Optimization of Laboratory and Utility Scale sCO2 Microchannel Heat Exchangers

Vacuum Process Engineering, Inc.

Introduction

Fabrication of microchannel heat exchangers (MCHEs) through the application of diffusion bonding processes yields several advantages. Diffusion bonding is a solid state joining process and is distinct from other metals joining techniques, such as brazing, soldering, GTAW and GMAW welding, in that parent strength and the precise geometrical microfeatures of the microchannels are maintained throughout the manufacturing process. Additionally, no brazing filler alloy is utilized, thereby mitigating related corrosion concerns. When accompanied with optimized microchannel design, diffusion bonded MCHEs offer high efficiency and reliable heat exchangers with extreme temperature, significant pressure containment capabilities and corrosive service conditions. Ideal applications for the diffusion bonding manufacturing process are high pressure and high temperature heat exchangers, such as supercritical CO_2, recuperation and renewable energy, and oil and gas.

Microchannel Heat Exchangers (MCHEs)

MCHEs for high temperature and high pressure applications can be created by diffusion bonding plates (or platelets or shims) of metal. The advantages of MCHEs are that they have few limitations on channel patterns and features as long as the pattern can be photochemically etched. MCHEs consist of a core (or multiple cores joined together), headers, nozzles and flanges. The core is created using diffusion bonding techniques, which reliably bonds a stack of photochemically microchannel-patterned and etched plates into a monolithic structure. The resulting core of the MCHE exhibits parent material strength suitable for withstanding extreme temperature and pressure service. This allows for higher effectiveness heat exchange and close approach temperatures.

Design Algorithms

The design of the MCHEs is defined by an algorithm, created through a CRADA partnership with Sandia National Laboratories, which utilizes the theories of heat transfer and fluid dynamics and advanced modeling tools in addition to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Section VIII Division 1 requirements. The software designs the entire heat exchanger, from the layout of the shims to the required thickness of the headers, all to a set of user-defined and inputted specifications by incorporating thermo-hydraulic and mechanical design equations. The output of the algorithm is the performance of the heat exchanger and the required dimensions. When determining the heat exchanger size, the software considers the shim length, width, quantity, side margins, etc., as well as the microchannel width, depth, zig zag angles, and spacing. Code validation work to date has confirmed design efficacy. The design algorithms provide for high effectiveness, close approach temperatures and ASME BPVC compliance.

MCHE Fabrication

The ASME BPVC specifies requirements for both diffusion bonding and brazing. Vacuum Process Engineering (VPE) holds a U-Stamp, a UM-Stamp, and a R-Stamp per ASME Section VIII Division 1. Designing and manufacturing stamped MCHEs is routine with operating pressures and temperatures up to 20MPa and 793K. However, higher temperatures and higher pressures are still within allowable working temperatures for ASME BPVC requirements and within the capabilities of VPE and the diffusion bonding techniques. Precision control of applied forces, temperature, time, shim surface preparation and process tooling enables repeatable and reliable bonding of shims, thus creating a core. Parent material strength and leak tight interfaces are routinely achieved in the diffusion bonding process. Fabrication of headers and nozzles followed by welding to ASME BPVC completes the basic MCHE. Testing to ASME standards assures reliability and compliance for operation to pressures in excess of 500 bar and temperature greater than 750°C.

Materials

Diffusion bonded MCHEs can be fabricated from a wide range of materials. The choice of materials depends upon requirements such as service conditions, pressure containment, corrosion, and much more. Some examples are listed below.

Table 1: Examples of materials from which diffusion bonded MCHEs can be manufactured.

Stainless Steel	**Nickel**	**Titanium**
Type 304 (UNS 30400)	Alloy 600 (UNS N06600)	CP Grade (UNS R50550)
Type 316 / 316L (UNS 31600 / 31603)	Alloy 625 (UNS N06625)	Grade 5 (UNS R56400)
Type 347 (UNS S34700)	Alloy 617 (UNS N06617)	
Duplex (UNS 31803)	Alloy 800H (UNS N08810)	
	Haynes 230 (UNS N06230)	
	Alloy 740H (UNS N07740)	

Parametric Optimization Studies

When designing a MCHE, there are specific parameters that can greatly affect the overall size and cost of the device. The plots below (Figure 1 through Figure 6) explore the effects of zig zag angle, duty overdesign, pressure drop and fouling factor on the overall size and subsequently cost of the heat exchanger. Four parameters were studied for their effects on core volume and mass: zig zag angle, duty overdesign, maximum allowable pressure drop and fouling factor. It is important to note that the cost of a core generally scales with core mass and core volume.

