# Advanced Technology for Large Scale (ATLAS) Powder Metallurgy–Hot Isostatic Pressing

*Technology Assessment*

**3002007401**

# Advanced Technology for Large-Scale (ATLAS) Powder Metallurgy–Hot Isostatic Pressing

*Technology Assessment*

3002007401

Technical Update, July 2016

EPRI Project Manager

D. Gandy

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

THE FOLLOWING ORGANIZATIONS PREPARED THIS REPORT:

**Electric Power Research Institute (EPRI)**

**Facio Consulting Group and Associates**

**This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.**

## NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

# ACKNOWLEDGMENTS

Electric Power Research Institute (EPRI)
1300 W.T. Harris Boulevard
Charlotte, NC 28262

Principal Investigator
D. Gandy

Facio Consulting Group and Associates
7764 Netherlands Drive
Raleigh, NC 27606

Principal Investigator
M. Williams

This report describes research sponsored by EPRI.

EPRI would like to acknowledge contributions to this report from the ATLAS Advisory Team, which consists of the following individuals:

L. Lherbier, Lherbier Consulting
V. Samarov, Synertech PM
Charlie Barre, Synertech PM
D. Novotnak, Carpenter Powder Products
H. Fraser, Ohio State University
S. Babu, University of Tennessee

---

This publication is a corporate document that should be cited in the literature in the following manner:

*Advanced Technology for Large-Scale (ATLAS) Powder Metallurgy–Hot Isostatic Pressing: Technology Assessment.* EPRI, Palo Alto, CA: 2016. 3002007401.

# PRODUCT DESCRIPTION

Heavy manufacturing of advanced materials required in aerospace, aviation, military, energy, electricity, off-shore oil and gas, and other applications is facing challenges to meeting the demand for large-scale components. This report provides a technical and financial assessment for procurement and commercialization of an Advanced Technology for Large-Scale (ATLAS) powder metallurgy–hot isostatic pressing (PM-HIP) and a Center of Excellence (COE), both of which will be required to advance the production of large-scale components.

## Background

Research performed by the Electric Power Research Institute (EPRI) and various stakeholders in the electricity sector has led to a growing interest in PM-HIP and acceptance of multiple American Society of Mechanical Engineers (ASME) Code Cases in recent years. Continued efforts through the ASME Boiler and Pressure Vessel Code and ASTM International will certainly lead to acceptance of PM-HIP within a few years in similar fashion to other processing methods (for example, forging, rolling, drawing) and product forms. Efforts by the Department of Energy (DOE) and EPRI have demonstrated the ability to produce not only large components, but also very complex components. Development needs across a variety of industries suggest that much larger HIP capacity and size capabilities are required to produce sizable components up to 3.1 meters (10 feet) in diameter. This feasibility report provides background and an industry analysis for establishing an ATLAS and a COE.

## Objectives

- To investigate and understand the need for a large HIP capability to manufacture large components across various industries
- To conceptually estimate the budget and commercialization costs necessary to install and operate a large HIP unit
- To describe the benefits offered through ATLAS and a COE

## Approach

EPRI enlisted a team of industrial advisors to assist in the development of this feasibility assessment. Specifically, the advisors assisted in an investigation of options around design, procurement, installation, and operation of a large 3.1 meters (10 feet) in diameter x 5 meters (16 feet) in length HIP unit. Considerable thought was applied toward the development of a COE that would provide expertise, laboratories, and capabilities to design, evaluate, research, scale up, and produce large components via PM-HIP. The proposed COE would specialize in process modeling, powder characterization, HIP tooling and design, control of mechanical properties, and new alloy design fundamentals.

## Results

The assessment determined that many industries (not just the electricity sector) have needs for very large PM-HIP capabilities. Increasing the current HIP unit size by 2x over today’s size would provide industry with significant processing advantages and capabilities:

- Replacement of large forgings with near-net-shaped (NNS) components
- Manufacture of giant preforms or billets with fine-grained isotropic properties that could be further processed via other manufacturing methods such as forging and ring-rolling

- Consolidation of very large castings
- Improved product yield (processing dozens of components at one time)
- Creation of new large structures with targeted properties (for example, composites, bi-metallics)

The assessment also generated a financial overview of ATLAS that reviewed the procurement of the 3.1-meter (10-feet) HIP unit, building and ancillary equipment, installation, staffing, operation, and the COE. Several funding options were provided including one potential commercialization strategy that involved funding via individual partnerships, U.S. government (DOE and/or Department of Defense), state and local funding, and a HIP operator.

## Applications, Value, and Use

Numerous potential large component applications are identified and reported here across six different industries. A few examples include pressure vessels, nozzles, pumps, vessels, landing gear, armament, rotors/shafts, compressor rings, and large gun or missile barrels. Such applications can readily take advantage of reduced materials production costs through minimizing the volume of material required during production and by reducing overall machining time. These two advantages alone provide significant value and often justify the use of PM-HIP; however, other advantages are also realized:

- Improved inspection via the inherent fine-grained microstructures found in PM alloys
- Alternative supply route for hard-to-obtain components
- Elimination of casting quality issues and rework
- Improved product yield by processing dozens of components at one time

## Keywords

Center of excellence
Heavy manufacturing
Hot isostatic press
Near-net shape
Powder metallurgy

# ABSTRACT

Manufacturers across several industrial sectors including aerospace, aviation, military, energy, electricity, and off-shore oil and gas have indicated that large hot isostatic pressing (HIP) capabilities would significantly expand the materials, products, and capabilities that they currently offer and allow components to be manufactured in a more timely fashion. The Electric Power Research Institute (EPRI) research has also shown that large HIP capabilities and capacities will be required over the next few decades to meet the demand for building new nuclear units. As such, this feasibility assessment was assembled to provide both a technical and financial assessment of industrial needs, applications, installation, and operation of a large HIP furnace, and development of a Center of Excellence (COE).

An Advanced Technology Large-Scale (ATLAS) powder metallurgy– (PM) HIP unit that is 3.1 meters (10 feet) in diameter x 5 meters (16 feet) in length and 2x greater in size than the largest U.S. HIP unit was assessed to provide large volume, size, and capacity capabilities. The COE could specialize in process modeling, powder characterization, HIP tooling and design, control of mechanical properties, and new alloy design fundamentals. The COE would be established to work with various industrial stakeholders on key technological challenges for introducing new products and technologies.

# EXECUTIVE SUMMARY

In 2010, the Electric Power Research Institute (EPRI) engaged with its utility members and other industry stakeholders to investigate powder metallurgy–hot isostatic pressing (PM-HIP) as a possible manufacturing process for fossil and nuclear applications such as large valves, pumps, headers, and flanges. Several large (>1000 lb [454 kg]) ferritic and austenitic stainless steel valves were produced, along with various other smaller components. The research generated considerable interest among EPRI's utility members and has ultimately led to several American Society of Mechanical Engineers (ASME) Code Cases, a new ASTM International nickel-based alloy specification, and an EPRI Roadmap for PM-HIP. Additional efforts are continuing to bring current ASTM specifications for ferritic, austenitic, and nickel-based alloys into the main body of the ASME Code under Sections I, II, III, and B31.1. Additional research is also now being focused on critical internals for nuclear reactor applications.

Concurrent to these efforts, research is underway within the U.S. Department of Energy (DOE) to examine the use of PM-HIP for large components fabricated from stainless steels, nickel-based alloys, and low-alloy pressure vessel steels. Several original equipment manufacturers have engaged with EPRI and DOE to look to bring PM-HIP to the nuclear industry.

The huge interest in PM-HIP in the electricity sector has prompted a need for even larger HIP capabilities. Applications include components for small modular reactors, advanced light water reactors, Gen IV reactors, ultra-supercritical fossil applications, and supercritical $CO_2$ applications. The largest HIP unit in the United States today is around 66 inches (1.67 m) in diameter, with slightly larger units (81 inches and 72 inches [2.0 m and 1.83 m]) in Japan and China, respectively. To take full advantage of the technology for very large-scale components, a much larger HIP unit is desirable. Manufacturers across several sectors (heavy manufacturing, aerospace, aircraft, off-shore oil and gas, military, and energy) have also indicated that larger HIP capabilities could significantly expand the materials, products, and capabilities that they currently offer and allow components to be manufactured in a more timely fashion.

As such, EPRI and an advisory team began investigating whether a larger HIP capability was possible. This EPRI report was developed to assess the feasibility of designing, financing, procuring, installing, and operating a large HIP furnace (3.1 meters (10 feet) in diameter x 5 meters (16 feet) in length). The project, named ATLAS—Advanced Technology for Large-Scale PM-HIP, seeks to significantly increase the size (by roughly 2x), capacity, and turnaround time for the production of large billets (for further processing) and components. This report investigates many of the critical questions around ATLAS and provides commercialization ideas for the industry and interested public to consider.

In addition to ATLAS, EPRI recommends that the establishment of a Center of Excellence (COE) be considered to work with various industrial stakeholders on key technical challenges for introducing PM-HIP products and technologies. The COE could be based at one or more universities that lead in powder and/or HIP technology development. The COE could specialize in process modeling, powder characterization, HIP tooling and design, control of mechanical properties, and new alloy design fundamentals. It could provide advice to industry stakeholders on how to develop and use certain components.

The commercialization of ATLAS (including the COE) is projected to cost on the order of $105–$110 million (USD), assuming operation for an initial six-year period. Co-funding would be sought from a number of sources including industry stakeholders, a HIP operator, state/local entities, and the U.S. government (Department of Energy and/or Department of Defense).

Successful financing, installation, and operation of ATLAS and the COE could once again put the United States in a strong leadership position in terms of heavy manufacturing. Example components that could be manufactured via the large HIP unit include:

- Reactor and reactor components
- Steam generators
- Turbine rotors, discs, and compressors
- Ballistic armament
- Large gun barrels and missile tubes
- Wing spars
- Titanium bulkheads for aircraft
- Titanium landing gear
- Consolidation of cast turbine casings

This report provides an overview of ATLAS, the COE, industrial applications, a Roadmap, commercialization ideas, and a proposed schedule.

# CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# 1 INTRODUCTION

In 2010, EPRI, together with several industrial stakeholders, initiated research to begin looking at PM-HIP for production of large components such as valves, pumps, flanges, etc. EPRI's efforts began with a feasibility study to assess capabilities around 316L stainless steel components. The results of the feasibility study proved successful and led to further development and demonstration of three large valves. The valves were destructively analyzed and properties were generated to assemble a 316L SS Data Package for ASME BPVC. The Data Package supported assembly and eventual acceptance of a new Code Case, CC N-834 for 316L SS components used in nuclear applications.

In parallel, a second data package and Code Case, CC 2270 for Grade 91 ferritic components was developed by EPRI and accepted by ASME BPVC for Section I fossil applications. More recently, a third Code Case for Grade 91 was accepted by ASME B31.1 for power piping applications. More recently, a fourth Code Case for a duplex stainless steel (S32906) (spearheaded by Sandvik) was recognized.

These efforts around PM-HIP have generated considerable interest by industry. In late 2015, ASME initiated a new Task Group under Section II-Materials to begin implementation of current ASTM specifications A988, A989, and B834 into Section II. There is general agreement that when properly controlled, HIP materials are comparable to wrought products in terms of strength and in many cases--better. As such, the Task Group was asked to identify what controls should be in place in the specifications sot that the question of quality of HIP products is no longer a concern. Furthermore, the intention is that wrought value properties can be assigned to HIP products as a default position for Section II.

Thus, for the electric power industry and other uses of ASME BPVC components, there is a relatively clear path for use of PM-HIP in the near future. There are still a few hurdles (in addition to full acceptance by Section II) that must be overcome however. One of the largest hurdles for the electric power industry is that most components used in this industry are quite large. Current HIP vessels are limited in size and as such limit the number of components that can be fabricated by this process. Larger HIP capacity is a must for wide-scale deployment of PM-HIP components.

A second major area/hurdle is to gain the U.S. Nuclear Regulatory Commission (NRC) acceptance. EPRI staff have continued to work with the NRC to make sure they are up to speed on developments in this area and they have to date been very interested in the technology. This is based on the fact that PM-HIP components are: 1) easier to inspect due to a homogeneous grain structure, 2) they provide near-net shaped parts, and 3) provide equal or better properties. Another area is to develop PM-HIP capabilities for pressure vessel steels (eg., SA508). EPRI, DOE, and a few OEMs are continuing research in this area. Finally, the use of PM-HIP components in highly irradiated areas of the reactor is also an area of continuing research.

The HIP capacity or HIP unit size limitation issue does not affect just the electric power industry. This report will describe a number of other industries which have expressed interest in larger HIP capabilities including: aerospace, aircraft, military, off-shore oil and gas, chemical, petroleum, and pulp and paper. This report was developed to assess the feasibility of designing, financing, procuring, installing, and operating a large HIP furnace. In addition, a Center of Excellence is proposed to work with various industrial partners on key technical challenges for introducing new PM-HIP products and technologies.

The report includes the discussions on the following topics:

- Industry Analysis
- ATLAS and Center of Excellence Overview
- Benefits to Users
- Benefits of ATLAS
- Global Analysis
- Roadmap
- Financial Analysis

# 2
# INDUSTRY ANALYSIS

Heavy manufacturing of advanced materials in the USA continues to decline, as much of the industry has moved overseas, where modern equipment and low labor costs have provided an attractive business model. ATLAS would seek to re-establish the USA as a leader in heavy manufacturing through the development and implementation of "large scale" powder metallurgy and hot isostatic pressing capabilities, while providing a key manufacturing capability to the rest of the world for high quality components.

Heavy manufacturing, defense, and energy industries in the USA and across the world are facing extreme challenges in meeting the demand for large-scale components with superior performance. The size envelope of these components often ranges above 1.5 meters in diameter. These components are often manufactured by high temperature thermo-mechanical processing of large cast alloy (e.g., steels, nickel, and titanium) ingots or by castings.

Until the last decade, the USA had a strong forging industry and played a critical role in the development of large-scale gas turbines and other heavy structures for aerospace and power generation. However, even with the USA's excellence in forging science and technology, there has been a steady decline of this industry domestically. Much of the large forging capacity and the larger HIP units are now located in foreign countries, including Japan, Italy, France, and Korea due to cost pressures and lack of modern infrastructures.

Domestic original equipment manufacturers (OEM's) are facing constraints to meet their demand for increasingly larger new and/or replacement parts. These constraints are mainly related to a lead-time of, on average, 6-24 months as dictated by demand imposed by foreign supply chains for these components. Based on the above constraints, most of the domestic energy, heavy manufacturing, chemical, aviation, and oil field services and equipment OEM's are reluctant to pursue significant design changes in their product lines that involve larger metallic forgings (e.g. disks for land-based turbines or jet engine casings). Many anecdotal references have been made by participating industries that innovative designs to improve energy efficiencies of large-scale turbines have been abandoned due to the lack of large-scale forging infrastructure and/or powder metallurgy-HIP capabilities. This clearly constitutes a direct threat to the USA's manufacturing competitiveness.

In its research and discussions with industry stakeholders, EPRI has identified several opportunities/applications through ATLAS-PM/HIP:

- Replacement of large forgings or castings with near-net shaped (NNS) preforms (powder ingots) with improved properties
- Manufacture giant billets or preforms with fine grained, isotropic properties that can be further processed via other manufacturing methods (forging, ring-rolling, etc.)
- Produce much larger castings and then HIP to them to achieve full consolidation (the size of castings for critical applications is currently limited by HIP furnace size)
- Improve product yield (process dozens of small/medium sized components at one time)

- Enhance properties and performance of large forgings through use of advanced PM alloys that are not available in cast or wrought state
- Create large, new structures with targeted properties (composites, blended, nano materials, etc.) or produce bi-metallic, cladded, or diffusion bonded components with enhanced properties
- Consolidation of 3-D printed components
- Application of surface cladding/coatings or bi-metallics for wear and corrosion applications

## 2.1 Specific Industry Analysis

**Nuclear Applications.** One of the next major developments in the nuclear world is small modular reactors (SMR's). The first SMR is scheduled for completion/operation around 2024-25. SMR's can consist of up to 12 reactors (total) at one site. SMR's are installed in modules or packs of 2 reactors, 4 reactors, 6 reactors, etc. Thus, reducing the overall initial cost that utility would assume. A SMR reactor costs approximately $1.5-$2.0B vs. an Advanced Light Water Reactor (ALWR), which is about $8-$10B.

Many of the components in an SMR can be readily fabricated with PM-HIP. In fact, ATLAS may be the only way to financially justify fabrication of some parts that may simply require forgings that are too thick and require a large amount of machining. ATLAS allows production of a near-net shaped component and reduces both material needs and machining. SMR components that could be manufactured via PM-HIP include: reactor vessel head, containment vessel head, nozzles, valves, pumps, etc.

Advanced Light Water Reactors (ALWRs) also require a substantial number of heavy forgings for applications such as pressure vessels, steam generators, pressurizers, large pumps and valves, etc. EPRI recently produced a report (3002005432) for ALWR applications where PM-HIP could be used to produce large near-net shaped components. The report highlighted PM-HIP components where today's technology (60-inch HIP furnace) versus tomorrow's potential technology (3.1m or 10ft diameter HIP furnace) could be utilized. All major ALWR designs (GEH ESBWR, GEH/Toshiba ABWR, Westinghouse AP-1000, Areva EPR, and MNES/MHI APWR) were covered in the report.

Lastly, for nuclear applications, it is also worth noting that GEN IV advanced reactor designs will utilize various high temperature nickel-based alloys. PM-HIP is ideal for such applications since it can produce NNS components and reduce overall materials and machining costs as compared to forgings. PM-HIP provides an avenue to produce very intricate designs, flow patterns, and cooling channels which may be another plus for GEN IV applications.

**Aviation Applications.** The aviation industry is the largest net exporter, and one of the largest contributors to our nation's gross exports at $89.6 billion, with a larger portion made up of commercial aircraft bound for foreign carriers. Hot isostatic pressing (HIP) technology investment will enable aviation manufactures to capture growing demand for advanced titanium, nickel, cobalt, composite, and 3D-printed parts for the world's bestselling jet engines. Steep ramp-up rates for narrow- and wide-body aircraft engines are increasing aviation's need for such capabilities.

Aviation components may include such items as: wing spars, bulk heads, landing gear, turbine rotors, discs and compressors, combustion rings, etc. PM-HIP offers a large advantage to this industry in that materials costs and machining can be dramatically reduced over conventional forged product forms. An example of a bulk head assembly that has required hours of machining is provided in Figure 2-1. NNS production of such an assembly could reduce machining time by hundreds of hours. A second example is forged landing gear as shown in Figure 2-2. Following forging, a number of hours are required to machine this component to final shape. Production of a NNS component via PM-HIP would eliminated many hours of machining time.

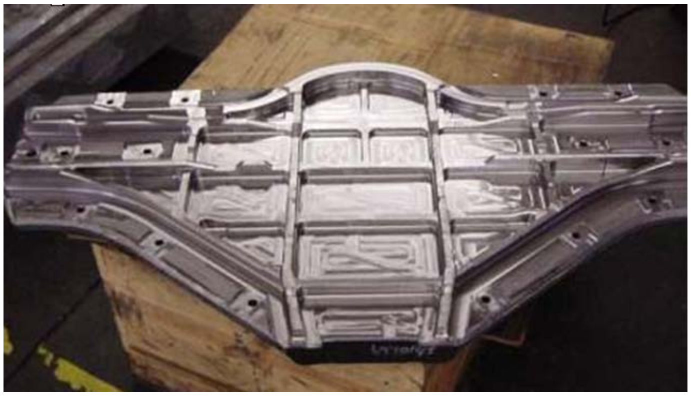


**Figure 2-1**
**Bulk head assembly requiring many hours of machining**


**Figure 2-2**
**High strength titanium landing gear that has been forged**

**Aerospace Applications.** The USA has a robust aerospace supply chain with capabilities in maintenance, repair, and overhaul, composites, metal-working, avionics, testing equipment, and coatings. USA-based suppliers are highly sought after partners for aerospace manufacturing programs at home and abroad. The aerospace industry currently utilizes HIP routinely, but larger billets and NNS components are always desired to boost capacity. Example components may include rocket engine boosters/nozzles rings, etc. Expensive nickel-based, cobalt-based, and titanium-based make PM-HIP a natural advantage for this industry. An example of a rocket nozzle extensions is provided in Figure 2-3.

