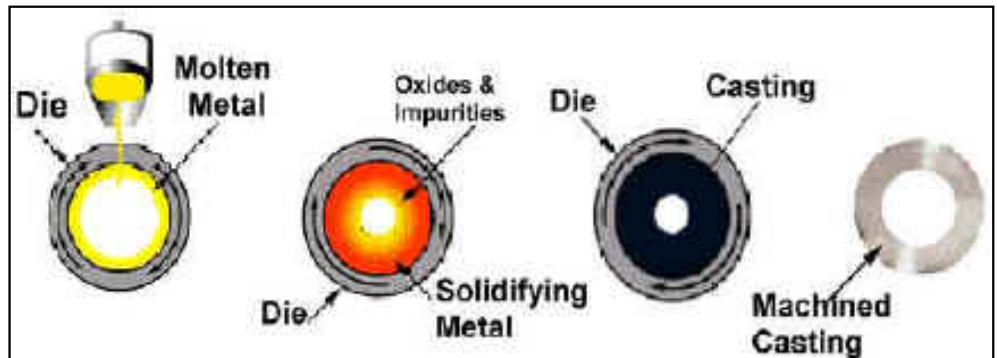
[Page 1](#)

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## ***Benefits of Centrifugal Casting***

In centrifugal casting the rapidly spinning mold (>1000 rpm) forces the molten metal against the "cold" wall of the mold. The metal solidifies from the outer diameter (OD) of the casting in towards the inner diameter (ID).



***Centrifugal casting has three primary metallurgical benefits:***

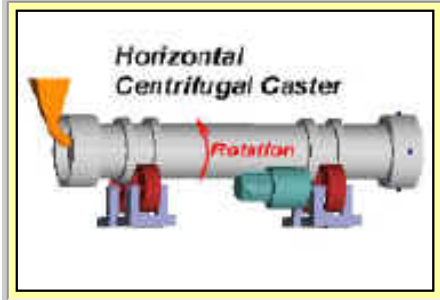
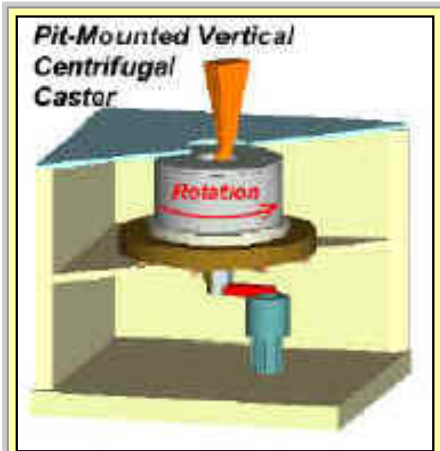
1. The rapid directional solidification from the OD to the ID produces a consistent grain structure with excellent strength and toughness.
2. The molten metal on the interior wall feeds the solidification front and shrinkage porosity is minimized without the use of risers or gating.
3. Under the centrifugal force, lighter inclusions and gas porosity in the molten metal strongly migrate to the interior bore.

*The ID of the cooled casting is then machined to remove the consolidated casting anomalies - oxides, impurities, and gas porosity.*

*Centrifugal casting produces a cast tube that is flaw free through its thickness with excellent mechanical properties.*




# Casting Orientation



Centrifugal castings are produced in either a vertical or horizontal casting orientation.

- **Vertical centrifugal casting** is more suitable for cylinders with a ring geometry (diameter-to-length ratio [aspect ratio] >1). Vertical machines are often mounted in a concrete pit below ground.
- **Horizontal centrifugal casting** is more suitable for tube geometries (diameter-to-length ratio [aspect ratio] <1). The horizontal machines are commonly mounted at floor level.

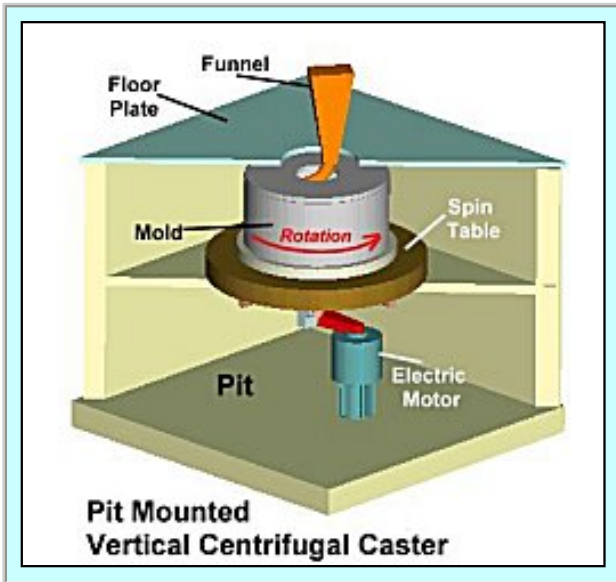
Choose which orientation is best for casting the accumulator cylinder (16" diameter and 30" long) -- **Vertical** or **Horizontal**



