UCRL-CONF-204471

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June 3, 2004

24th AIAA Aerodynamic Measurement Tech and Ground
Portland, OR, United States
June 28, 2004 through July 1, 2004

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The RDHWT/MARIAH II energy addition, run time, and mass flow rate requirements imply large air and nitrogen fluid volumes at the highest practicable static enthalpy. The objective of the gas supply concept development is the satisfaction of ultra-high pressure (UHP), high temperature thermodynamic requirements in a facility with acceptable safety and economic risks. The primary challenges for the mechanical design are connecting multiple volumes at pressures greater than 1,400 MPa and temperatures greater than 500 K; fabricating high strength steel sections approximately 2 m in typical dimension, and reacting the pressure-related forces in the system. In the "octahedral module" concept, four UHP intensifiers and two UHP manifolds are arranged in an "octahedral" geometry that results in acceptable deviatoric stresses at cross bores. Multiple modules join to provide the required UHP volume at a stagnation pressure of 2100 MPa and stagnation temperature of 750 K.

I. Introduction

The Radiatively Driven Hypersonic Wind Tunnel/ Magnetohydrodynamic Accelerator Research Into Advanced Hypersonics (RDHWT/MARIAH II) energy addition, run time, and mass flow rate requirements imply large air and nitrogen fluid volumes at the highest practicable static enthalpy. The objective of the gas supply concept development is the satisfaction of an ultra-high pressure (UHP), high temperature thermodynamic requirement to provide 30% to 40% of the required flow energy in a facility with acceptable safety and economic risks. The primary challenges for the mechanical design are connecting multiple volumes at pressures greater than 1,400 MPa and temperatures greater than 500 K; fabricating high strength steel sections approximately 2 m in typical dimension, and reacting the pressure-related forces in the system. Further, the economics of capital construction, operational costs, and amortization of the UHP hardware over its fatigue lifetime introduce additional constraints on the design. Fortunately, UHP design principles are well understood; and sophisticated, finite element analysis (FEA) computer codes can model the thermal and mechanical responses for complex geometries. Both full- and sub-scale experiments to explore new UHP ideas reduce further the financial and Environmental, Safety, and Health (ES&H) risks.

The Medium Scale Hypersonic Wind Tunnel (MSHWT) has a performance goal of true air, Mach 12, q = 2000 psf flow in a 1 m diameter test section for run times in excess of 10 seconds. Companion papers[1,2,3,4,5,6] describe the MSHWT concept and the energy addition subsystem. This paper contains a description of the design concept for the UHP gas supply.

II. UHP Subsystem Design Approach

Maximizing the enthalpy at low entropy in the UHP gas source drives the gas supply subsystem design to ultra-high pressure (P > 1000 MPa) and high temperature (T > 500 K). Material properties, operability, lifetime costs, wind tunnel systems integration, and a low-to-moderate risk design strategy constrain the pressure-temperature design envelope. A total static enthalpy target of 2500 kJ/kg for the MSHWT guides the selection of a specific operating pressure and temperature, which has evolved to (2100 MPa, 750 K) for the air stagnation condition. The challenges that must be met by the design are the high deviatoric stresses in the UHP containers, the degradation of materials properties owing to the high operating temperature, and the material reactivity owing to the high oxygen fugacity. Further, owing to the real gas properties of the dense air (stagnation density ≈1200 kg/m^3), the high

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stagnation enthalpy results in a recovery temperature in excess of 1600 K at the nozzle throat wall, requiring some means of protecting the throat wall from the high fugacity oxygen in the air flow. An outer, coaxial flow of cooler, relatively inert nitrogen separates the hot, reactive air flow from the nozzle wall; but introduces significant complexity to the UHP design. Finally, these exceptional challenges overlay the usual difficulties in UHP operations owing to seals, friction, force reaction, and containing blast and fragments in off-normal events.

Steady MSHWT total flows of the order of 160 kg/s for run times of 1 to 10 s define the total system volume of approximately 0.2 m^3 for each second of flow in a single cycle process. The basic building block for this volume is a UHP intensifier, shown in Figure 1. The intensifier consists of a low pressure volume (1(b)) in a low pressure ram, a UHP volume (1(f)) in a UHP container (1(e)), and low pressure (1c)) and UHP pistons (1(d)) that connect the two volumes. The force on the UHP piston is a balance of the low pressure acting on the large area of the low pressure piston and the high pressure acting on the small area of the UHP piston. A selected length/diameter ratio of about 12 for the UHP piston; and a maximum bore diameter of about 200 mm for the UHP container, limited by the fabricability of large forgings of high performance steel, defines the size and number of UHP intensifiers. Fabrication, operability, and gas supply subsystem costs result in selection of a three layer compound cylinder approach for the UHP containers. Environmental, Safety, and Health (ES&H); operability; and gas supply subsystem costs result in selection of a 35 MPa nitrogen storage system for the process energy and an approximately 100:1 pressure ratio for the UHP intensifier.