Table 2: Approximate sizes and performance ranges for laboratory and utility scale MCHEs.

Laboratory Scale	Utility Scale
Single Core Units	Multi-Core Units
Typically <1MW	Typically 1 to 40+ MW
100kg to 2,000kg	+2,000kg

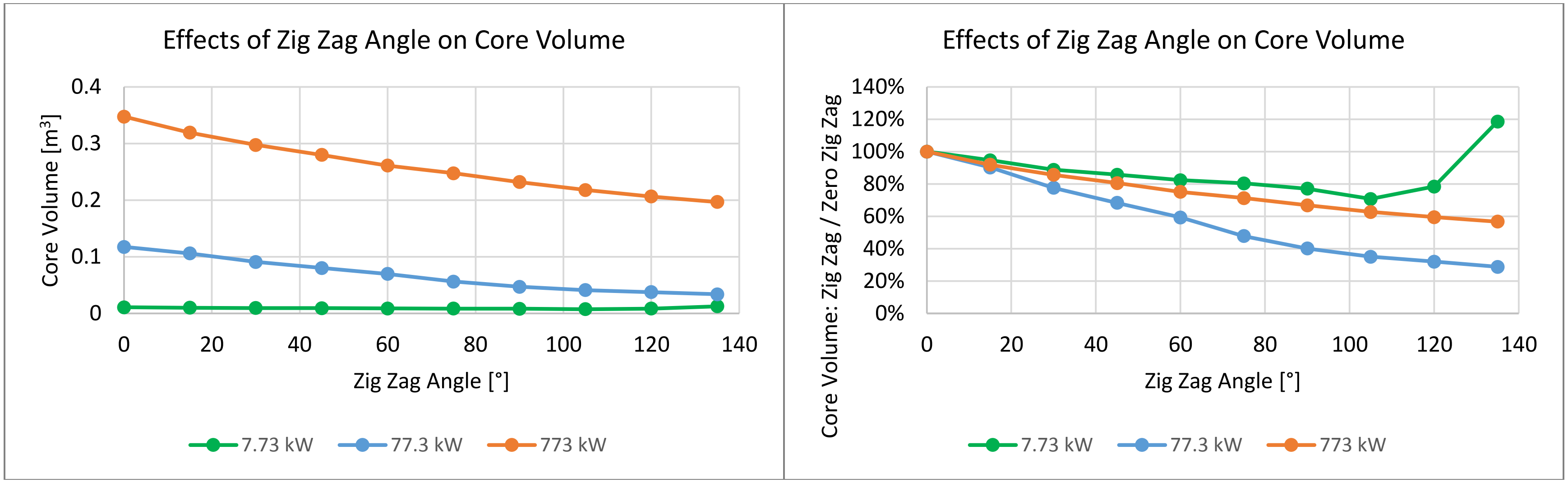

Figure 1: The effects of zig zag angle depend on the capacity (duty) of the heat exchanger. For both the 77.3 kW and 773 kW systems, the core volume decreases with increasing zig zag angle. This is true for 7.73 kW as well, except for angles of 120° to 140°.

