A Design Study in Nickel-Based Superalloy Castings

Floatwall Panels for a Jet Engine Combustor

Design Study Outline

Start the Design Study !

Acknowledgment --

The metalcasting design studies are a joint effort of the American Foundry Society and the Steel Founders' Society of America.

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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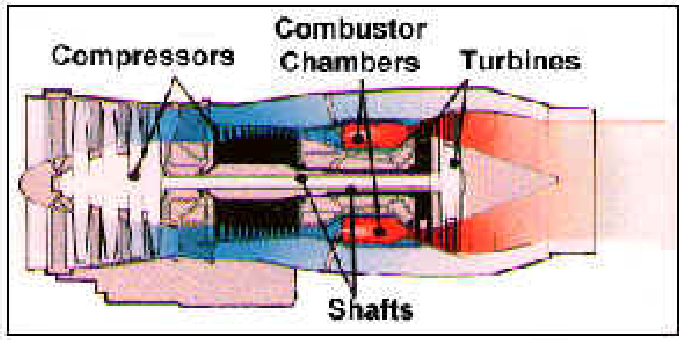
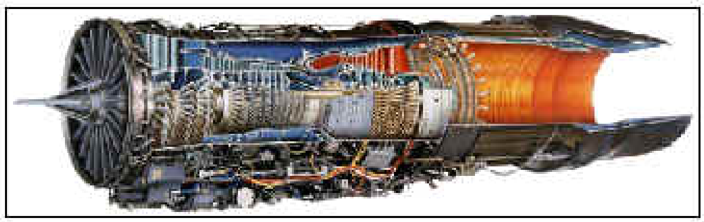
Combustor Floatwall Panels - Application

<u>The Application</u> -- **Combustors serve as the containment vessels for the mixing of fuel and air and their subsequent combustion in the turbine engine. The combustor controls the flame and directs combustion gases into the turbine section, while maximizing energy retention in the hot gases.**



- **The combustor has to survive high temperatures, thermal shock, high frequency acoustic loads, and attack by reducing and oxidizing gas mixtures, sulfur, and alkaline elements**
- **The efficiency, reliability, durability and reparability of the combustor are critical factors in achieving operation goals and reducing maintenance costs, both in dollars spent and lost engine time**



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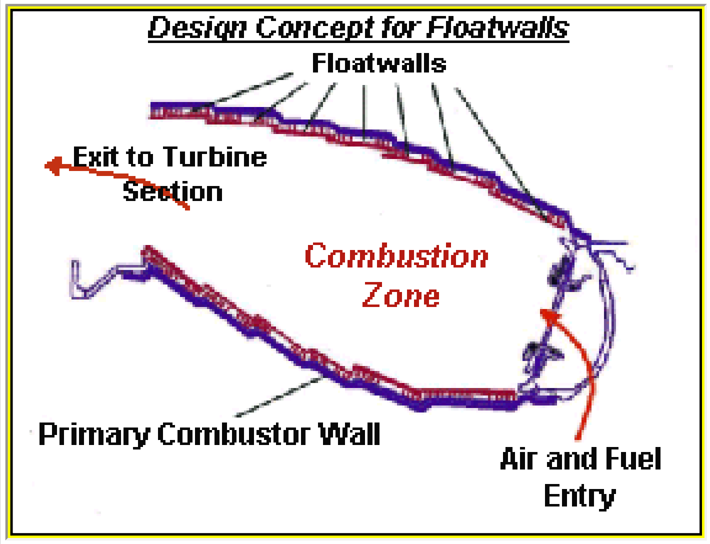
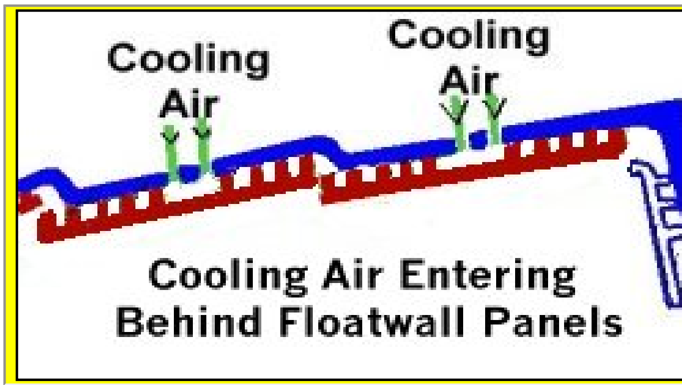
Function and Design

Component Function and Design -- **In this combustor design, the walls of the combustor are lined with thin panels (called floatwalls) made with nickel- based superalloys.**

The panels serve two functions. They contain the hot combustion gas and act as thermal barriers, reducing energy loss from the hot gases.

- **The panels are designed to be offset from the combustor wall to provide a flow channel for air to cool the back of the panels.**
- **Each panel has several hundred to several thousand small pins on the air channel side. These pins establish the offset distance and act as high-surface-area features, improving heat transfer from the panel to the by-pass air and cooling the panel itself.**
- **The cooling air flows across the back pins, picking up heat, and then flows into the combustor across the front face of the panels.**
- **The air flow acts as an additional barrier protecting the hot surface of the next panel in line. The preheated air also improves the fuel efficiency of the engine over the use of cold air for the same purpose.**





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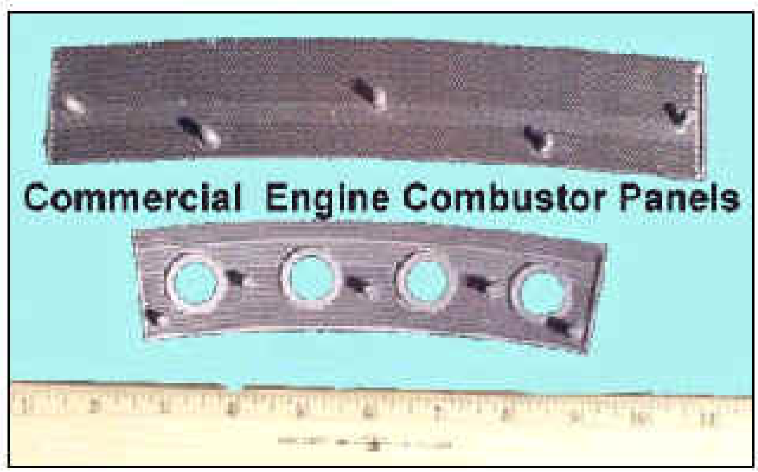
Combustor Floatwall Panels -- Description

Panel Description -- Floatwall panels are produced in a range of sizes for a variety of different engines for several turbine manufacturers.

- **Panel heights range from about 0.8" to 4" (measured parallel with the engine centerline).**
- **The long dimension (curved to match the radius of the combustor wall) varies from about 4" up to 8".**
- **Weights range from 1.5 ounces to as high as 8 ounces.**
- **Panels for commercial turbine engines are thicker and heavier than their military counterparts.**



Typically, panels are 1.5" by 6" in size, with a wall thickness of < 0.050" and a weight of 4-5 ounces.