**Figure 2-3**
**Rocket nozzle extensions**

**Off-Shore Oil and Gas Applications.** This industry has been one of the leaders to date in using PM-HIP to manufacture heavy components. Specifically, pumps, valves, manifolds, headers, underwater blow-out preventers, drilling parts/components, and other large components have been produced and are routinely finding their way into under-water applications in the North Sea. Duplex stainless steels and nickel-based alloys are the preferred materials of application. Figure 2-4 is an example of a large manifold produced by Sandvik for off-shore applications.

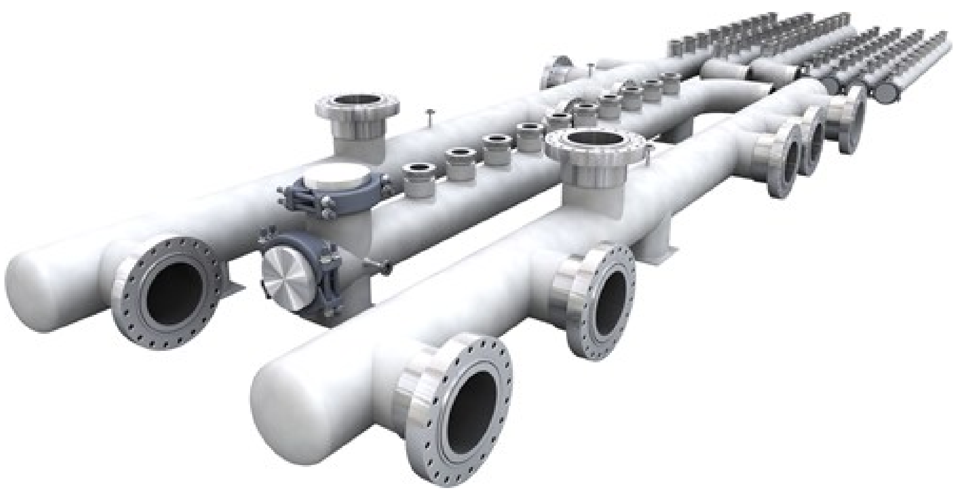


**Figure 2-4**
**Super duplex stainless steel manifold for off-shore applications produced by Sandvik**

**Military Applications.** Defense spending patterns tend to be dictated in the short term by threat levels. In the long term, economic prosperity plays the largest role in military spending. Although threats to the USA and its allies have increased in both Eastern Europe and the Middle East, these threats have become overshadowed by long-term economic factors. Military spending is contracting. Taking the USA as an example, the country's annual decline in defense investment from 2010-1015, is 5.4%. Some sectors (for example, civil helicopters) of the defense industry are expanding.

Because spending is less, military buyers desire more efficiency. Suppliers are searching for ways to provide more efficient, innovative products. Military suppliers with commercial-aerospace businesses are experiencing the 12th year of continuous growth. Several military applications come to mind including the following:

- U.S. Navy – reactors and reactor components for ships and submarines; large gun barrels and missile tubes; ballistic armament, and combustion turbine rotors/shafts/rings; wear or corrosion applications
- U.S. Army – ballistic armament for tanks and other ground vehicles; large gun barrels and missile tubes for howitzers and tanks, wear or corrosion applications
- U.S. Airforce – wing spars, turbine rotors/shafts/rings; landing gear, wear or corrosion applications

Military aircraft engines also have their special needs, which may be satisfied by near net shape HIP. Static components, with complex geometries, have been addressed previously with great success, for example, engine casings. However, with the enhanced properties of the new PM alloys there is a real advantage to be gained by application of PM HIP to a larger number of large-scale engine components. There has been much effort directed towards the exploitation of dual-microstructure and multi-alloy components (e.g., hybrid disk) that are difficult to fabricate by forging, while PM-HIP has demonstrated possibilities of creating such structures. Large airframe structures such as wing spars will also benefit from near net shape HIP enabling to substantially decrease the “buy to fly” ratio. Another key defense industry that will benefit from the ATLAS PM-HIP commercialization is armament for military tanks and armored personnel carriers. The ability of HIP to join dissimilar metals and composite materials on a large scale will enable new means for development of protective armament.

Figure 2-5 shows a large casting. Such castings are susceptible to voids, pockets, etc. generated during solidification. HIP has been used form many years to consolidate castings in smaller components. A larger HIP furnace capability could significantly reduce the amount of repair and rework required for large castings while providing enhanced overall properties.

Another military example is in the area of armament. PM-HIP is ideal for providing bi-metallic or ceramic blocks for armament applications. Armament is used for tanks (Figure 2-6), personnel carriers, ships, etc.

**Figure 2-5**
**Application of HIP to large castings could be used to eliminate hours of repair and rework often applied to such structures**

**Figure 2-6**
**Ballistic armament is required for tanks and other personnel carriers**

**Chemical, Petroleum, and Pulp and Paper.** These industries, similar to the nuclear industry, utilize large pumps, valves, pressure vessels, headers, sweep-o-lets, spargers, etc. PM-HIP is ideal for many of these applications in that it can reduce the overall volume of material required to fabricate a component and reduce machining costs.

# 3
# ATLAS AND COE OVERVIEW

This EPRI report was developed to assess the feasibility of designing, financing, procuring, installing, and operating a large HIP furnace. The project, named ATLAS—Advanced Technology for Large Scale PM-HIP, seeks to significantly increase the size (by roughly 2X), capacity, and turn-around time for the production of large billets (for further processing) and components.

## 3.1 ATLAS HIP Capability

ATLAS is a large 3.1 meters in diameter by 5 meters in length HIP unit that is ~2X larger than any other HIP unit in the USA. The large HIP unit would enable industry to manufacture a large number of components found in a SMR, LWR, ALWR, and advanced reactors (Gen IV). A number of OEMs involved in nuclear power are seeking to manufacture larger PM-HIP components, along with several partners from other industries including: chemical, aviation, aerospace, off-shore oil and gas, and the military. ATLAS commercialization would likely be driven by industry stakeholders organized in form of one or several "for-profit" entities.

Avure/Quintus, the leading HIP equipment manufacturer, has conceptually designed the 3.1m diameter by 5m length HIP unit. The anticipated utilization for the unit is between 1700-1800 hours per year. Specifics for the ATLAS unit (which Avure refers to as TerraPi can be found in the Appendices)

## 3.2 Center of Excellence (COE)

It is recommended that the commercialization of ATLAS be supported by a Center of Excellence (COE) to work with various industries on key technical challenges for introducing new PM and HIP products and technologies. The COE could be based one or more universities that lead in powder and/or HIP technologies. The COE would require staffing, including 1) industry experts and 2) academia (one or more professors at each university). The staffing should also include post-doctoral students and graduate students to encourage next-generation development.

The key contribution of the COE to the overall scope of the ATLAS program is that it would provide expertise, laboratories, and capabilities to design, evaluate, research, scale up and produce large components via PM-HIP, many of which have never been produced in the past. It would also facilitate continuous improvement toward PM-HIP applications well into the future. *The COE would specialize in process modeling, powder characterization, HIP tooling and design, control of mechanical properties, and new alloy design fundamentals.* It would advise industry stakeholders on how to use certain alloys and components. The COE should be a "non-profit entity."

The total cost for the ATLAS commercialization project is projected at $105-110 million to include six years of operation (see details in Section 8).

# 4
# ATLAS USERS

As part of its collaborative research program, EPRI, in conjunction with Carpenter Powder Products, Synertech PM, and several valve manufacturers have demonstrated powder metallurgy (PM) and HIP technology to manufacture large, near-net shaped products with excellent mechanical properties. These products can be manufactured at or below forging costs and with shorter lead times. This technology has been recently demonstrated for manufacturing low-alloy, stainless steel, and nickel-based component structures for the fossil and nuclear power industry. The materials processed by this route were verified and validated and have received ASME BPVC Code approval.

In addition, the above research has also led to the use of PM-HIP technology to create graded structures for valve applications with superior wear/galling resistance surfaces, net shape corrosion resistant impellers for gas compressors, and manifolds for rocket engines. With these initial successes, industry has requested a substantial increase in the volume envelope of this technology as an alternative to heavy forgings. This innovative idea has formed the basis for the commercialization of ATLAS PM-HIP.

Although ATLAS focuses on deployment of powder metallurgy-HIP, we envision synergistic advantages for other components/technologies including: *large-scale casting* and *additively manufactured components*. For example, the size of the critical castings is limited by the size of USA HIP furnaces (1.6 meters). With the development the large HIP facility, industry will be able to process large-scale castings. HIP of castings is often used to eliminate voids, seams, laps, or other issues that may have been produced during the casting process.

Additively manufactured (AM) parts are also commonly processed via HIP following production of the part to consolidate voids, laps, or anomalies that may have been developed during production as well as to reduce residual stresses. At this point, it is also important to point out that AM is envisioned for use of relatively small parts. Today's AM chambers are roughly 16" x 16" x 16" which allows components of up to roughly 100 lbs (45kgs) in weight. Chamber sizes will increase, but deposition rates still remain slow. PM-HIP provides much larger size and weight capabilities. Components have been produced that are several tons in weight with uniform properties. So a clear differentiation can be drawn between AM and PM-HIP in terms of size and quality. It is further important to note that almost all AM parts are processed following manufacturing using HIP technology to eliminate defects.