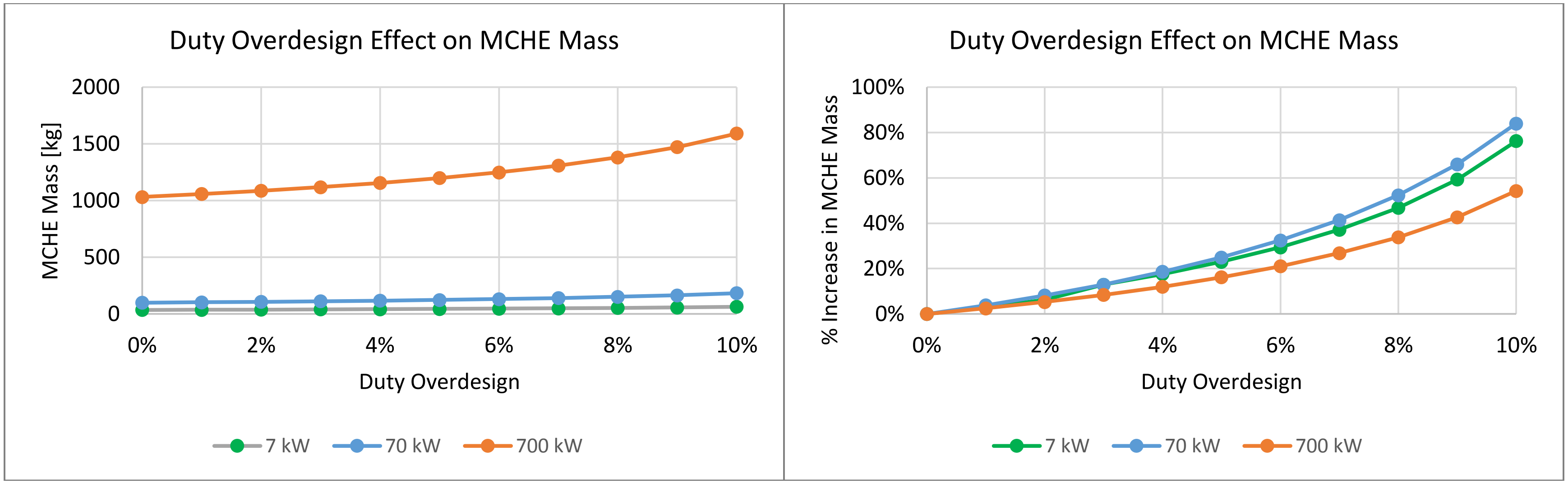

Figure 2: Increasing the duty overdesign increases the total heat exchanger mass for all systems: 7 kW, 70 kW, and 700 kW.

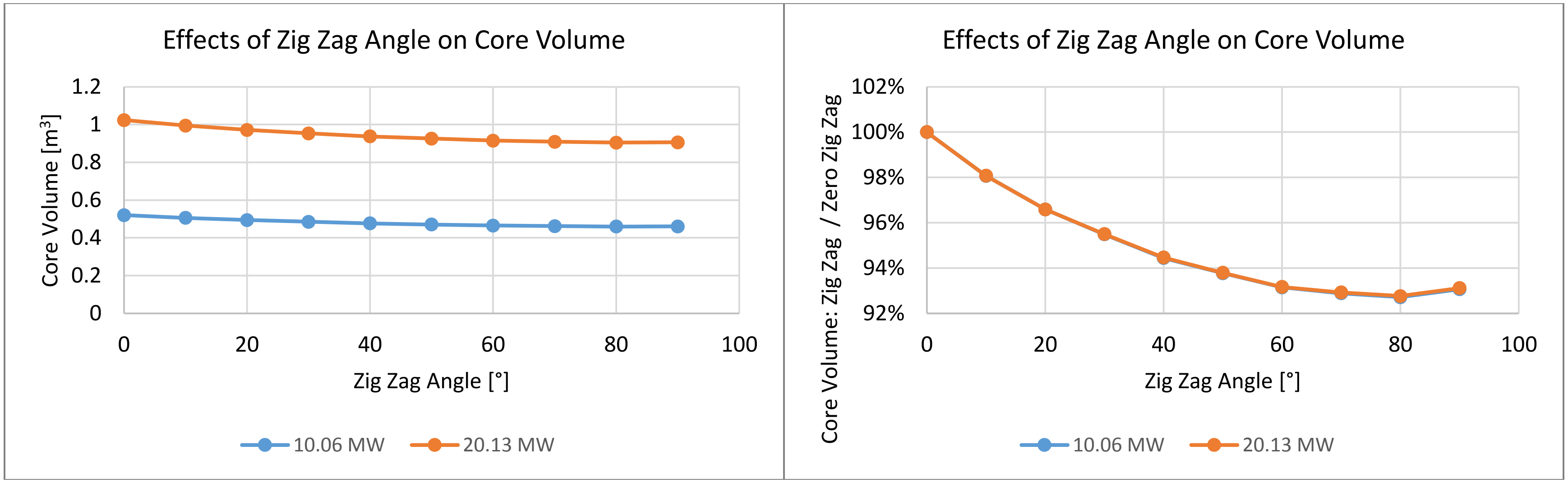

Figure 3: The effects of zig zag angle depend on the capacity of the heat exchanger. For both the 10.6 MW and 20.13 MW system, the total core volume decreases with increasing zig zag angle (and typically with a greater pressure drop).