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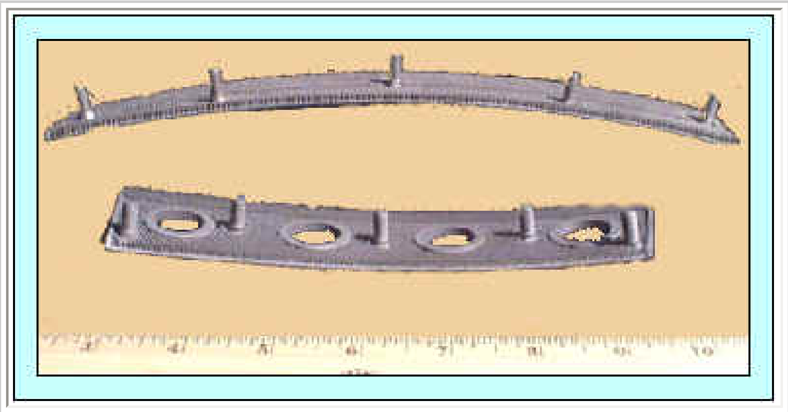
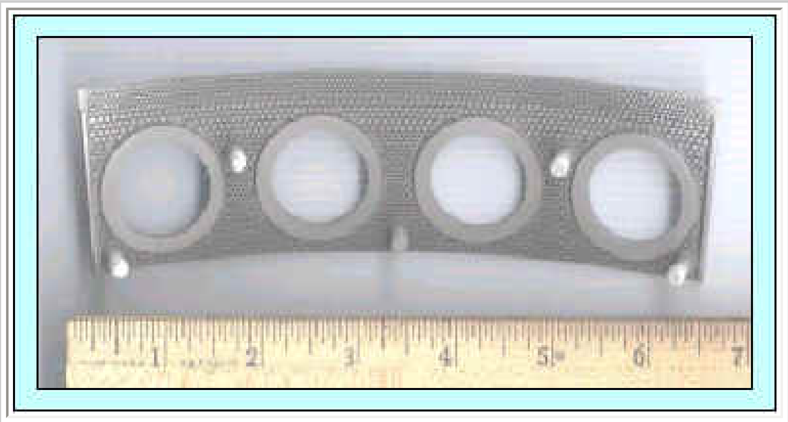
Combustor Floatwall Panels - Description





- **Pin counts vary from 500 to 3,000 per panel, depending on panel size and design.**
- **Panels have four to ten studs generally spaced along the long dimension of the casting. Studs are either threaded to accept a locking nut or flanged to take a locking clip.**

These attachment studs allow for simple and quick replacement of damaged or degraded panels during periodic inspection and overhaul of the engine.

- **Some panels have holes with thickened rims along the length to permit dilution air to pass into the combustion zone.**

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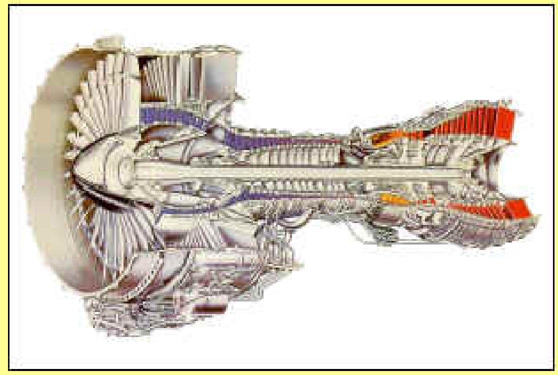
Manufacturing Challenges

- **Depending on the engine size and design, the number of panels in an engine combustor may range from 60 to 140 per engine set.**

- **Hitchiner Manufacturing, Gas Turbine Division, produces approximately 100,000 panels per annum for more than 14 production engine configurations, both military and civilian.**



The challenge in manufacturing these panels was to select the best combination of metal alloy and fabrication method that would meet the performance and production targets, specifically --

-- Achieving high temperature alloy performance.
-- Producing the cooling pins and attachment studs with the desired accuracy.
-- Meeting the required dimensional tolerances for fit and function.

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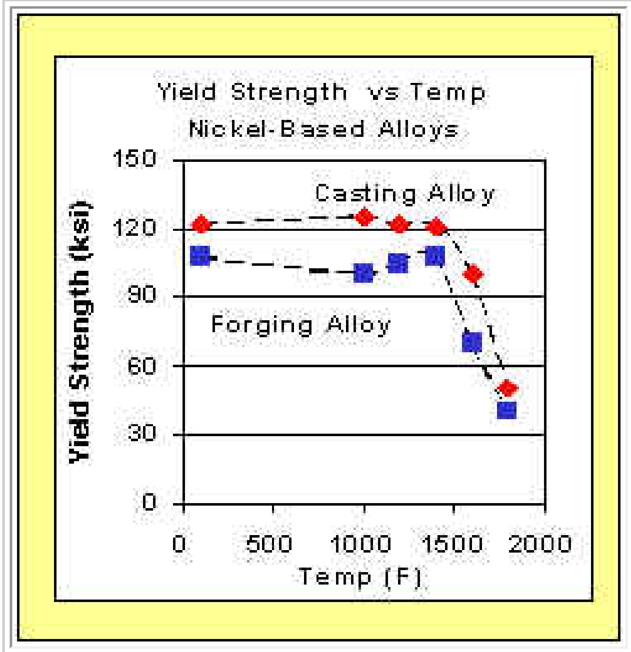
Alloy Selection

High Temperature Nickel-Based Superalloys

- **The panels are produced from nickel-based superalloys, which provide the high temperature strength retention, creep resistance, oxidation and corrosion resistance, and castability required for turbine engine applications.**
- **The most sophisticated of the superalloys are too strong at high temperatures to be forged into shapes or rolled into sheet.**
- **In addition, the alloys are not weldable, so many conventional fabrication methods are unavailable.**



Casting is the most cost-effective production method for forming these complex shapes with high performance nickel-based superalloys

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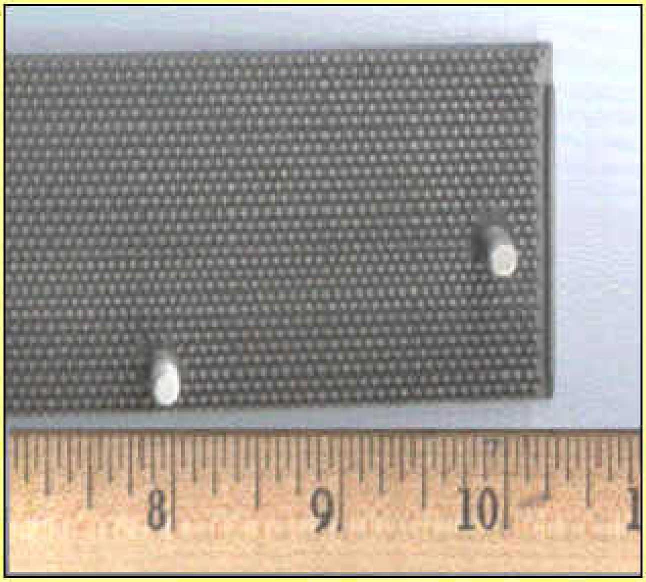
Requirements for Precision Features and Tolerances



- **The thermal performance and the fuel efficiencies of the floatwall panel design are critically dependent on the precise fabrication of the cooling pins.**
  - ***The high count and small size of the pins could only be produced economically by precision investment casting***
- **Dimensional control and reproducibility are crucial to prevent gaps and air leakage around studs, between panels and the combustor shell, or between neighboring panels.**
- **Machining costs can be reduced if the threads and flanges on the studs can be formed in the casting process.**

These precision pin features and the tolerance requirements can be cost effectively achieved only by metalcasting.