The manufacture of near-net shaped (NNS) components requires unique knowledge of modeling, capsule design, component shrinkage, HIP processing, and mechanisms of the powder consolidation. As an example, for a 3 meter capsule, the shrinkage during HIP will be greater the 450 mm (18"). Predicting and maintaining reasonable tolerances for such component sizes is extremely difficult and can only be achieved through the expertise of very experienced individuals and superior modeling capabilities. Industry stakeholders require access to industry experts with demonstrated expertise in a variety of PM-HIP technology areas, which can assist in bringing new “very large” products to the market. Through the commercialization of ATLAS, industry stakeholders would able to bring products to the market in a timely fashion and can eliminate expensive trial and error (and long lead times) often associated with large castings or forgings.

ATLAS benefits industry stakeholders by targeting large components (and large volumes) that cannot currently be produced using today’s manufacturing processes. The use of PM-HIP provides the ability to manufacture large components that exhibit both higher quality and improved properties over conventional processes. Conventional cast and wrought technologies may often be more expensive due to the need to the need to suppress the initial inherent defects found in large ingots, the need for additional forging operations to produce a final product, the use of sophisticated inspection technologies, and re-welding of the defects, etc. On the contrary, ATLAS near-net shape PM-HIP will lead to cost reduction per lbs. for large components as it consists primarily of four elements:

- Cost of powder material (reduced with larger quantity);
- Cost of HIP- more or less fixed per lbs. (less when a full load cycle is used)
- Cost of HIP tooling (decreasing per lbs. of powder with the size of the parts)
- Cost of the final machining (reduced for the near net shapes (NNS) compared to forgings)

The benefits to industry users include the ability to produce larger, newer and/or replacement parts, more rapidly, demonstrate innovative energy efficiency, and increased global competitiveness. ATLAS provides an alternate supply route to deliver an entirely new component within a 4-6 month period following placement of an order vs. an average of 12-24 months based upon demand often encountered today.

The process also enables one to fabricate intricate designs (e.g., to enhance flow rates) that cannot be produced by other conventional methods. Innovative new materials design, processing, application, and manufacturing will be required to achieve high temperatures and withstand corrosive conditions associated with new plant designs. The proposed ATLAS effort will provide a definitive avenue to produce large nuclear components with innovative designs, superior claddings, dissimilar metal joints, and functionally graded properties.

The Center of Excellence could serve various industries with the ability to provide expertise, laboratories, and development capabilities, which will facilitate continuous improvement toward application of PM-HIP across industries. The COE could specialize in process modeling, powder characterization, HIP tooling and design, control of mechanical properties, and new alloy design fundamentals. It could advise industry stakeholders on how to use certain alloys and components.

“Heavy Section Manufacturing” is defined as one of the six key enabling manufacturing technologies for deployment of nuclear energy plants under the *DOE Advanced Manufacturing Methods for Nuclear Energy Roadmap*. Within this area, PM-HIP is highlighted as the key manufacturing production technology that DOE will focus to re-establish the U.S. manufacturing base in the production of large nuclear components. The technology is described as a “transformational technology” that would enable the U.S. to meet virtually all of the heavy section manufacturing demands. In addition, large diameter, nickel-based turbine discs are highly desirable for gas turbine applications and would spur considerable growth across this industry toward higher output (MW) turbines. Similarly, large steam/gas turbine rotors would benefit from larger PM-HIP capabilities that could facilitate use of multiple materials across multiple stages of high temperature turbines. Other industries that would significantly benefit from much larger HIP capabilities include off-shore/deep sea oil and gas, oil sand, petroleum and chemical industries where large valves, pumps, headers, bends and manifolds are required.

This project is relevant to other presidential initiatives including the national network of manufacturing innovation institutes (America Makes, Light Weight Innovations for Tomorrow), DOE Advanced Manufacturing Office missions, the DOE Nuclear Energy program, and the Fossil Energy Program. Specific applications for PM-HIP across the energy arena were discussed in Section 2 of this report.

ATLAS aligns with the DOE NEET (Nuclear Energy Enabling Technologies) program as well as with DOE's mission to facilitate development/deployment of small modular reactors and advanced generation nuclear plant (AGNP) technologies over the next few decades.

ATLAS also aligns well with the needs of The Department of Energy Nuclear Energy (DOE-NE). Many advanced reactors will require advanced, high temperature materials and clad/coatings which cannot currently be manufactured with conventional processes (casting, forging, extrusion, etc.) today. ATLAS will provide industry with an option to manufacture advanced high-temperature alloys under very controlled chemistry and heating/cooling conditions and produces highly inspectable, near-net shaped components.

HIP in the aviation industry HIP involves the simultaneous application of high pressure and temperatures to significantly improve the mechanical properties and quality of cast products, such as blades and structures for jet engines. In addition, the process increases the density of 3D-printed parts made of powdered metals, improving product consistency, strength, and lifespan. All titanium, 3D-printed, and some nickel parts for jet engines must be treated by the HIP process.

For U.S.-based military suppliers to be successful in the future, they need to be able to develop more affordable products, adapted to each individual market. Replacement parts must also become more affordable and specific. ATLAS will enable these suppliers to be more responsive to their individual market's needs. Suppliers will be able to make these products more affordable. For the growing sectors within defense, such as civil helicopters, ATLAS will encourage this growth through innovation and time to delivery.

There are also very specific needs for the Department of Defense (DOD) applications. An extreme example is the very large structures in liquid fueled rocket engines. The weight problem that is of primary importance is addressed by using low-density alloys, such as Ti-alloys. Forging of large billets of Ti-alloys is very difficult due to extreme strain rate sensitivity at the forging temperature, which results in strain softening and highly localized deformation, which in turn leads to defects. As the properties of net shape PM HIP components have reached or even exceeded those of forged parts, forging issues can be avoided by using near net shape HIP of powder Ti-alloys.

Special needs for aerospace/military PM technology may include the ability to react rapidly to a need for surge production in response to a military emergency. Near-net shape PM-HIP will be able to quickly implement increased production rate without the need for forging tools. Military aircraft engines also have their special needs, which may be satisfied by near net shape HIP. Static components, with complex geometries, have been addressed previously with great success, for example, engine casings. However, with the enhanced properties of the new PM alloys there is a real advantage to be gained by application of PM-HIP to a larger number of large-scale engine components. There has been much effort directed towards the exploitation of dual-microstructure and multi-alloy components (e.g., hybrid disk) that are difficult to fabricate by forging, while PM-HIP has demonstrated possibilities of creating such structures.

# 5
# BENEFITS OF ATLAS

| Feature | Potential Benefits |
|---|---|
| **Worldwide Leader** | Leadership in heavy manufacturing<br>Increased global competitiveness<br>Quality and reliability<br>Reduced delivery time<br>Reduced political instability |
| **Diversify the Supply Base** | More options for manufacturing<br>Alternate supply route for long lead-time components<br>Less manufacturing uncertainty |
| **Center of Excellence** | Expertise as manufacturing changes<br>Facilitate quality improvement<br>Become an industry leader |
| **Innovation** | Able to quickly respond to changes in needs<br>Able to manufacture new components quickly<br>Able to fabricate intricate designs<br>Moves industries forward<br>Facilitates continuous improvement<br>Accelerates business model |
| **From forging and/or casting to PM technology** | More cost effective |
| **Manufacture larger shapes** | Meets specific needs |
| **Faster production turn-around times** | Manufacture more components<br>Reduces wait time for revisions |
| **Inspectability** | Inspection of large cast components is challenging due to the non-homogenous microstructure within castings. Castings can contain voids, pockets, segregation of tramp elements, inclusions, hot tears, secondary phases and non-metallic particles that make inspection of cast components difficult. The use of PM to produce alloys and components results in a uniform, homogenous microstructure that is inspectable in terms of both detection and sizing. |
| **Near-Net Shaped (NSS) Components** | Requires minimal machining and clean-up<br>Reduced component weight<br>Dollar savings in the overall production of the component |
| **Energy efficiency** | Cost savings |
| **ATLAS Knowledge regarding modeling, capsule design and mechanisms of the powder consolidation** | Faster lead times<br>Less trial and error<br>Cost savings |

# 6
# GLOBAL ANALYSIS

There are no known entities currently considering installing a large HIP unit like ATLAS. The current state-of-the-art HIP facility is in Japan and is 81 inches (2.0 m) in diameter. The largest unit in the USA is a 66-inch (1.5 m) diameter unit. Sweden also has two reasonably large units (71 and 58 inch (1.67m and 1.47m diameter) as shown in the Table 6.1. The largest HIP unit in China is a 63-inch (1.6m) diameter unit. Thus, ATLAS would roughly double the size of USA capabilities in HIP.

Five to ten years from now, other global stakeholders (e.g., Japan, Korea, China) will likely follow with a large HIP unit in response to the success of ATLAS.

**Table 6-1**
**HIP unit size vs country**

| Company | HIP Unit Size (diameter x length in inches) | Country |
|---|---|---|
| **Kinzaku Giken** | 81 x 164 | Japan |
| **BodyCote** | 71 x 130 | Sweden |
| **BodyCote** | 58 x 146 | Sweden |
| **BodyCote** | 66 x 100 | USA |
| **BodyCote** | 49 x 98 | UK |
| **ATI** | 51 x 115 | USA |
| **Alcoa Howmet** | 59 x 80 | USA |
| **Alcoa Howmet** | 42 x 97 | USA |
| **Kittyhawk** | 47 x 79 | USA |

# 7
# ROADMAP

It is recommended that industry address technical- and business-related challenges through assembly of a Roadmap to define the path to success. The Roadmap would establish a framework for physical PM-HIP infrastructure and develop a Center of Excellence to work with industry to address key technical challenges for introducing new products and technologies.

Specific emphasis will be placed on: 1) identification of technology gaps, 2) powder design, quality and manufacturing, 3) HIP process design and modeling to manufacture near net shapes, 4) advanced alloy design via thermodynamic modeling, and 5) technical and business challenges.

Representatives from multiple disciplines should be involved in development of the roadmap to assure proper representation and integration across industry. These would likely include 4-year engineering technology institutes, universities, national laboratories from DOE, DOD, NASA, industries, and non-profit organizations. The goal of the effort would be to provide a concise roadmap that can be used by industry over a 20- year period and re-establish heavy manufacturing in the USA. Priority R&D activities would also be established.