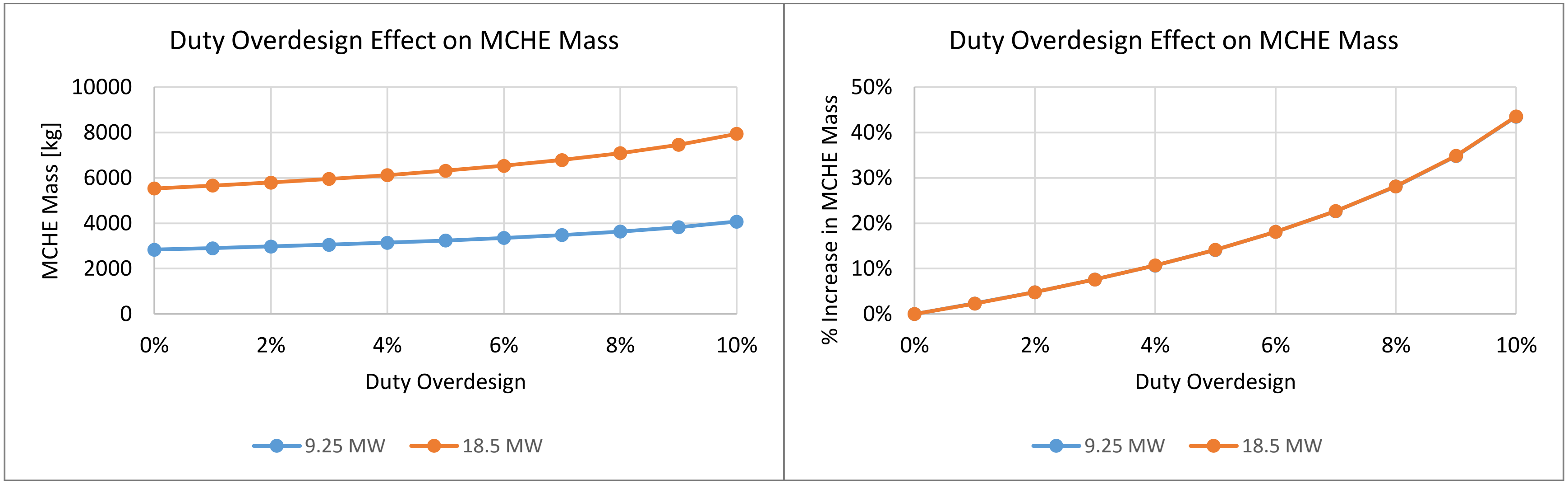

Figure 4: Increasing the duty overdesign increases the total heat exchanger mass for all systems: 9.25 MW and 18.5 MW.