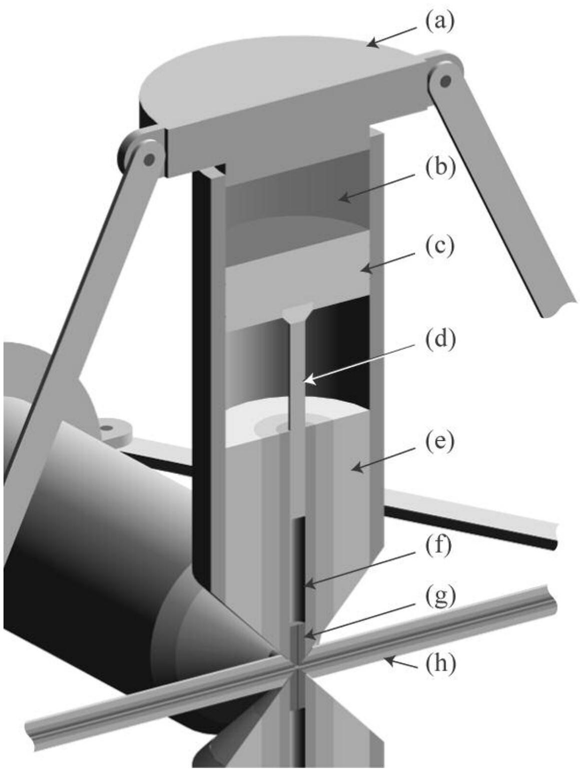

Figure 1 UHP intensifier. (a) hydraulic ram end closure, (b) low pressure hydraulic fluid, (c) hydraulic piston, (d) UHP piston, (e) 3-layer, compound cylinder UHP vessel, (f) UHP gas, (g) UHP end closure, and (h) UHP manifold.

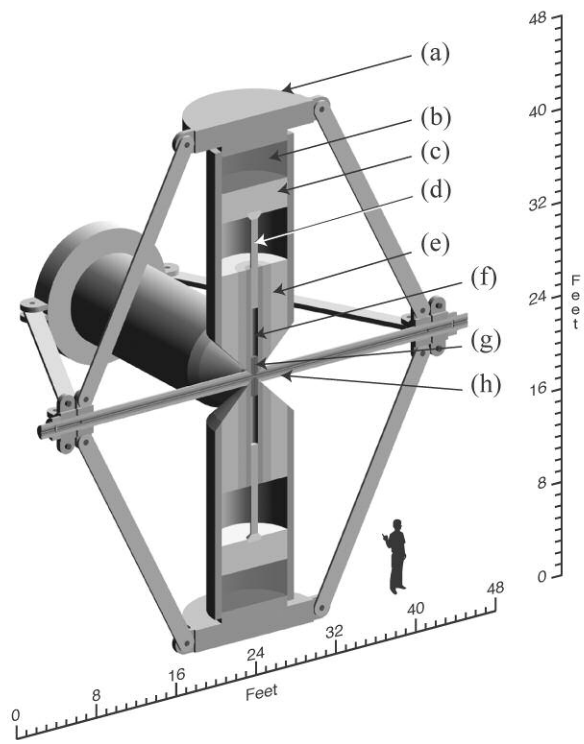

Figure 2 A cutaway schematic of the MSHWT design concept "octahedral" module. (a) hydraulic ram end closure, (c) hydraulic piston, (d) UHP piston, (e) 3-layer, compound cylinder UHP vessel, (f) UHP gas, (g) UHP end closure, and (h) UHP manifold.

Joining UHP volumes in a geometry that meets other systems requirements implies cross bore connections, which break the desirable cylindrical symmetry for UHP design. Cross bores cause a stress concentration that reduces the maximum design pressure using a compound cylinder approach. Thus the first challenge to be met is joining multiple intensifiers with acceptable deviatoric stresses in the cross bore region. The solution to this problem has evolved steadily, resulting in an "octahedral module" approach that meets the current MSHWT UHP subsystem requirements. In the octahedral module concept, four UHP intensifiers and two UHP manifolds are arranged in an “octahedral” geometry to form a module, shown in Figure 2. Figure 3 shows how multiple modules connect to make up the required total volume and mass for a process gas. Figure 4 shows how the air and nitrogen process gas streams join and form the coaxial flow through the nozzle using two, additional special purpose modules.