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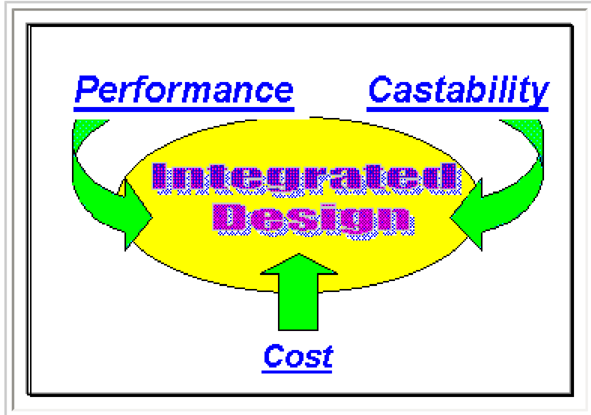
The Casting Design Issues

The casting design engineers at the Hitchiner Manufacturing, Gas Turbine Division, had three imperatives for an integrated casting design.

- ***Design for Performance***
- ***Design for Manufacturability/Castability***
- ***Design for Cost***



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

- **Select the *molding process* to produce the precision features and meet tolerances**
- **Choose the *casting process* to insure alloy quality and control costs.**
- **Develop the *mold configuration* to optimize metal flow and maximize** loading
- **Design the *gating system* to produce sound castings.**

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Molding Process Choices

Investment Pattern Assembly for Floatwall Panels

In considering the physical size, production quantity, complexity, tolerance requirements, and cost targets for the floatwall panels, two variations of the disposable pattern molding process had potential application for producing the panels-

- ***Investment Casting*** **-- the casting is produced in a mold formed by coating a wax pattern with a ceramic shell.**
- ***Lost Foam Casting*** **- the casting is produced in a mold formed by compacting sand around a expendable polystyrene pattern.**

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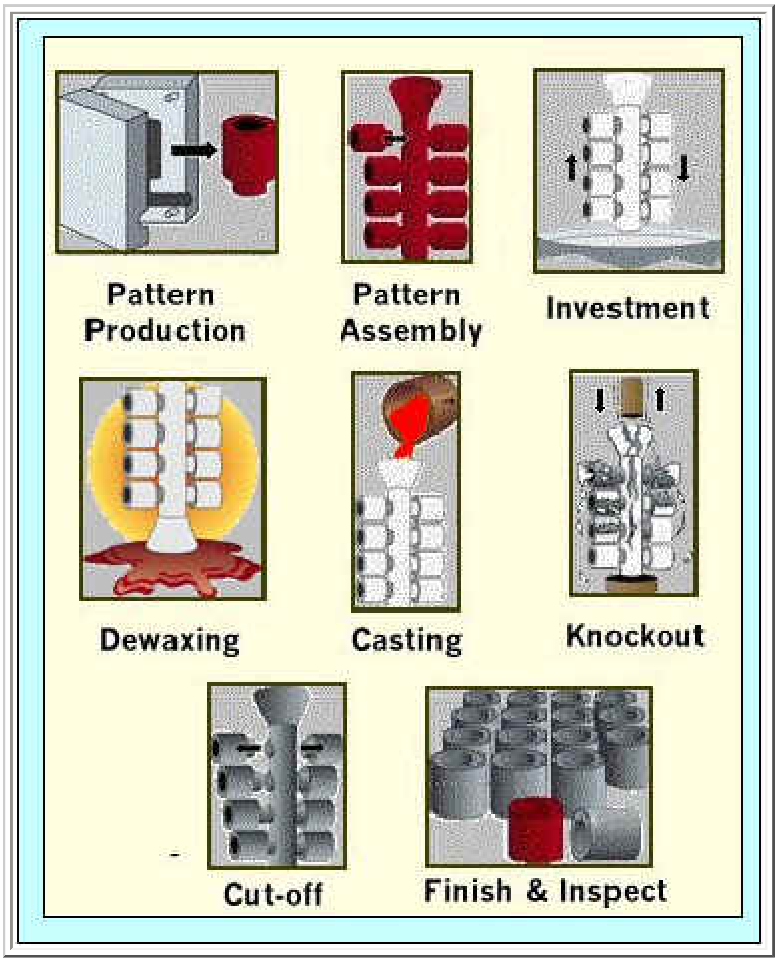
Investment Casting

The basic steps of the investment casting process are:

- **Production of heat-disposable wax or plastic patterns in a precision tool.**
- **Assembly of these patterns onto a gating system.**
- **"Investing," or covering the pattern assembly with ceramic to produce a monolithic mold.**
- **Melting out the wax pattern assembly to leave a precise mold cavity. Firing the ceramic mold to remove the last traces of the pattern wax and cure the ceramic mold.**
- **Preheating the mold for casting and pouring the metal into the mold.**
- **Knockout, cut-off, finishing, and inspection of the casting.**



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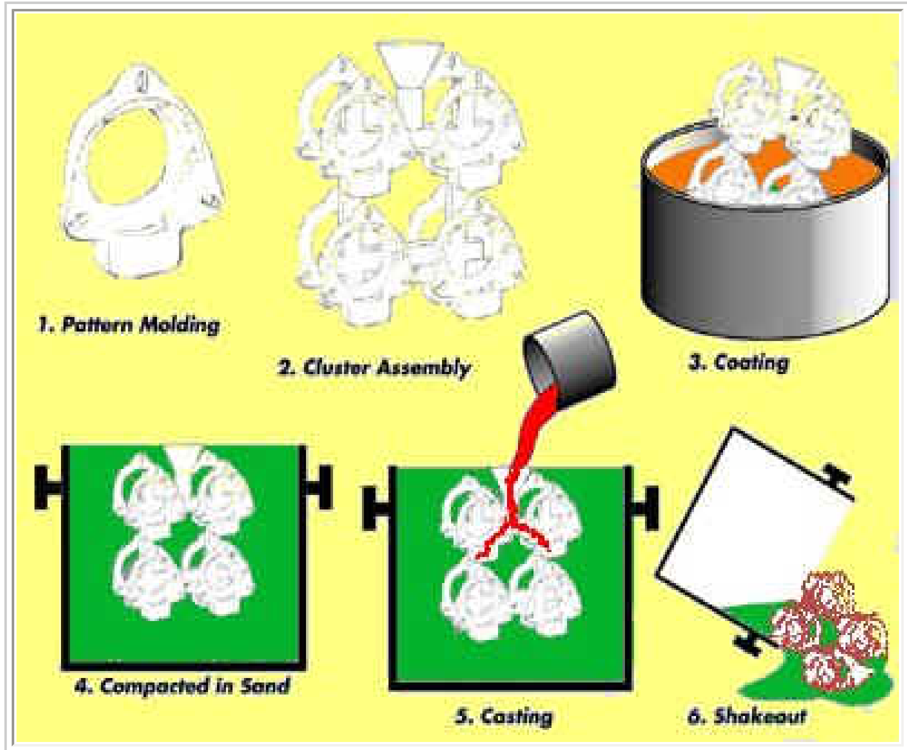
Lost Foam Casting