[Back](#)



## Vertical Orientation



In vertical casting the mold is upright and spinning around its vertical axis. The vertical casting machine can be installed at floor level or in a pit.

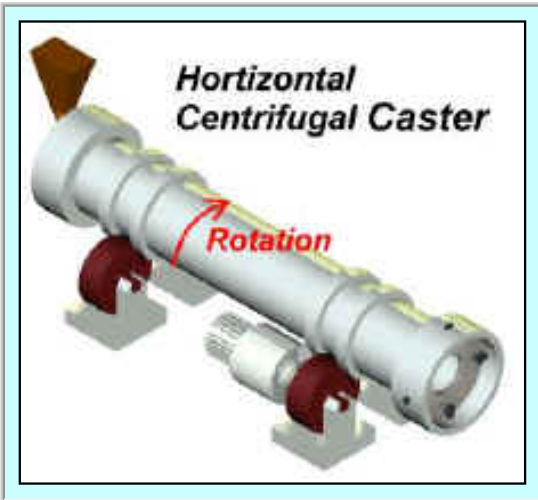
- Vertical casting is more suitable for castings with high aspect ratios (>1), cone shapes, or parts with features on the OD.
- Long molds in a vertical orientation require deep pits or high cranes, which raises capital costs and complicates metal handling
- Because of the effect of gravity, vertical castings tend to have a taper (~1/8" per foot) on the inside bore which has to be machined out. Or higher RPMs can reduce the taper.

Set-up costs are higher and turn-around times are longer for vertical systems, compared to horizontal centrifugal casting.

*Vertical centrifugal casting is not the best orientation for the accumulator cylinder.  
[Go back and select another orientation.](#)*



## Horizontal Orientation



In horizontal casting the long axis of the mold is parallel to the floor and the mold spins around its horizontal axis.

- Horizontal casting machines are more convenient for metal handling on longer castings and have fewer length limitations.
- The cylinder wall thickness is uniform from end-to-end, because there is no gravity effect along the horizontal axis.

Set-up costs are lower and mold prep times are shorter for horizontal systems, compared to vertical centrifugal casting.

**Horizontal casting is the best choice for the accumulator cylinder.**  
**[Go to the Next Design Issue!](#)**



[Back](#) [Next](#)

18



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[Page 1](#)

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# The Centrifugal Casting Process

The centrifugal casting process has 5 steps--

1. Preheat the steel mold and coat the mold interior with the refractory ceramic coating (applied as a spray slurry).
2. Melt the metal in the furnace.
3. Rotate the mold, pour the metal, and spin the mold until the casting solidifies.
4. Remove the casting from the mold after solidification.
5. Clean, heat-treat and machine the finished casting.



Metal Pouring into a Horizontal Mold



[Back](#) [Next](#)

19



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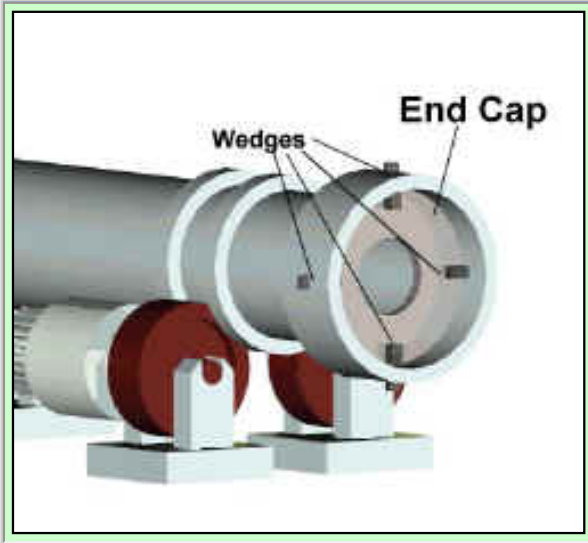
[Page 1](#)

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## Mold Preparation

One or both ends of the mold have removable end caps which are held on with wedges or clamps. Removing the end cap allows removal of the casting from the mold.