# 8
# FINANCIAL ANALYSIS

The ATLAS HIP facility and COE will require six key assets: a) ATLAS HIP unit, b) a spare furnace, c) building infrastructure and ancillary equipment, d) ATLAS maintenance costs, e) staffing to operate the facility, and e) COE Operational Costs. The HIP unit itself represents a majority of the overall costs and is projected at $60-65M. A spare HIP furnace is also required in case the furnace is inadvertently damaged during operation. This assures that operation can continue essentially uninterrupted.

The projected costs for the ATLAS building and ancillary equipment is projected at roughly $25 million. Staffing costs for operation of the large-scale HIP facility are estimated at roughly $0.830M per year, or $5M over six years.

The COE would likely be based at one or more universities. It would require staffing of one or more professors at each location. Personnel will be post-doctoral students and graduate students. Estimated annual cost of the COE personnel is $1.75M per year, or $10.5M over six years. Based on feedback from industrial advisers, the COE should be funded separately such that it can begin almost immediately.

The total cost for the ATLAS project is projected between $105-110 million (if the COE is included). Without the COE, the cost would be $95-100M range.

**Table 8-1**
**Estimated costs for ATLAS**

| | |
|---|---|
| ATLAS HIP Unit (3.1m x 5m) Acquisition | $60-65M |
| Spare HIP Furnace | $4.5M |
| ATLAS Building and Ancillary Equipment | $25M |
| ATLAS Maintenance | From Unit Revenue |
| ATLAS HIP annual payroll/staffing (start-up period; from revenue thereafter) | $5M |
| Center of Excellence Operational Costs ($1.75M annually) | $10.5M |
| **Total** | **$105M - $110M** |

Because of the scale of the investment, government funding/support from DOE and/or DOD is expected to be critical to successfully establish the manufacturing capability. A number of potential investor options are provided below.

## 8.1 Investor Options

Three investor options are considered here including: 1) Sole Ownership, 2) Venture Capital Investment, and 3) Consortium Partnership. This report focuses predominantly on the latter option.

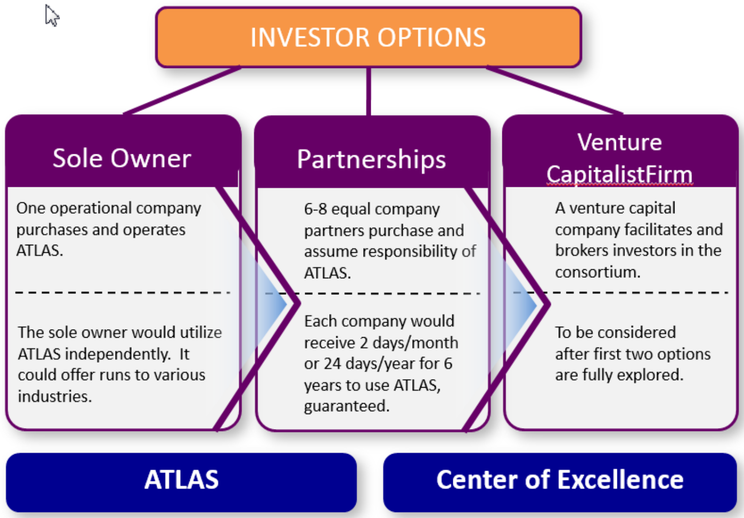



**Figure 8-1**
**Investor options**

**Option I -- Sole Owner.** The first option for financing ATLAS is the sole owner model. One operational company would purchase and use ATLAS. It could offer ATLAS runs to various other industries. A sole owner may or may not require DOE/DOD investment.

**Option II – Venture Capitalist.** The second option for financing ATLAS is the Venture Capitalist model. A VC would invest in ATLAS and hire someone to operate it. A VC owner may or may not require DOE/DOD investment.

**Option III– Consortium Partnerships**. This option involves 7-8 equal industry partners for ATLAS. The partners would create a consortium that owns and assumes responsibility of the project. An operational company would be selected to build the facility.

The first two options identified above are relatively straightforward and further discussion is not warranted. They would simply require investment by either entity. The third option (Consortium Partnerships) does require further discussion/explanation.

A Consortium will require investment by several industrial partners, the operator of the HIP facility, state/local government, and U.S. government funding (DOE or DOD). Assuming a total budget of around $110M, Table 1 provides four different options. The first two options examine one scenario wherein 7 or 8 industrial partners are involved and the U.S. government *co-funds at 34.5%*. The second three options assumes 7 or 8 industrial partners and *40% government funding*. Individual funding options for each partner is shown in red for each of the four options. Other options do exist, but these four potential funding options are presented for illustration purposes.

**Table 8-2**
**Potential funding options for a consortium**

***Option III-a. 6-8 Partners (Assuming 34.5% Govt Funding)***

| | |
|---|---|
| 7 Industrial Partners ($8M each) | 56 |
| HIP Operator (essentially a 8th partner) | **8** |
| State/Local Funding | **8** |
| U.S. Govt Funding (34.5%) | **38.0** |
| Total Budget | **$110M** |

| | |
|---|---|
| 8 Industrial Partners ($7.2M each) | 57.6 |
| HIP Operator (essentially a 9th partner) | **7.2** |
| State/Local Funding | **7.2** |
| U.S. Govt Funding (34.5%) | **38.0** |
| Total Budget | **$110M** |

***Option III-b. 6-8 Partners (Assuming 40% Govt Funding)***

| | |
|---|---|
| 7 Industrial Partners ($7.33M each) | 51.33 |
| HIP Operator (essentially a 8th partner) | **7.33** |
| State/Local Funding | **7.33** |
| U.S. Govt Funding (40%) | **44.0** |
| Total Budget | **$110M** |

| | |
|---|---|
| 8 Industrial Partners ($6.6M each) | 52.8 |
| HIP Operator (essentially a 9th partner) | **6.6** |
| State/Local Funding | **6.6** |
| U.S. Govt Funding (40%) | **44.0** |
| Total Budget | **$110M** |

Again, the above options are provided for “illustration purposes” only.

The above options require a one-time investment by an industry partner organization. In return, that organization would receive one HIP cycle run of ATLAS each month for six years. A total of 12 HIP cycles per year (one per month) would be guaranteed for each member participant by participating in ATLAS. Over six years, a total of 72 HIP cycles would be realized by each organization.

Let’s assume the second option from the above table is what is ultimately decided upon by the group. At $7.2M over 6 years, the actual equivalent cost per HIP run would be $7.2M/72 cycles = $100,000. If I can fabricate multiples of a large component and HIP them simultaneously, the cost becomes even more affordable. Also remember that NNS components are generated which can reduce both materials and machining costs.

If the cost is $6.6M over 6 years, then per run equivalent cost would be $6.6M/72 = $91,667 per cycle.

## 8.2 Workshop Feedback

In early February, 2016 EPRI hosted an ATLAS PM-HIP Workshop to solicit industry interest and feedback on the COE and regarding assembly of a potential consortium pull together ATLAS facility. Both the Meeting Minutes and the Agenda for the Workshop are provided in Appendix A.

## 8.3 Project Update—July 2016

EPRI and a number of industrial advisors are continuing to pursue the COE and ATLAS. The goal is to have the COE off the ground in 2016 and to follow with initiation of ATLAS in 2017-18 timeframe.

It is anticipated the COE will be operated by a university. On-going discussions are underway and facilities to house the COE have been identified. A funding structure for the COE has also been identified and further correspondence will be forth coming to potential industrial members.

Additionally, the Industrial Advisory Team has been investigating brownfield sites that could be equipped/modernized at a considerably lower cost than the $25 million anticipated for a new ATLAS building/facility. Work is continuing to identify and secure a facility. It should also be pointed out that the facility will require access to water for shipping and need to have access to large electrical power capabilities.

# 9
# REFERENCES

1. W.B. Burdett, P. Hurrell, A. Gilleland, “Hot Isostatic Pressing of Type 316L Powder for Pressure Retaining Components, ASME PVP-2004, July 25-29, 2004, San Diego, CA, MK-04-031.
2. W. B. Burdett and C.T. Watson, “Hot Isostatic Pressing of Type 316L Powder for Pressure Retaining Components,” ASME PVP-2005, July 17-21, 2005, Denver Colorado, PVP 2005-71711, p. 7.
3. J.L Sulley and I.D. Hookham, “Justification and Manufacturing Quality Assurance for the Use of Hot Isostatically Pressed, Reactor Coolant System Components in PWR Plants,” Proceedings of ICAPP’08, Anaheim, CA, June 8-12, 2008, Paper 8110, pp. 8-20.
4. I. Hookman, B. Burdett, K. Bridger, J.L. Sulley, “Hot Isostatically Pressed (HIPed) Thick-Walled Component for a Pressurized Water Reactor (PWR) Application,” Proceedings of ICAPP’09, Tokyo, Japan, May 10-14, 2009, Paper 9389, p. 7.
5. J.L Sulley, I.D Hookham, B. Burdett, and K. Bridger, “Introduction of Hot Isostatically Pressed Reactor Coolant System Components in PWR Plants,” Proceedings of the 18th International Conference on Nuclear Engineering, ICONE 18, Xi’an China, May 17-21, 2010, ICONE 18-30253.
6. T. Jelfs and B. Burdett, “Hot Isostatic Pressing of Inconel 600 and 690 Powders for Pressure Retaining Components,” ASME PVP 2011, July 17-21, 2011 Baltimore Maryland, PVP2011-57194.
7. L.W.Lherbier, J.F.Radavich, “An Evaluation of PM Waspaloy” Proceeding of 11th International Symposium on Advanced Superalloys – Production and Application”, May 21-25, 2007, Shanghai, China.
8. L.W.Lherbier, D.J.Novotnak, “Effect of Thermal History on the Properties and Microstructure of Large Hip’ed PM Superalloy Billet”, Proceedings of 11th International Symposium on Superalloys, September 14-18, 2008, Champion, Pennsylvania.
9. A.Eklund, et al, “Corrosion Properties of PM Hip’ed Stainless Steel”, 15th Nordic Corrosion Congress, May 19-21, 2010, Stockholm, Sweden.
10. J.Scanlon, et al, “Mechanical Properties of PM Hip’ed Stainless Steel – A Comparison to Conventional/Rolled Material, PowderMet 2010 Conference, June 27-30, 2010, Hollywood, Florida.
11. B.Bengston, et al, “Mechanical Properties of PM Hip’ed Stainless Steels”, Stainless Steel World Conference, October 5-7, 2010, Houston, Texas.
12. D.J.Novotnak, L.W.Lherbier, D.W.Gandy, “Manufacturing Large Complex PM Hip Shapes”, Euro PM 2011 Conference, October 9-12, 2011, Barcelona, Spain.