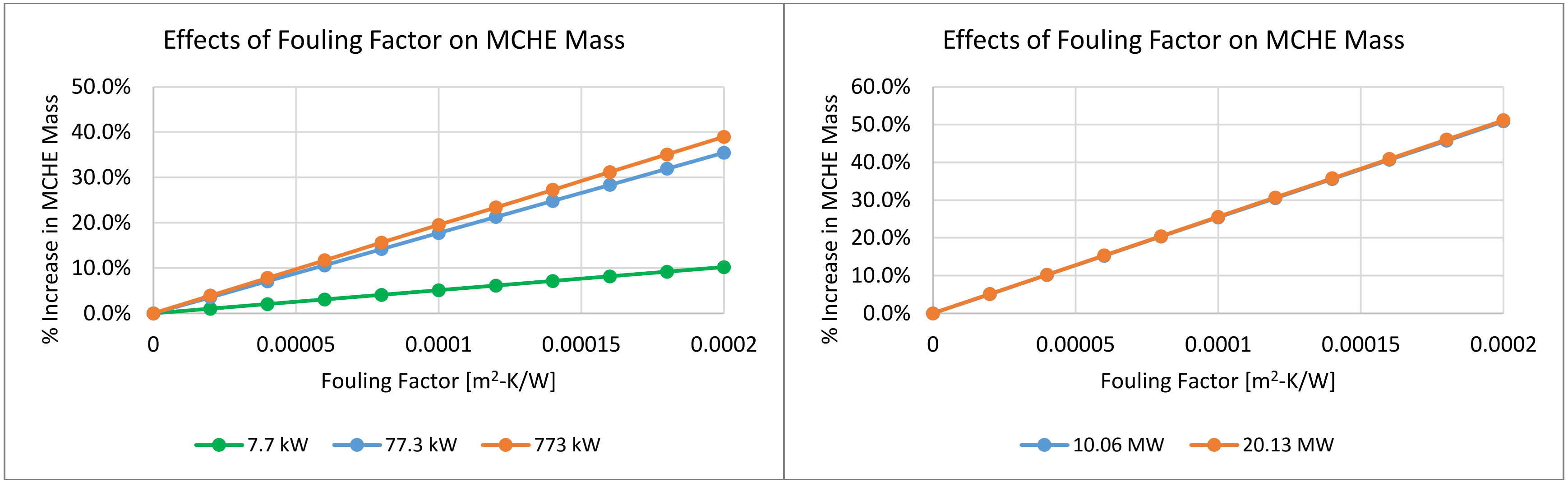

Figure 5: Increasing the fouling factor increases the total heat exchanger mass for all systems: laboratory scale and utility scale.

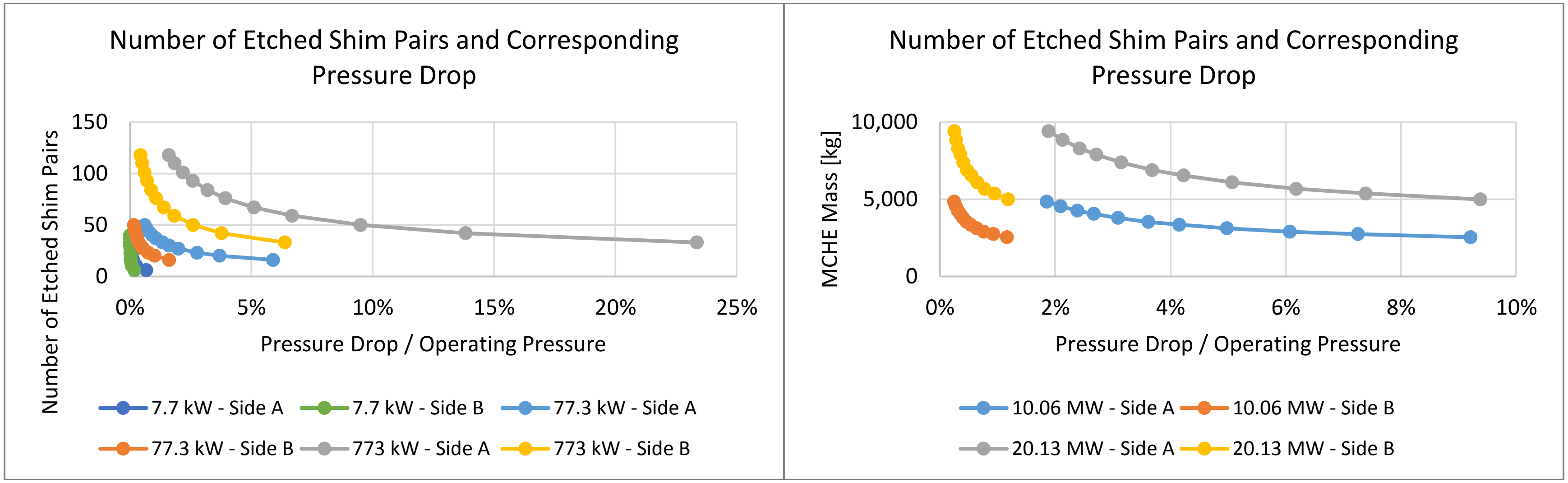

Figure 6: Depending on the operating conditions of the fluids (Side A and Side B), the higher the pressure drop the smaller, and less costly, the MCHE.

About VPE

The development of MCHEs benefits from the outstanding and unmatched facilities, and from the decades of diffusion bonding experience, of Vacuum Process Engineering (VPE), Inc. VPE has developed proprietary bonding methods and manufacturing processes, including building hydrocarbon processing units, gas-to-liquid conversion devices, and waste energy recovery heat exchanger recuperators. VPE has extensive experience in engaging R&D endeavors that lead to low, medium and high volume production-level work. The newly expanded Sacramento manufacturing facility covers 120,000 square feet and the Massachusetts manufacturing site is home to the world's largest vacuum hot press (VHP). With VHP and VPE's experience in diffusion bonding, MCHE manufacture for utility-scale applications is possible. Certifications include AS9100:2009 rev C, ISO 9001:9008, ASME Sect. VIII Div.1. (Pressure Vessel U and UM-Stamps), ITAR registration and many industry and customer-specific certifications.