- A critical step in mold preparation is spray coating the interior wall of the steel mold with a ceramic slurry at a controlled thickness.
- The ceramic coating serves as a wetting agent that promotes the flow of the molten metal into the mold, controls the heat transfer during solidification, and acts as a parting coating for casting removal.



[Back](#) [Next](#)

20



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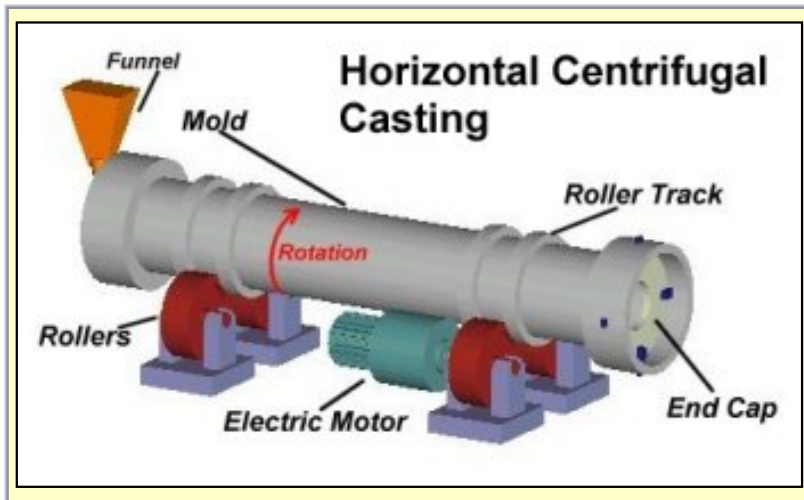
[Page 1](#)

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## Horizontal Mold Rotation

The cylindrical steel mold is supported on roller wheels at specific points along its horizontal length. An electric motor spins the drive wheel which transfers the rotary motion to the mold, reaching spinning speeds greater than 1000 rpm.



- Rotational speeds are calculated against the radius of the mold and the weight of the casting.
- The speed is set to pick up and hold the molten metal against the mold wall through the full rotation without liquid slippage on the wall or dropping ("raining") at the top of the rotation.



## Thermal Management

**Solidification in the mold is carefully controlled by management of five thermal factors in the casting process.**

1. Preheating the mold to a specified temperature.
2. Tailoring the composition and thickness of the ceramic coating on the interior of the mold to control the heat transfer rate into the mold wall.
3. Controlling the pour temperature of the molten metal in the ladle.
4. Water cooling the outer diameter of the mold to accelerate cooling and solidification at the critical point in the casting process.
5. Adding an exothermic compound ("liquidizer") to the interior of the mold to prevent premature solidification of the interior bore of the casting.



The controlled directional solidification from the outer diameter to the inner diameter of the cylinder produces a sound casting with uniform grain structure and excellent mechanical properties.



[Back](#) [Next](#)

22



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[Page 1](#)

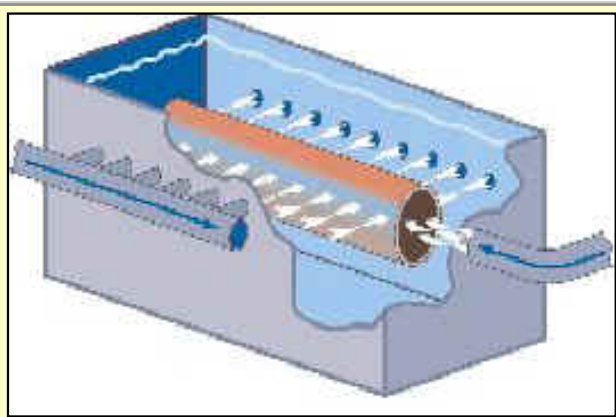
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## Heat-Treating and Machining

The cooled casting is cleaned by abrasive blasting to remove any ceramic mold coating or surface oxidation.

Controlled heat treating and quenching are essential to produce the required metal microstructure for the required mechanical and corrosion resistant properties.