Whereas the intensifier octahedral module satisfies the total UHP volume requirements for the air and nitrogen process streams, the UHP subsystem requires two other UHP components and a low pressure energy storage, distribution, and control infrastructure. The first of the UHP components is a means of dealing with the strict geometry requirements of the linear modular arrangement. In Figure 4, a “transfer module” collects the air flow from the linear array of UHP air modules and turns it 90° into a manifold along the wind tunnel nozzle axis. This module is somewhat smaller than the gas supply modules and does not contain UHP intensifiers. The manifold connects to the second, additional UHP component, the “nozzle module,” which a) collects the nitrogen flow from the linear array of UHP nitrogen modules, b) joins the air and nitrogen flows coaxially, and c) makes the connection to the wind tunnel nozzle.

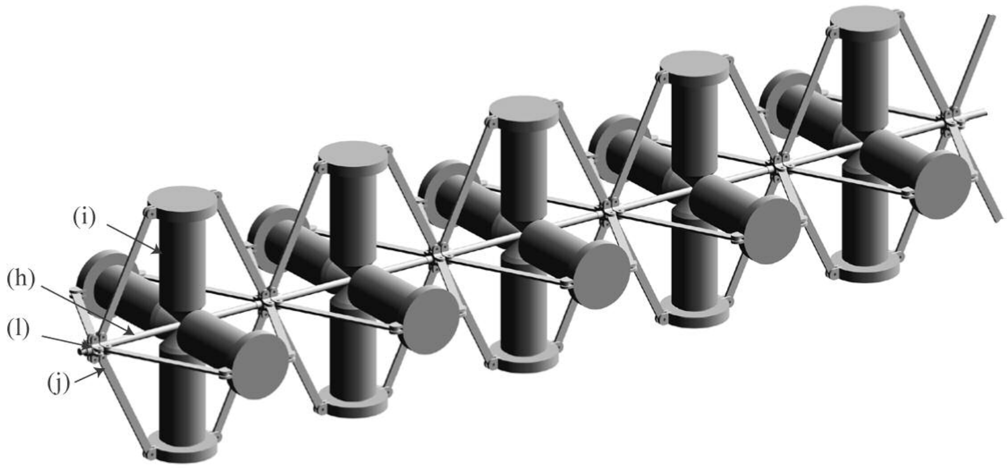

Figure 3 Connection of *n* octahedral modules to make up the required UHP gas volume. A module may be disconnected easily from adjacent modules for servicing.

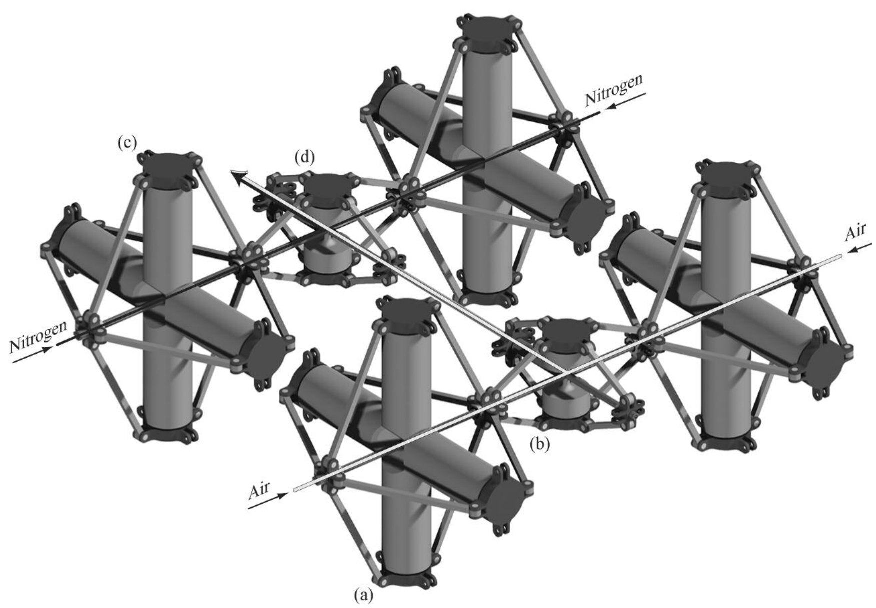

Figure 4 Transfer and nozzle modules. (a) UHP air supply octahedral module, (b) transfer module, (c) UHP nitrogen supply octahedral module, and (d) nozzle module. The transfer module collects the air flows and redirects them along the axis of the wind tunnel. The nozzle module collects the nitrogen flows, converges them coaxially around the core air flow, and passes the coaxial flow to the nozzle.