The basic steps of the lost foam casting process are:

- **Production of patterns in a precision tool with expendable polystyrene (EPS) beads (Heat expands and bonds the beads to produce a rigid pattern).**
- **Assembly of the patterns onto a gating system.**
- **Coating the pattern assembly with a refractory wash coat.**
- **Forming the mold by compacting dry sand around the coated pattern in a one piece flask.**
- **Pouring the metal into the mold with vaporization of the EPS pattern.**
- **Shakeout, cut off, finishing, and inspection of the casting.**



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Molding Process Selection

The two molding processes (Investment Casting and Lost Foam Casting) both have relative advantages and limitations, as shown in the following table.

	Investment Casting	Lost Foam Casting
Typical Casting Weight Range	0.10 to 10 lb.	1 to 1000 lb.
Minimum Wall Thickness	0.035"	0.100"
Typical Tolerance Capability	+/- 0.003"	+/- 0.005"
Cores for Interior Features	Not Required	Not Required
Pattern Removal Step	Dewax Step Required	No Pattern Removal Step (Pattern evaporates during casting)

Given the requirement for detailed features, thin walls and precision tolerances, which molding process (Investment Casting or Lost Foam Casting) is most suitable for producing the floatwall panels?

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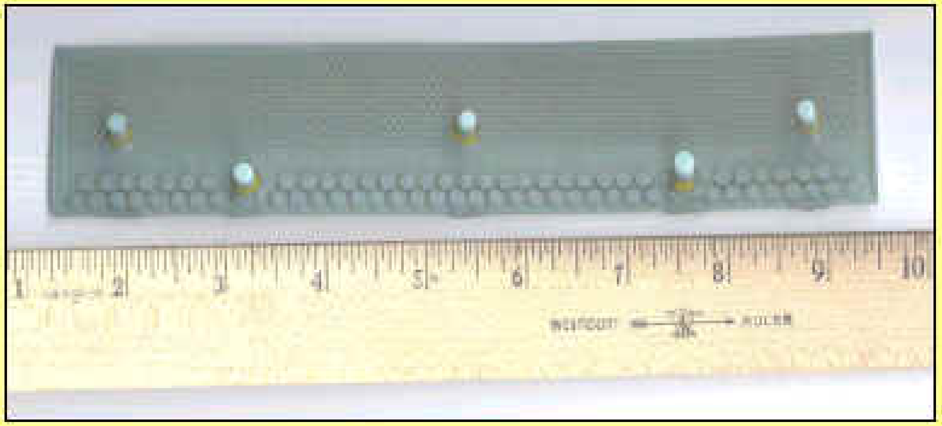
Investment Casting

The investment casting process has the capability to produce the floatwall panels in the size and quantity required and to:

- **Produce the thin walls (<0.050") and fine pins (<0.60" diameter)**
- **Provide the desired tolerance for the threads and flanges on the mounting studs.**

The dewaxing step is required for investment casting, but is not a major cost or time factor.



Wax Pattern for a Floatwall panel.

Investment casting *is* the best molding process for the floatwall panels.

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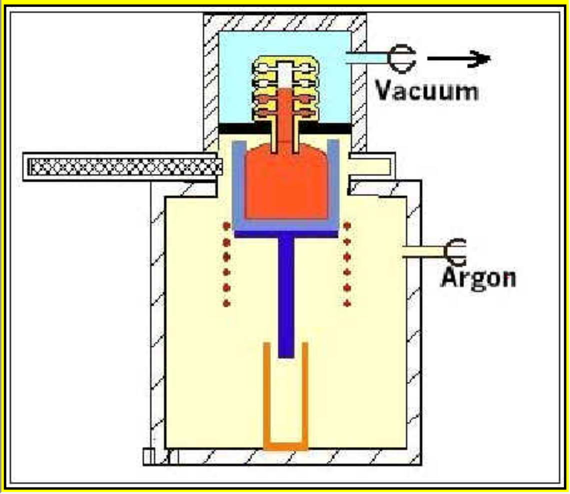
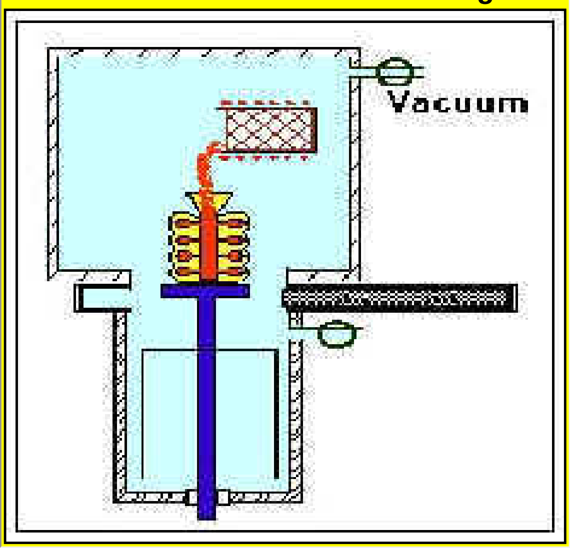
Casting Process Selection

Countergravity Low-Pressure Vacuum



Conventional Vacuum Casting



With the selection of investment casting, Hitchiner engineers faced the following challenges in casting the nickel-based superalloy.

- **The alloy is expensive and highly reactive in the molten state and must be protected from oxygen exposure during the melting and casting process.**
- **Metal yield must be maximized by minimizing metal retained in the gating system.**
- **The walls of the castings are very thin and fill-out of the panels is challenging.**

Hitchiner engineers had two casting process from which to choose--

- ***Countergravity Low-Pressure Vacuum (CLV)***
- ***Conventional Vacuum Casting (CVC)***