Forced Flow Quench Tank at Spuncast

- The accumulator cylinder is furnace heat treated to 2050F and then cooled to 1900F.
- The cylinder is then water quenched in a specially designed immersion bath with forced water flow on the cylinder OD and through the center ID. The forced flow on the OD and ID ensures rapid quenching and the optimum microstructure.

After heat-treating and quenching, the cylinder is rough machined on the outer diameter, inner bore, and two end faces to surface finish of 250 RMS.

*The cylinder is sent out for finish machining.*



[Back](#) [Next](#)

23



[Return to SFSA](#)  
[Home](#)  
[Page](#)

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[Page 1](#)

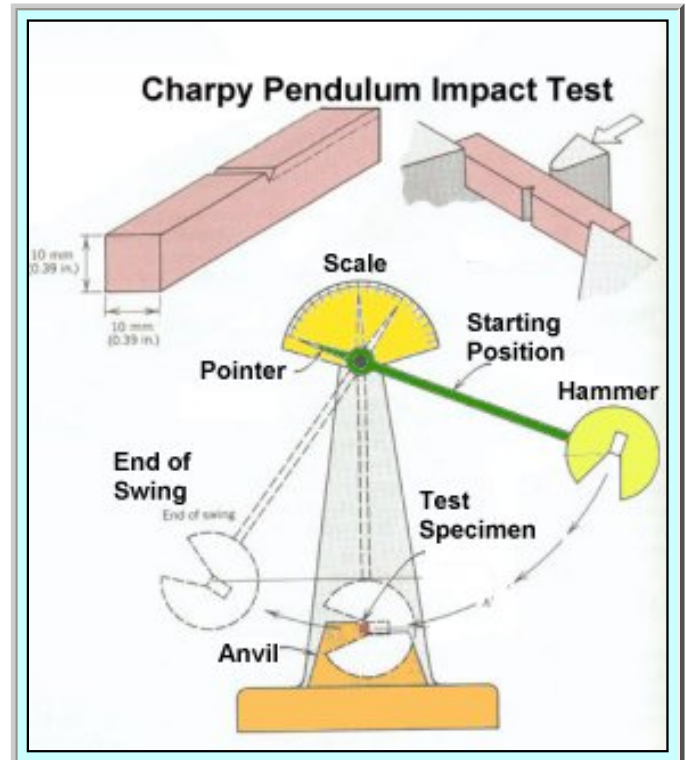
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## Quality Assurance

**The Spuncast foundry applies ISO-9000 defined procedures at each stage of the casting process to assure quality.**

- Precise control of the alloy composition through emission spectroscopy analysis of the ladle chemistry.
- Mechanical testing of the heat-treated casting.
  - Tensile strength and Charpy pendulum impact testing of witness bars.
  - Brinell hardness testing on selected areas of the casting.
- Non-destructive testing of the machined casting per Mil Spec T0974-AS-G1B- 010/271
  - Liquid Penetrant Testing
  - X-ray radiography



[Back](#) [Next](#)

24



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## Lessons Learned

1. By using a single alloy that offers strength, corrosion- resistance and wear-resistance, the expensive and difficult dual-metal casting process is avoided.
  - o This lowers the direct production cost (by 20%) and produces more uniform castings with markedly reduced scrap rates.
2. The modified duplex A890 alloy dramatically reduced in-service failure, down-time, and system repair/ replacement costs.
  - o In-service inspection of the duplex alloy cylinders over the six year production shows no significant wear and there have been no in-service failures.
3. The single alloy design eliminated the need for chrome plating with the attendant cost, time, and reliability risk.
  - o But even more importantly, it helped the Navy meet the DoD mandated requirement to eliminate/reduce chrome plating in defense systems with its attendant environmental costs and hazards.



[Back](#) [Next](#)

25



[Return  
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Home  
Page](#)

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# Summary

## Hydraulic Accumulator for Navy Submarines

- Spuncast has been producing the accumulator cylinder as a duplex stainless steel centrifugal casting for over six years, supporting repeated retrofit buys from the Navy and shipyard contractors.
- Centrifugal duplex steel castings save money, improve reliability, and reduce down-time in this application.



For further information on centrifugal casting of steel and iron alloys, contact --  
**Alan Holtz at Spuncast, Inc. Phone-- 920-261-7853**  
*E-mail -- [aholtz@spuncast.com](mailto:aholtz@spuncast.com) Web Site = <http://www.spuncast.com>*

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[Back](#) [End](#)



[Return  
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Home  
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