13. S. Tahtinen, "In-Vessel Materials Studies at VTT," VTT Industrial Systems, Association Euratom-Tekes, Annual Seminar, Paasitorni, Helsinki, May 30-31, 2005.
14. A. Pertti and H. Hanninen, personal communication, July 4, 2011.
15. ASTM Standard A988/A 988M-07, Standard Specification for Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves, and Parts for High Temperature Service.
16. ASTM Standard A989/A 989M-07, Standard Specification for Hot Isostatically-Pressed Alloy Steel Flanges, Fittings, Valves, and Parts for High Temperature Service.
17. D. Gandy, et al, *Program on Technology Innovation: Manufacture of Large Nuclear and Fossil Components Using Powder Metallurgy and Hot Isostatic Processing Technologies*, EPRI Report 1025491, May 2012.
18. D. Gandy, J. Shingledecker, L. Lherbier, "The Manufacture of Large, Complex Power Plant Components Using Powder Metallurgy and HIP Technologies—A Feasibility Study," EPRI Advanced Materials Conference, Santa Fe, New Mexico, October 2010.
19. D. Gandy, J. Shingledecker, L. Lherbier, and D. Novotnak, "Powder Metallurgy for Producing Nuclear and Fossil Components," CSC11 Corrosion Solutions 8th International Conference, Lake Louise, Alberta Canada, October 2011.
20. D. Gandy, J. Shingledecker, and J. Siefert, "Overcoming the Barriers for PM/HIP Technology in Large Nuclear and Fossil Components," ASM Advanced Materials & Processing Magazine, January 2012.
21. D. Gandy, J. Shingledecker, L. Lherbier, and D. Novotnak, "Powder Metallurgy Methods for Producing Components," Stainless Steel World, November 2011.
22. Introduction to PM HIP Technology, European Powder Metallurgy Association, 2012, www.empa.com.
23. D. Gandy, PM-HIP Research for Structural and Pressure Retaining Applications in the Electric Power Industry, Structural Materials for Innovative Nuclear Systems (SMNIS-3), Workshop Proceedings, Idaho National Laboratory, Idaho Falls, October 7-10, 2013.
24. D. Gandy, J. Siefert, L. Lherbier, D. Novotnak, PM-HIP Research, Applications, and Technology Gaps for the Electric Power Industry, HIP-14, Stockholm Sweden, June 2014.
25. D. Gandy, J. Siefert, L. Lherbier, D. Novotnak, PM-HIP Research for Pressure Retaining Applications Within the Electric Power Industry, Proceedings of ASME 2104 Small Modular Reactors Symposium, SMR-2014, Washington, DC, April 15-17, 2014.
26. D. Gandy, PM-HIP Research for Structural and Pressure Retaining Applications in the Electric Power Industry, Advanced Nuclear Manufacturing—Powering the Future of Nuclear Innovation, Pocatella, Idaho, May 18-20, 2015.

# A

# ATLAS WORKSHOP MEETING MINUTES AND AGENDA

**Advanced Technology for Large Scale (ALTAS) PM-HIP**
Reunion Resort, Orlando, Florida
February 2-3, 2015
--Meeting Minutes--

Day 1 of the kickoff meeting for ATLAS began with introductions, a welcome message from D. Gandy (EPRI), and an overview of the key meeting objectives which are as follows:

- To understand industry *manufacturing needs/requirements* for large PM-HIP components
  - Materials, size of components, castings, large billets, preforms, volume, shorter turn-around, etc.
- Review proposed 3.1m (D) x 5m (L) HIP unit, including installed costs.
- Discuss *commercialization options*, including a potential consortium.
- Highlight potential industry–government opportunities.

The final agenda for the meeting is included in Attachment 1.

Next, several technical discussions were made by ATLAS advisory team members to describe the state of knowledge around manufacturing of powder metallurgy-hot isostatic pressed (PM-HIP) components. These included the following presentations:

- Technical Merits of Large HIP (L. *Lherbier*)
- Large Components Potentially Manufactured via HIP (V. *Samarov*)
- Description of Large Unit – TeraPi (A. *Eklund*)
- Powder Canning, Design, and Filling (V. *Samarov*)
- Center of Excellence (H. *Fraser*)

All presentations are available to meeting participants through an ftp site. It should also be noted that the presentation by A. Eklund provided details on the 3.1m x 5m HIP unit.

Several industrial attendees also described applications where larger capabilities in PM-HIP could have been advantageous in the past or could assist in the future. Examples of large Ti and Al castings > 80” in diameter were presented. Industrial members who provided some additional thoughts included: J. Sears (GE), A. Goldsworth (Rolls-Royce), G. Jalewalia (Boeing), and C. Armstrong (Westinghouse). Elliott Turbines in a letter supported the PM HIP approach with an example of > 70” diameter Waspaloy disc.

Day 2 of the meeting began with discussions/review of some of the key items from the previous day. Some of the specific questions/items included:

- Is the current powder capacity sufficient to meet industry needs if we begin making a large components under ATLAS? Attendees felt it was and that additional capacity could be installed in reasonably short term if powder capacity begins to be short.
- Assuming the proposed HIP furnace is built at 3.1m x 5m, is a final product of 2.5m diameter (due to shrinkage during consolidation) sufficient to meet industry needs/requirements? Attendees indicated that larger is always better, but the size of the proposed furnace (120 inches) is 33% larger than today's largest furnace in Japan (which is 81 inches in diameter) and 2 times larger than the largest HIP furnace in the U.S. and will provide industry with terrific capabilities for large preforms, components, and casting consolidation.
- Production of the 3.1m HIP unit is expected to take 2 years from the date of order. If building of the facility and installation of the HIP unit are performed in parallel, it is believed the total time from date of order to commissioning will be around 30 months.
- Attendees also discussed ASME inspection criteria. It was suggested that we first continue striving to gain acceptance of ASME recognition for product manufacture beyond the current four accepted Code Cases. Once this is accomplished, then we work with the Book Sections (I, III, VIII) to educate them on the fact that HIP components are typically greater than 99.7% dense and that flaws (if any) will be considerably smaller than those found in wrought, forged, or cast products. Thus, different "flaw tolerance criteria" may be an attribute that we seek in the future.
- It was also noted that the HIP process can be used to eliminate welds in certain cases. This could be a huge benefit for nuclear applications where industry is trying to minimize welds and the required inspections thereof.
- Discussions were also heard around ATLAS unit utilization. Kittyhawk believes the utilization factor will be around 33% or around 10-11 cycles per month. The unit is capable of around 30 cycles each month (assuming 1 days/cycle).
- There is a need to develop direct cost comparison information to provide to potential industrial partners, DOE, DOD, NIST, and others such that PM-HIP can be directly compared to castings and forgings costs. A couple of technical cost models were described by S. Mashl (Michigan Tech.)
- Attendees suggested that we also emphasize the "green" factor of PM-HIP as compared to castings or forgings. It was also suggested that PM-HIP uses less energy costs and fuel consumption.
- S. Mashl (Michigan Tech) offered to provide the justification package for the CERN end covers for the super-collider in Switzerland.
- D. Swindells (Albert Duvall) offered to supply some forging costs so that we can better compare PM-HIP costs versus other processes.

Following ~75 minutes of open discussions among the attendees, D. Gandy provided a brief overview of estimated costs for purchase and installation of the unit and three of scenarios that industry consider for funding ATLAS. Estimated costs were on the order of \$105-\$110M U.S. Next, C. Barre (Kittyhawk/Synertech) provided a detailed "cost proposal" for funding ATLAS.

During the Breakout sessions, attendees focused on two issues: Finances and the Center of Excellence. During the Financial breakout session, attendees discussed options for obtaining funding from sources outside of industry including:

- Use of a restored “Brownfield site” such as the Piketon Ohio site. The site is government owned and would be viewed favorably in terms of economic development and provide security.
- Use of other government sites, including closed sites or national laboratories.
- Securing workforce training dollars
- Ask DOD to pay for a spare furnace assuming industrial partners fund the unit acquisition.
- State/local support for economic and job development. It is believed that ATLAS could result in >100 employees which would be involved in powder manufacture, canning, gas production, machining, and unit operation. A more detailed analysis was recommended.

**Action Items** from the discussions on Finances included the following:

- Begin investigating potential government/Brownfield sites such as Piketon and others to minimize land acquisition costs and to provide some infrastructure.
- Socialize the ATLAS concept with DOE, DOD, NIST, and other government agencies.
- Create a LLC. (Note: This is an action item that does not involve EPRI. This is not part of EPRI’s charter to set up companies).
- Obtain “Letters of Intent” from perspective industrial partners. Again, this will be performed by another organization, not EPRI.
- Define what the “backup plan” may be if for some reason this falls through. How else would industry fund ATLAS? It was suggested that some discussions with venture capitalist be considered as both a “gut check” and to see if a VC might be interested in funding ATLAS entirely.

**Action Items/Discussion** on the Center of Excellence (COE) included:

- The COE being a part of ATLAS project should be separate from ATLAS HIP. It should be operated by a university research institute (not a university per se) or another nonprofit organization.
- Another option is for the COE to be a separate LLC. Attendees liked the former option however.
- Members of ATLAS would automatically have access to the COE, but the COE could also solicit membership outside of ATLAS.
- COE could follow the same path of other recent manufacturing centers such as America Makes, Lift, Manufacturing Demonstration Facility (MDF), others.
- Review what types of issues/problems other manufacturing centers (America Makes, etc.) encountered during startup.
- A few additional discussion items/topics surrounding the COE are shown in Attachment 2.