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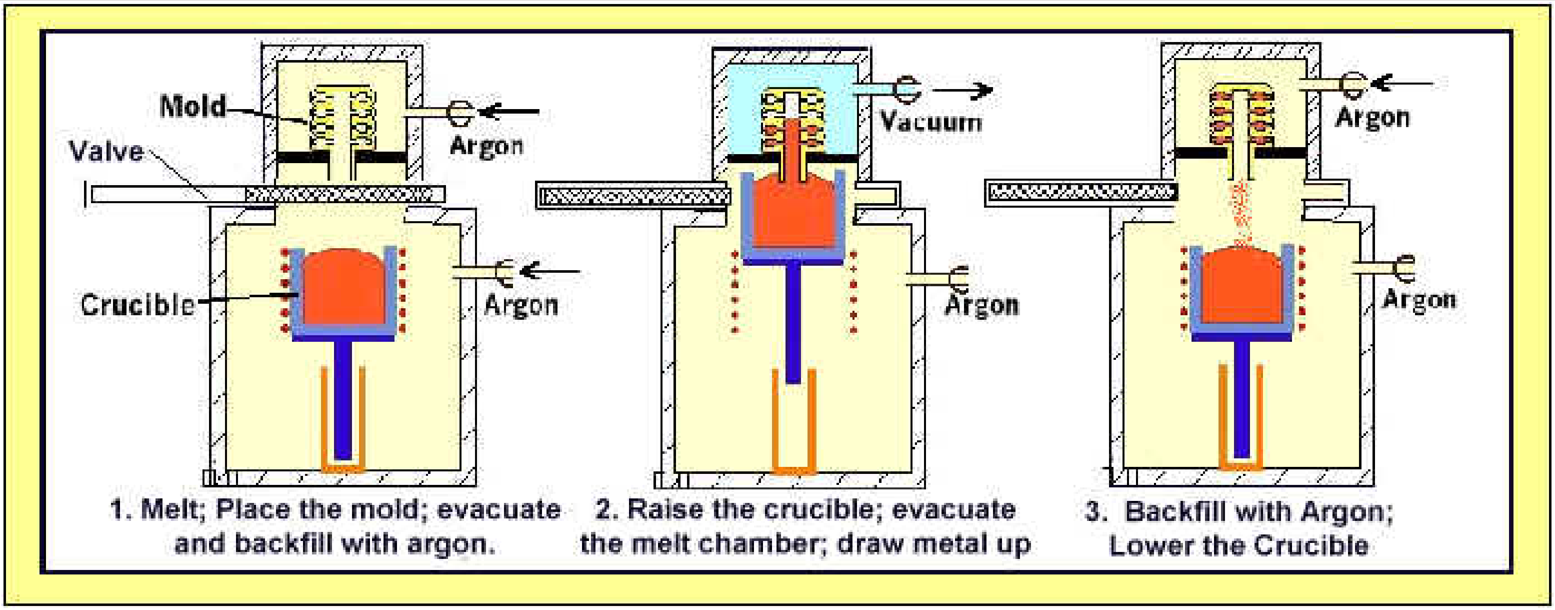
Countergravity Low-Pressure Vacuum (CLV)



In CLV, the melting and pouring process consists of three major steps in a two chamber vacuum system.

> **1. Melt the metal under vacuum in the isolated lower chamber. Position the preheated mold in the upper mold chamber. Evacuate the chambers with the mold and the extended mold snout and backfill both chambers with argon.**
>
> **2. Open the isolation valve and raise the melt crucible, immersing the mold snout into the crucible. Evacuate the upper chamber so that liquid metal is drawn up into the mold cavity. Hold the vacuum for the time required for the castings and gate stubs to solidify.**
>
> **3. Release the vacuum and backfill with argon, allowing the still-molten metal in the central sprue to return to the crucible. Lower the crucible into the melt chamber, close the isolation valve, and evacuate the melting chamber.**

After casting and initial cooling, open the upper chamber and remove the casting in the mold. Allow the mold to cool and remove the ceramic, leaving the individual, free-standing castings.

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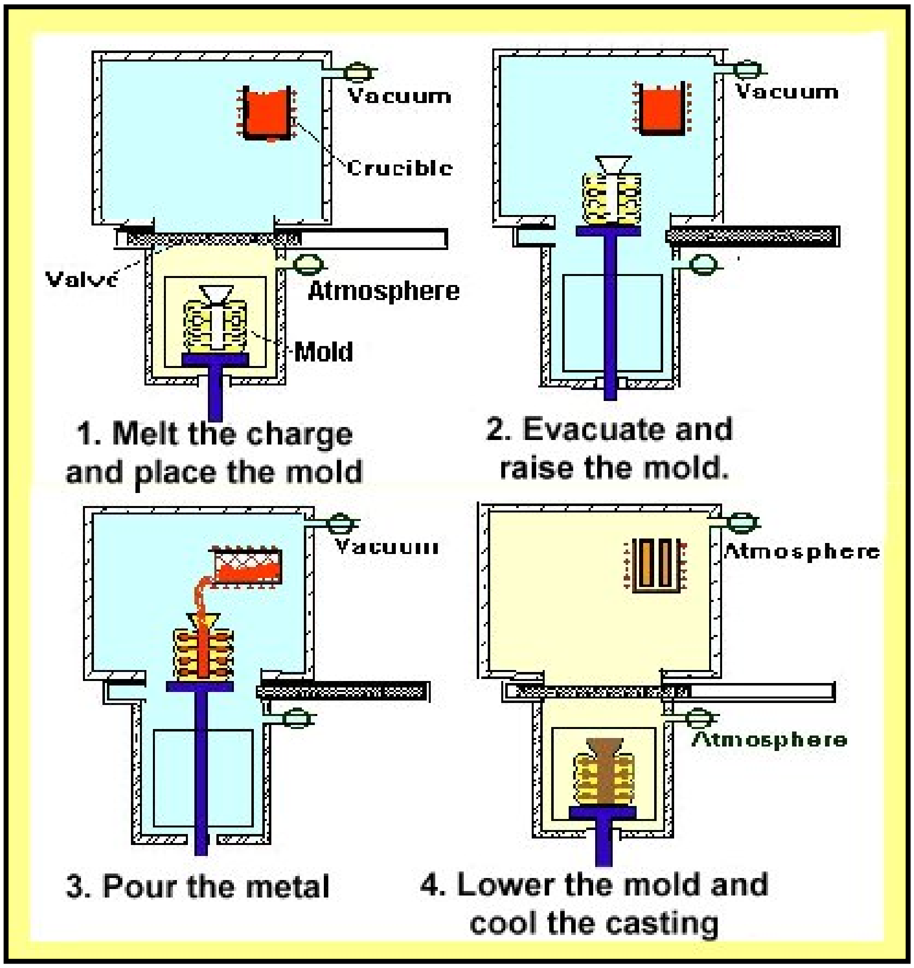
Conventional Vacuum Casting (CVC)



In CVC, the melting and pouring process consists of four major steps in a two chamber vacuum system.

1. Melt the metal in the crucible under vacuum in the isolated upper chamber. Heat the melt to the casting temperature. Position a preheated mold with pour cup on the mold ram in the lower chamber.

2. Evacuate the lower mold chamber. Open the isolation valve and raise the mold on the ram to the pouring position.

3. Tilt the crucible and pour the liquid alloy into the mold.

4. Lower the mold back into the mold chamber and close the isolation valve. Release the vacuum. Remove the mold from the chamber and apply exothermic material to the pour cup.

After mold removal, allow the mold and casting to cool. Remove the ceramic mold, leaving individual castings connected to the central runner system. Recharge the crucible.

Which casting process (CLV or CVC)
is best suited for producing the floatwall panels in nickel-based superalloy?