ATTACHMENT 1

# FINAL AGENDA

## ADVANCED TECHNOLOGY FOR LARGE SCALE (ATLAS) PM-HIP

February 2 – 3, 2016 • Reunion Resort

| DATE: TUESDAY, FEBRUARY 2, 2016 | | |
|---|---|---|
| **TIME** | **TOPIC** | **PRESENTER** |
| **12:00 pm** | Registration | |
| **12:30** | Welcome and Introductions | *D. Gandy, EPRI* |
| | Review of ATLAS Key Objectives | *D. Gandy* |
| | Why ATLAS?– Project Overview | *D. Gandy* |
| **1:00** | Technical Merits of Large HIP | *L. Lherbier, Consultant* |
| **1:45** | Large Components Potentially Manufactured by HIP | *V. Samarov, Synertech* |
| **2:30** | Participant Needs / Requirements – Speakers(2) | *J. Sears, GE;*<br>*A. Goldsworth, Rolls-Royce* |
| **3:00** | Afternoon Break | |
| **3:30** | Avure / Description of Large HIP Unit | *A.Eklund and R. Thunholm, Quintus Technologies* |
| **4:15** | Powder Canning, Design, and Filling | *V. Samarov* |
| **4:45** | Center Of Excellence (COE) Overview | *H. Fraser, OSU* |
| | Wrap up Day 1 review / next steps/ Dinner | |
| **5:30 pm** | Adjourn | |
| **6:30 pm** | Dinner – Location *Forte Grille* on site | *All* |

| DATE: WEDNESDAY, FEBRUARY 3, 2016 | | |
|---|---|---|
| **TIME** | **TOPIC** | **PRESENTER** |
| **7:30 am** | Breakfast | |
| **8:30** | Review of Day 1 & Questions | *D. Gandy/M.Williams, Facio* |
| **9:00** | Investor Options & Budget Overview | *D. Gandy* |
| **9:30** | Kittyhawk/Synertech Proposal | *C. Barre, Kittyhawk* |
| **10:00** | ATLAS Timeline to Launch | *M. Williams* |
| **10:20** | Morning Break | |
| **10:50** | Breakouts (2)<br>• Budget and Financial Discussion<br>• Center of Excellence | *Session Leaders* |
| **12:00 pm** | ATLAS Breakout Reports/Read outs –working lunch | *Session Leaders* |
| | Wrap up – follow up plan | *Gandy/Williams* |
| **1:00 p.m.** | Adjourn | |

## Attachment 2.
## Center of Excellence—Breakout Discussion Topics

**Question 1:** ***Does the proposed scope for the CoE seem appropriate?***

The group felt that the topics were useful and would qualify as those to be investigated in a Center of Excellence for HIP. It was emphasized that it is important to aim at development of new knowledge particularly for PM-HIP of large structures, going beyond current capabilities. For example, the degree of computational modeling should be extended beyond the prediction of shape change during a given HIP cycle and design of cost efficient HIP tooling, to include cost modeling, predictions of microstructural evolution and mechanical properties as well as the quality of as HIPed surfaces. For the aerospace industrial sector, it is important for the CoE to generate confidence in HIP as a manufacturing method for rotating parts and static parts that are fatigue limited. Emphasis is made regarding cost modeling. Thus, it is essential to be able to generate reliable estimates of costs of given jobs as input to decisions being made by customers whether to make use of the ATLAS facility.

**Question 2:** ***Would industry use the CoE?***

A simple answer was offered uniformly by the group: Definitely! It is important to deal with any IP issues upfront. The activities of the Center of Excellence would lead to increases in confidence in PM HIP with industry. As a result, the group felt the Center would contribute significantly to the provision of industrial support for the ATLAS consortium by proactive development of solutions for large structures and generating efficient models for cost and material local properties and offering solutions for difficult to process materials. COE will be able to develop the PM HIP process for the specific perspective applications for the ATLAS members. The activity of the COE will then proactively prepare solutions for industry while the ATLAS HIP is being built

**Question 3:** ***Is the proposed composition of personnel (academic (faculty, post-docs and students), and industrial persons) appropriate?***

The mix of personnel was considered by the group to be appropriate with a PI selected from Industry. It was understood that the majority of the workforce would involve students (undergraduate and graduate), post-doctoral fellows, visiting technologists and faculty. Students and fellows are necessary but the core of the COE activity that can attract funding from both Government and Industry must be a “fusion” of academic knowledge and research capabilities with the experience and advanced technologies coming from industry

**Question 4:** ***Who should oversee the operation and activities of the CoE?***

The notion of a governing Industrial Advisory Board was considered appropriate and useful.

**Question 5:** ***What should be the next steps for the CoE?***

Work with Government Agencies and Industry to secure co-funding and get started.

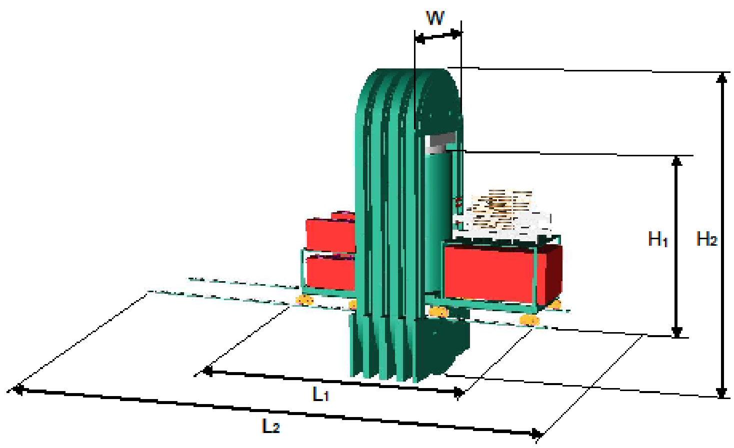
# *B*
# TERRA PI—DESIGN OF HIP UNIT

# Product Data Sheet

## QUINTUS® Hot Isostatic Press

QIH 3.14 x 5.0– 1050 – 1250M URC

### 1 Pressure vessel




Avure Technologies AB
Quintusvägen 2, Box 343 • SE-721 66 VÄSTERÅS, Sweden
Tel: +46 21 327000 • Fax: +46 21 327305
VAT-No: SE556064177001 • Orgnr: 556064-1770

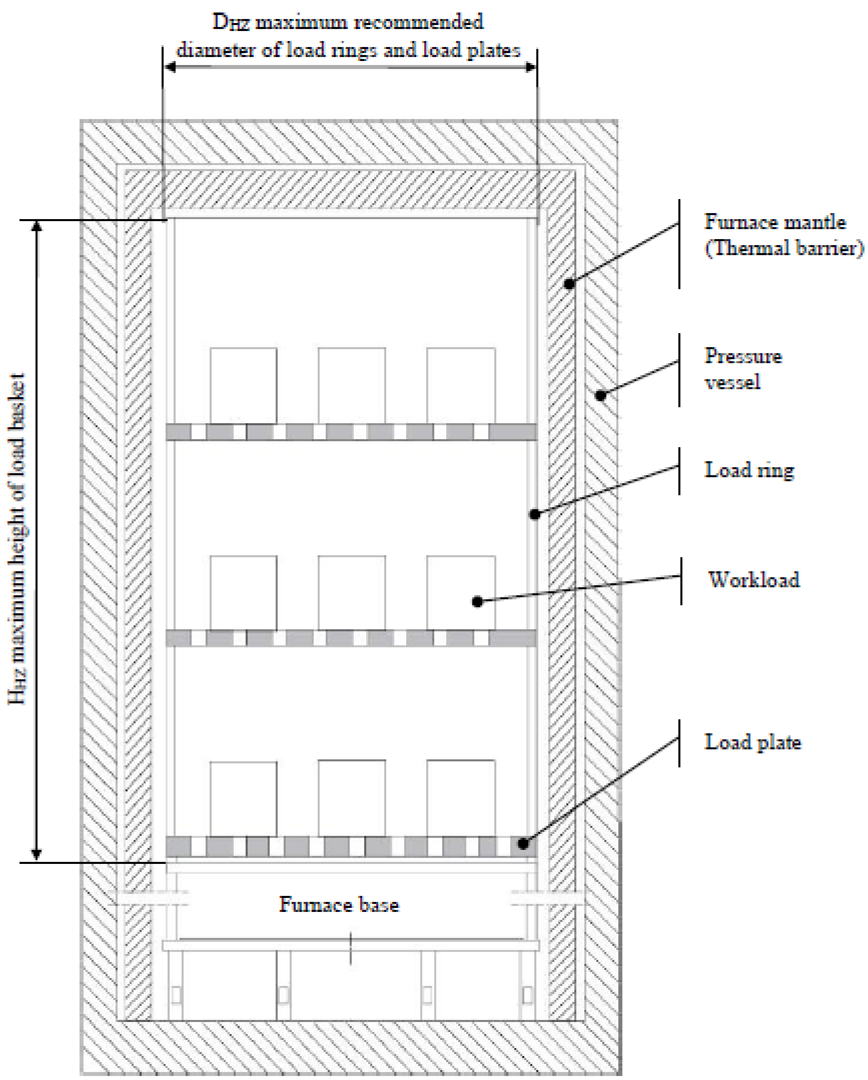
| | | |
|---|---|---|
| Max. operating pressure | MPa | 105 |
| Max. design pressure | MPa | 116 |
| Internal diameter | mm | 3520 |
| Internal height | mm | 6770 |
| Pressure vessel volume | $m^3$ | 65,8 |
| $H_1$ = Height to upper end of cylinder from floor level, approx. | m | 8,2 |
| $H_2$ = Total height. | m | 16,3 |
| $L_1$ = Length, approx. | m | 13,5 |
| $L_2$ = Length, approx. | m | 30,0 |
| W = Width, approx. | m | 7,5 |
| Total weight, approx. | kg | 1 500 000 |
| Weight of heaviest part approx. | kg | 300 000 |
| Minimum calculated fatigue life: | | 10.000 cycles to max. pressure according to ASME and with max. thermal loading/rapid cooling speed. |



Avure Technologies AB
Quintusvägen 2, Box 343 • SE-721 66 VÄSTERÅS, Sweden
Tel: +46 21 327000 • Fax: +46 21 327305
VAT-No: SE556064177001 • Orgnr: 556064-1770

## 2 Furnace

### 2.1 Furnace definitions




Avure Technologies AB
Quintusvägen 2, Box 343 • SE-721 66 VÄSTERÅS, Sweden
Tel: +46 21 327000 • Fax: +46 21 327305
VAT-No: SE556064177001 • Orgnr: 556064-1770

## 2.2 Molybdenum furnace 1250 °C

| | | |
|---|---|---|
| Maximum operating temperature | 1250 | °C |
| Maximum height of workload, $H_{HZ}$ | 5000 | mm |
| Maximum diameter of workload, $D_{HZ}$ | 3140 | mm |
| Maximum weight of workload incl. load cans | 85000 | kg |
| Maximum temperature deviation at steady state within the charge volume, at temperatures between 500 °C and maximum temp. and pressures above 20 MPa using workload TC control | +/- 15 | °C |
| Number of radial heating zones | 9 | pcs |
| Number of base heating zones | 3 | pcs |
| Plug in and feed through for workload TC type TBD | 16 | pcs |
| Nominal power, approx. | 8000 | kW |

Note!