Back **Choose a casting process**

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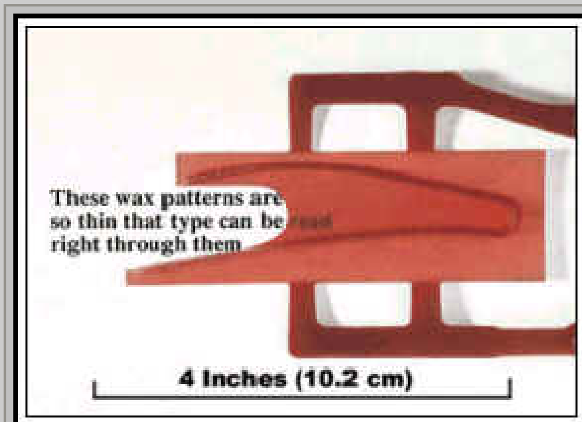
Countergravity Low Vacuum (CLV)

Countergravity low vacuum (CLV) casting is the best method for producing the floatwall panels

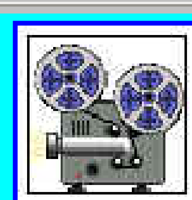
- **The molten metal is protected from oxygen during melting and casting.**
- **The differential pressure under which the metal is drawn into the mold ensures fill-out of very thin sections and fine surface details (See photo to the right)**
- **Metal flow is less turbulent, reducing oxide inclusions and other turbulence-related defects.**
- **Preheated mold cavities can be filled at lower melt temperatures, producing finer and more uniform grain size.**
- **Return of the molten metal from the sprue and gates to the crucible following casting improves casting-to- gate ratios and dramatically reduces alloy costs.**



Thin wax pattern for CLV casting

QuickTime Video of Countergravity Casting (2.0 Meg)

Download QuickTime Viewer



CLV is the best casting process for the floatwall panels.

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Mold Configuration and Part Orientation

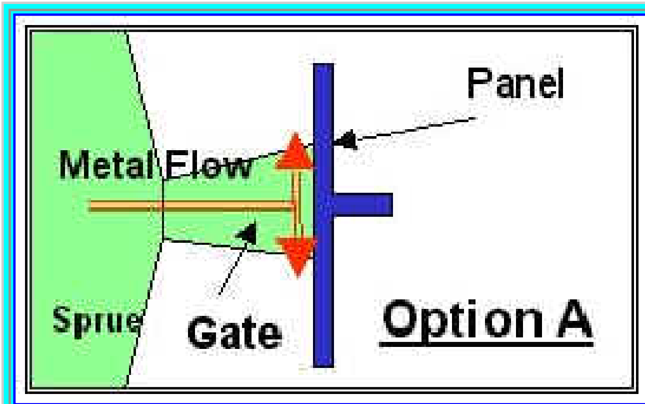
- **The orientation of the parts in the investment mold is an important factor in determining mold loading, metal flow control, solidification progress, and finishing operation difficulty.**

  The panel should be oriented so metal flows uniformly and smoothly into the mold.

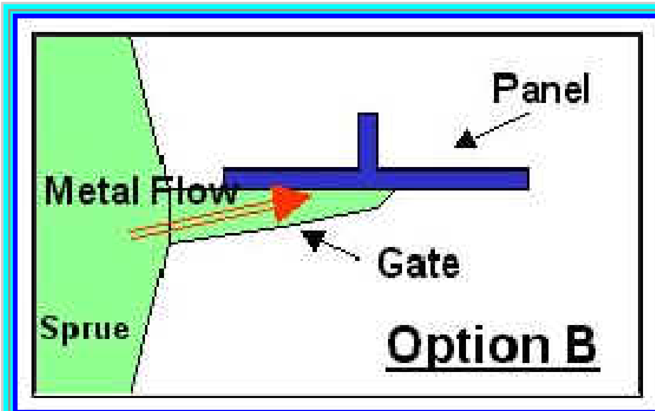
  The gates should be positioned so that gate stubs can be easily cut from the panel and ground to the required tolerance.

  The panels should be oriented to maximize the number of panels in the mold and provide maximum yield.

- ***The panels can be oriented in the mold so that metal flows into the back face from two approaches, either perpendicular into the face or parallel over a panel edge, as shown in the two figures to the right.***



Option A -- Gate into the Face



Option B -- Gate over the Edge

Choose the panel orientation (Option A or Option B) which provides smooth and direct metal flow, simplifies gate cut-off, and maximizes yield.

Choose an Option

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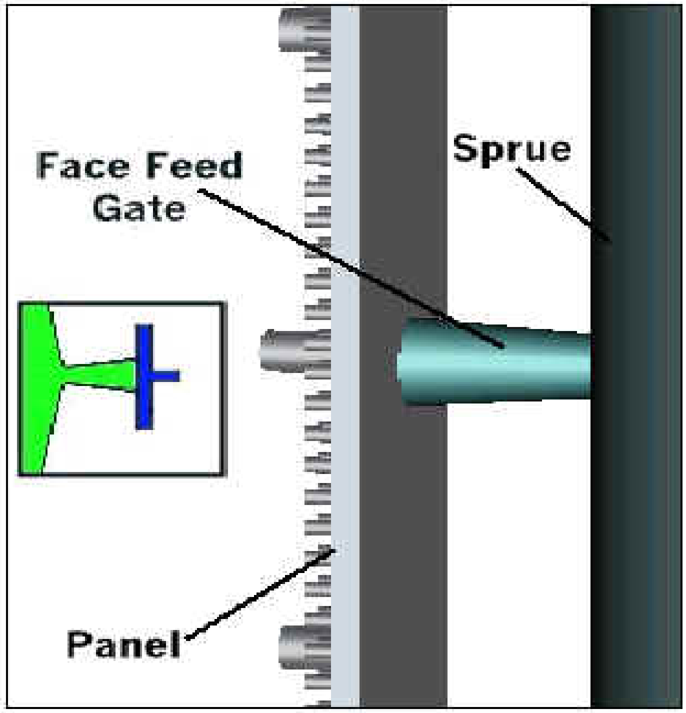
Option A - Gating Directly into the Face



Option A - Gate into the Face

In Option A, metal flows directly into the face of the float wall panels.

This gate-panel orientation has three shortcomings.

- **The metal must "turn" 90 degrees immediately after entering the mold cavity in order to flow into the edges. This interrupts the established flow momentum and causes turbulence which results in defects.**
- **The gates themselves are on the flat face and are difficult to cut off close to the surface without damaging the casting.**
- **Each casting utilizes about 45 degrees of angle around the sprue so only about 8 castings can be assembled around the full 360 degree arc.**

Option A is not the best part orientation.