All data given in each section are preliminary except those underlined.
Avure follows a policy of continuous product development and we reserve the right do deviate from this Technical Description without compromising with the technical characteristic of the equipment.

Avure Technologies AB
Quintusvägen 2, Box 343 • SE-721 66 VÄSTERÅS, Sweden
Tel: +46 21 327000 • Fax: +46 21 327305
VAT-No: SE556064177001 • Orgnr: 556064-1770

### 2.2.1 Estimated typical cycle times

The cycle time is calculated for a typical cycle 1250°C, 105 MPa with a 66800 kg steel load. Load weight includes load cans.

| Cycle step | Natural cool | URC |
|---|---|---|
| Vacuum pumping / flushing 2 times | 65 | 65 |
| Equalizing | 50 | 50 |
| Pumping and heating | 360 | 360 |
| Sustain / hold | 0 | 0 |
| Cooling to 200 °C | 2000 | 460 |
| Equalizing reclaim of gas | 50 | 50 |
| Recovery pumping to 40 bar | 190 | 190 |
| Exhaust | 30 | 30 |
| **Total (min) excluding sustain/hold time** | **2745** | **1205** |
| **Total (hours) excluding sustain/hold time** | **45,8** | **20,1** |

The above cycle time require that pipe dimensions between the gas system and gas storage do not restrict the gas flow.

Avure Technologies AB
Quintusvägen 2, Box 343 • SE-721 66 VÄSTERÅS, Sweden
Tel: +46 21 327000 • Fax: +46 21 327305
VAT-No: SE556064177001 • Orgnr: 556064-1770

## 3 Control system

| | | |
|---|---|---|
| Programmable controller (PLC): | Allen-Bradley | |
| HMI system | Wonderware InToch | |

## 4 Gas compressor system

| | | |
|---|---|---|
| Number of piston compressors | 4 | pcs |
| Power consumption for piston compressors | 4 x 55 | kW |
| Maximum pumping capacity at 15 MPa suction pressure | 1090 | Nm3/h |
| Maximum pumping pressure for piston compressor | 105 | MPa |
| Number of diaphragm compressors | 1 | pcs |
| Power consumption for diaphragm compressor | 132 | kW |
| Maximum pumping capacity at 15 MPa suction pressure | 1360 | Nm3/h |
| Maximum pumping pressure for diaphragm compressor | 40 | MPa |

## 5 Vacuum system

| | | |
|---|---|---|
| Number of pumps | 1 | pcs |
| Vacuum capacity | 4210 | $m^3/h$ |
| Power consumption | 30 | kW |

## 6 Cooling system, vessel

| | | |
|---|---|---|
| Number of pumps for vessel cooling circuits | 1 + 1 hot stand by | |
| Type of pump for emergency cooling | Gas-driven | |
| Power consumption | 110 | kW |

## 7 Cooling system, electrical power supply

| | | |
|---|---|---|
| Number of pumps for electric power supply cooling circuits | 1 + 1 hot stand by | |
| Power consumption | 11 | kW |

Avure Technologies AB
Quintusvägen 2, Box 343 • SE-721 66 VÄSTERÅS, Sweden
Tel: +46 21 327000 • Fax: +46 21 327305
VAT-No: SE556064177001 • Orgnr: 556064-1770

## 8 Site utilities

### 8.1 Electric power

| | | |
|---|---|---|
| Supply voltage, 3 phase: | 400V (+/-5%), 50 Hz | |
| Totally installed motor power, approximately: | 600 | kVA |
| Furnace supply voltage, 3 phase: | 690V (+/-5%), 50 Hz | |
| Totally installed furnace power, approximately: | 9000 | kVA |

### 8.2 Cooling water supply

| | | |
|---|---|---|
| External cooling water flow at normal operation, approx. | 213 | $m^3/h$ |
| External cooling water flow at rapid cool, approx. | 640 | $m^3/h$ |
| External cooling water flow at emergency cool, approx. | 72 | $m^3/h$ |
| Minimum pressure | 0,3 | MPa |
| Maximum pressure | 0,6 | MPa |
| Maximum inlet temperature: | 30 | °C |
| Cooling power needed at normal operation, approx. | 2485 | kW |
| Cooling power needed at rapid cool, approx. | 7470 | kW |

### 8.3 Pressure medium

The pressure medium in the pressure vessel is clean argon gas according to Avure Technologies AB specification. The gas supply line to the take-over point is to be delivered by the Buyer.

To transfer the gas between the gas storage and pressure vessel as per this documents calculated cycles times a minimum pipe diameter of 35 mm is required.

| | | |
|---|---|---|
| Recommended gas storage water volume. | 262 | $m^3$ |
| Gas storage pressure | 20 | MPa |

It is recommended that the gas storage is built up of several gas containers to form a gas battery of the volume needed.

It is also recommended that the gas storage will be filled from tank with the aid of a cryogenic pump and an evaporator.

The gas storage shall be provided with a safety valve for storage protection, a gauge for reading the storage pressure and a shut-off valve to isolate it.

The gas supply line from the gas storage shall have a block and bleed valve.

Avure Technologies AB
Quintusvägen 2, Box 343 • SE-721 66 VÄSTERÅS, Sweden
Tel: +46 21 327000 • Fax: +46 21 327305
VAT-No: SE556064177001 • Orgnr: 556064-1770

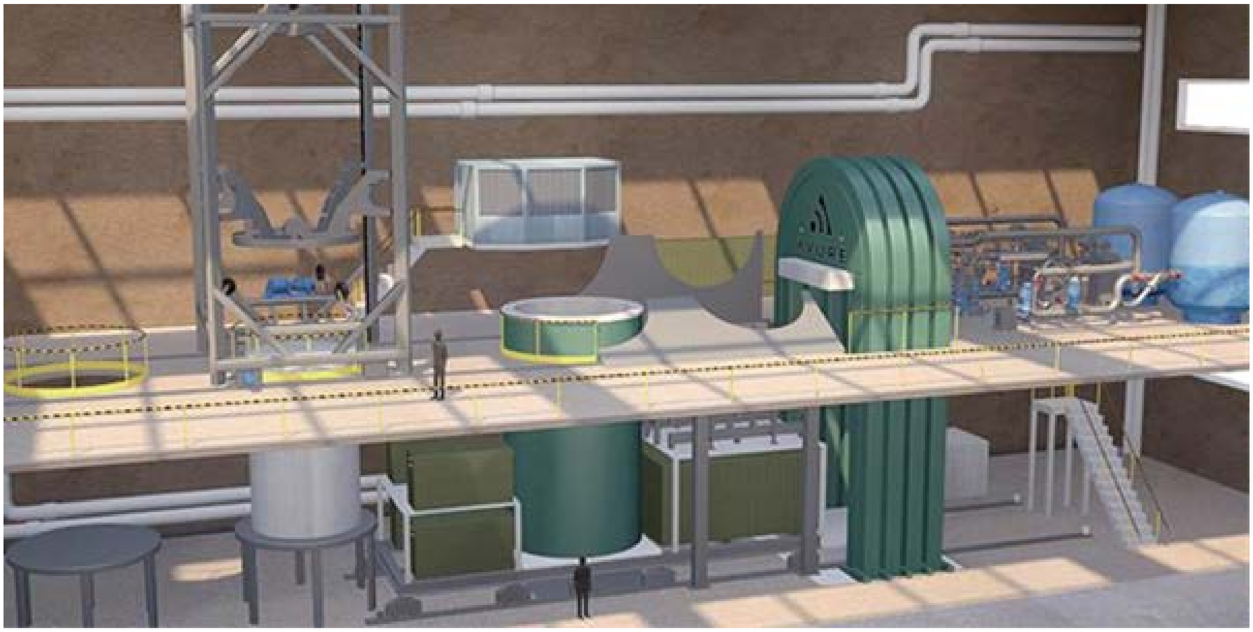
### 8.4 Fluids

| | |
|---|---|
| Oil for hydraulic pumps | ISO VG 46 |
| Vacuum pump oil | According to supplier's specification |
| Inhibitor for the closed vessel cooling system | Sodium Nitrite base as per Avure's specification |
| Type of water for the electric power cooling system | Distilled water |

### 8.5 Operating environment

| | | |
|---|---|---|
| The pressure vessel is designed to operate | 0-24 | hrs / day |
| Ambient temperature | 10-40 | °C |
| Humidity maximum | 90 | % |

Avure Technologies AB
Quintusvägen 2, Box 343 • SE-721 66 VÄSTERÅS, Sweden
Tel: +46 21 327000 • Fax: +46 21 327305
VAT-No: SE556064177001 • Orgnr: 556064-1770



## Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

**The Electric Power Research Institute, Inc.** (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity



3002007401

**Electric Power Research Institute**
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com