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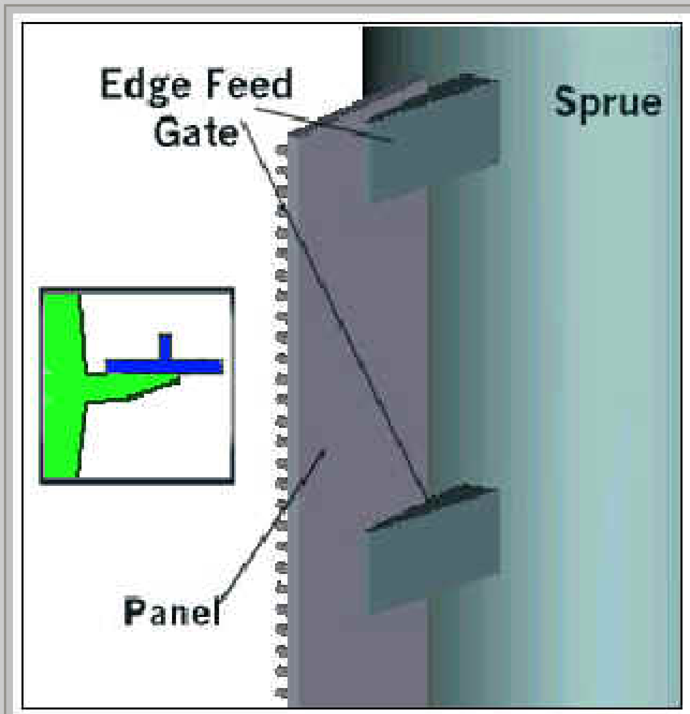
Option B - Gating Over the Panel Edge



Option B - Gate Over the Panel Edge

In Option B, metal flows over the edge of the floatwall panels.

This gate-panel orientation is preferred for three reasons.

- **The metal enters the part cavity and does not need to change its basic direction to flow to the edge of the panel and give complete fillout.**
- **Cut-off of the gates is parallel with the casting edge and is quick and easy to do without casting damage.**
- **Each casting utilizes about 18 degrees of angle around the sprue. So only about 20 castings can be assembled around the full 360 degree arc. This is 2.5X as many castings as compared to the face orientation of the panels.**

Option B is the best part orientation.

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Gating System Design

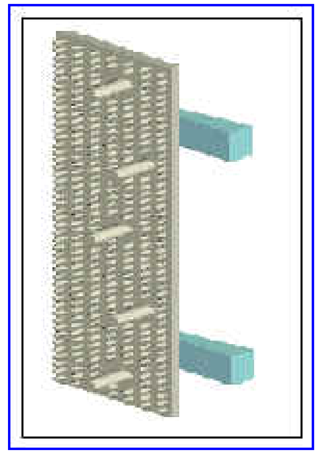
The gating system (sprue and gates) serves as the path by which molten metal flows into the pattern cavity and feeds the shrinkage which develops during casting solidification. Proper design of the gating system is critical in meeting two important requirements.

- **Short flow paths and fast metal flow prevents casting misruns due to premature solidification.**
- **Relatively heavy sections which will solidify more slowly require direct gating contact to provide molten metal for feeding shrinkage during solidification.**

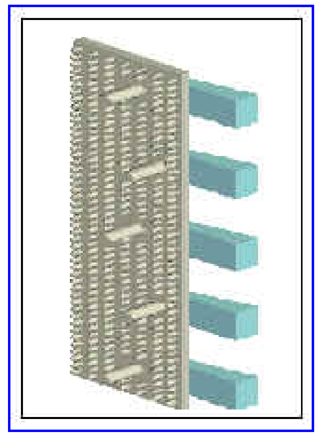
Two different gating designs are shown in the drawing to the right --

- **Option A- Two gates near the top and bottom of the casting**
- **Option B -- Five gates, each oriented on an attachment stud.**

Option A --
Two gates (top and bottom) feeding over the panel edge



Option B --
Five gates oriented on the mounting studs feeding over the panel edge.



*Choose the gating system (**Option A** or **Option B**) which provides the best metal flow into the mold*

Back *Choose an Option*

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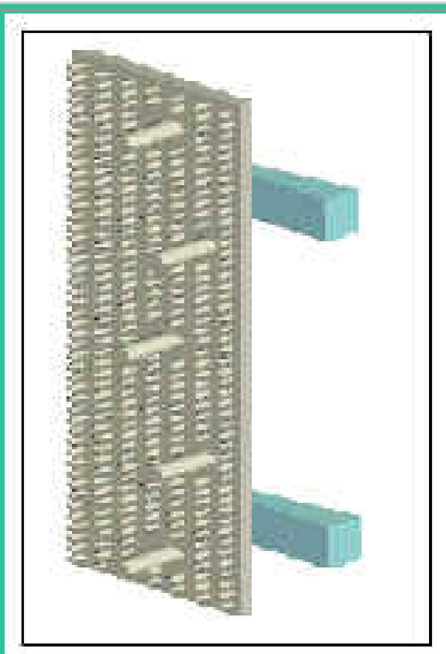
Option A -- Two Gates over the Panel Edge



Option A -- Two gates over the panel edge

In Option A, the gating system consists of two gates feeding metal into the mold cavity near the top and bottom of each panel.

This gating approach has two shortcomings:

- **The distance the metal needs to flow through the thin wall is quite long with a high risk of misruns and unfilled wall sections.**
- **Gates do not feed directly into the heavier stub sections of the casting (which would be the last to solidify), so shrinkage porosity is likely to form.**

Option A is not the preferred gating system design

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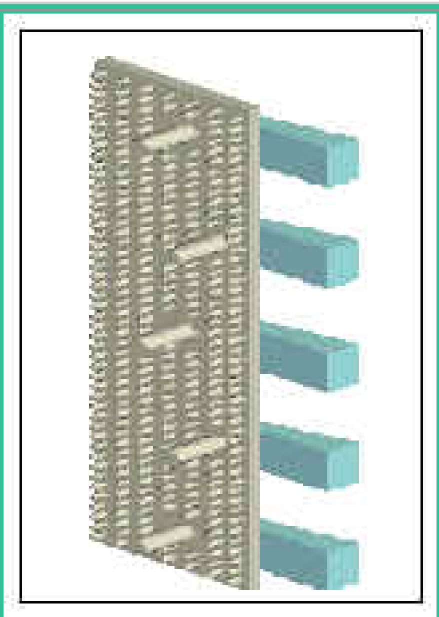
A Design Study in Nickel-Based Superalloy Castings-- Combustor Floatwall Panel

Option B -- Five Gates over the Panel Edge



Option B -- Five gates over the panel edge

In Option B, the gating system consists of five gates feeding metal into the mold cavity along the length of the casting.

This gating approach is preferred because:

- **Metal feed directly into the panel from multiple positions with short flow paths, reducing the risks of misruns and unfilled wall sections.**
- **The heavier stub intersections with the casting wall (the last sections to solidify) are individually fed by direct gate contacts.**

There should always be liquid metal in the gating system to feed solidification shrinkage and prevent the formation of porosity in the casting.

Option B is the preferred gating system design

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Aluminum Tool for the Wax Pattern

Aluminum Tool for Wax Pattern

Aluminum Tool with Ejection Pins Extended to Push the Pattern Out

- **An aluminum tool is used to produce a wax pattern for the investment casting process. The tool is precision machined to give the desired shape, details, and dimensional tolerances in the wax pattern.**
- **The photo on the left above shows the bottom half of the aluminum tool in which the wax is injected.**
- **A critical tool feature, shown in the photo on the right, is the use of an ejection pin backing each cooling pin on the wax pattern. The ejection pins insure that the pins on the wax pattern are not damaged during pattern removal from the tool.**

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Pattern Investment and Casting

Pattern Assembly after Investment with Slurry Coating

- **The photo to the left shows the pattern assembly after investment in the slurry bath.**
- **The individual panel patterns are attached to the 3" diameter central sprue and gate system.**
- **This assembly consists of 48 panel patterns in two levels of 24 panels each.**

- **The photo to the right shows a mold after casting and cooling with a mold section cut away.**
- **The center sprue is open and free of metal.**
- **A floatwall panel with gate stubs is shown in the lower left corner.**

Sectioned Mold with Casting Removed

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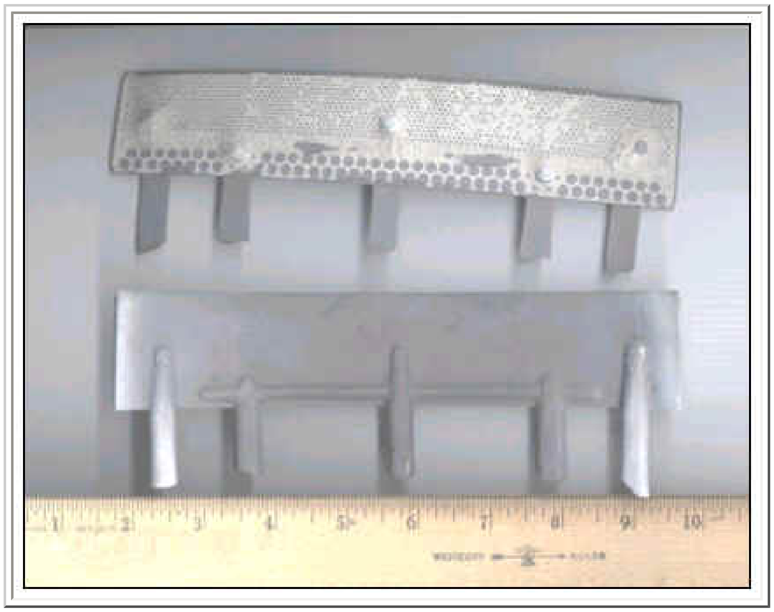
Cleaning and Finishing Operations



After casting and solidification are complete and the mold has cooled, the cleaning/ finishing steps are -

- Remove the ceramic mold material with a pneumatic hammer.
- Cut off the gate stubs.
- Remove residual ceramic from the casting using a liquid caustic bath.
- Belt grind the remaining material at the gate contact locations.
- Sand blast the surface of the casting for a 125 RMS finish

As-Cast Panels Directly Out of the Mold

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Quality Assurance

Finished Floatwall Panel (Before Pack Coating)

After the final cleaning, the castings are inspected against producer-defined acceptance criteria.

- **Visual and dimensional inspection**
- **Non-destructive evaluation by Fluorescent Penetrant and Radiography.**

The panels are sent to a sub-contractor for a pack aluminide coating to enhance oxidation and sulfidation resistance.

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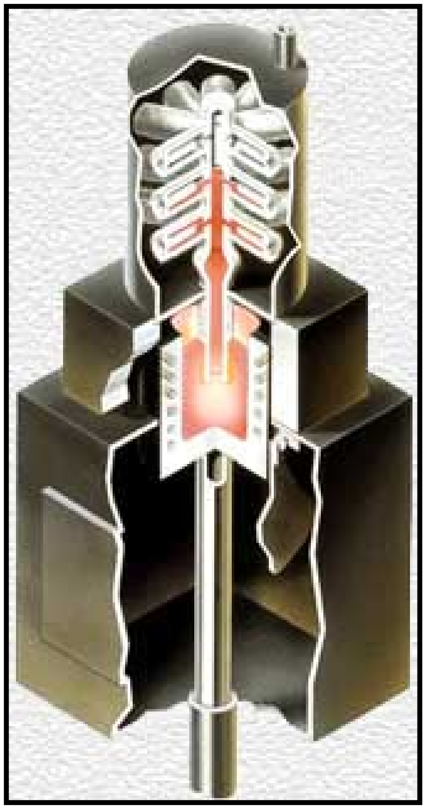
Lessons Learned



Hitchiner Manufacturing has been producing the floatwall panels for over 15 years and is currently producing about 100,000 panels per year for the aerospace industry.

The successful production of these panels in a wide variety of sizes and configurations illustrates --

- **The ability of the investment casting process to produce castings in virtually any configuration in which a wax pattern can be formed, with an unmatched capability for thin walls and fine surface features.**
- **The unique capability of the countergravity low-pressure vacuum (CLV) casting process for producing thin wall castings in highly reactive alloys.**
- **The ability to produce large numbers of castings from single molds with highly efficient material utilization.**

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Summary

Combustor Floatwall Panel

The floatwall panels for the jet engine combustors are produced in a wide variety of configurations with countergravity low- pressure vacuum (CLV) investment casting.

- ***The high count and small size of the cooling pins on the panels could only be produced economically by precision investment casting.***

For further information on the production of this and other investment castings, contact

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Web Site = http://www.hitchiner.com

Acknowledgment --

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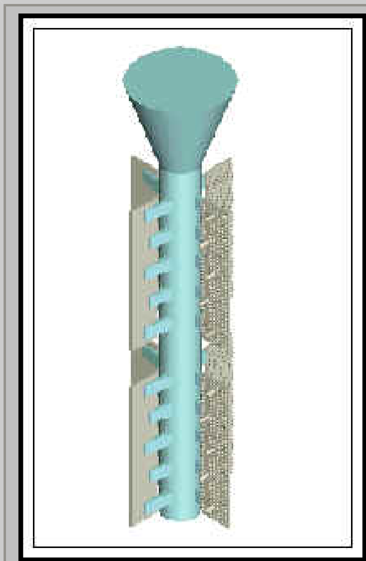
Conventional Vacuum Casting (CVC)

Conventional vacuum casting (CVC) is not the best process for producing the floatwall panels.

- **In CVC the molten alloy is protected from oxygen contact during melting and casting, but residual oxides floating on the melt surface are much more likely to enter the mold during pouring.**
- **Variability (from one pour to the next) of the pouring process and of metal flow into the mold cavities makes reliable casting fill-out difficult.**
- **Metal flow is much more turbulent, increasing the chance for entrapped oxide inclusions.**
- **Solidified metal in the sprue and gating dramatically increases alloy usage and cost, compared to CLV.**



Conventional vacuum casting with gates and sprue that need to be removed

CVC is not the best casting process for the floatwall panels.

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Lost Foam Casting

The lost foam process has the capability to produce the floatwall panels in the size and number required and has an advantage in not requiring a dewaxing step.

But the lost foam casting process does not have the capability to:

- **Produce the thin walls or fine pins of the panels**
- **Meet the desired tolerance for the threads and flanges on the mounting studs.**

Two Part Lost Foam Pattern
for an Automotive Crankshaft

Lost foam casting *is not* the best molding process for the floatwall panels.

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