III. UHP Subsystem Major Components

A. Octahedral Gas Supply Module

The "octahedral" geometry* directs the pressure-related forces along the axes of the four UHP intensifiers to provide a nearly hydrostatic stress where the intensifiers and two UHP manifolds (UHP pipes) join. In Figure 1, the end closure of the hydraulic ram in a UHP intensifier (1(a)) is free to move axially. The pressure force on the end closure, which owes to the low pressure hydraulic fluid driving the ram and is proportional to the pressure in the UHP vessel, is reacted by two load frame tie rods, shown in Figure 2. One tie rod from each of the four intensifiers connects to a collar on a manifold. One manifold reacts half the total axial forces of the four intensifiers using a 2:1 tie rod:manifold length ratio. Whereas a UHP intensifier is force neutral (except for gravitational forces), the end closure of the intensifier (1(g)) is free to move axially in response to the pressure forces owing to the UHP gas; just as the end closure to the hydraulic ram is free to move in response to the low pressure hydraulic fluid. The axes of the four UHP end closures lie along two perpendicular axes in a plane, meeting in the cross bore region at the origin. The two manifolds lie along a line normal to this plane and also meet in the cross bore region near the origin. The forces on each of these six components have the same magnitude, within variations owing to friction and mechanical tolerances, so that the contact stresses they produce can be adjusted and balanced to provide both a low deviatoric stress and pressure seals at the interfaces in the cross bore region. The Finite Element Analysis (FEA) of the cross bore region shown in Figure 5 demonstrates this idea.

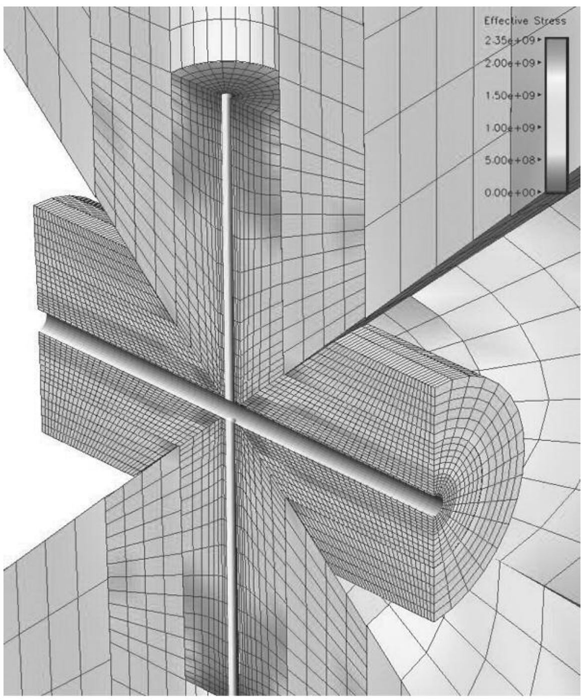

Figure 5 FEA of the octahedral gas supply module cross bore region at a gas pressure of 2100 MPa. The end closures of the four UHP intensifiers and the three layer compound cylinder manifolds meet to form a cross bore. Gas from the intensifiers flows through the manifolds to adjacent gas supply modules. The von Mises stresses in the cross bore region are within the allowable stress of the pressure vessel material. The contact stresses between the components are greater than the gas pressure.

Two important features of this geometry are passive control of the stresses in the cross bore region and the self-alignment of the six UHP components. A disadvantage is the vulnerability to buckling, as the arrangement is similar to trying to join six pencils at a point. The seals at the interfaces between the intensifier end closures and manifolds are "brute force" pressure seals, which require the normal stress at the interface to be greater than the pressure. In conventional laboratory-scale UHP work, these seals have a pressure limit of about 1400 MPa owing to strength of materials. In this design, however, the normal stress at the interface increases in proportion to the gas pressure inside the cross bore, so that the deviatoric components of the total stress at all gas pressures are well within the failure curve of the material. The self-aligning feature, which ensures the normal stresses at the junction interfaces are similar as the pressure changes, owes to the octahedral symmetry, the axial degree of freedom of the intensifier end closures, and the fact that the pressure-related forces are much larger than the gravitational forces. However, the possible instability to buckling of the intensifiers and operational convenience in assembling, testing, and moving the gas modules require surrounding the intensifiers and manifolds with a space frame (not shown). The space frame provides rigidity in the buckling directions, but must have a degree of freedom along the axis of each intensifier and manifold. The frame also provides a means to satisfy module seismic stability and movement requirements. These are non-trivial, since a MSHWT octahedral module having a 200 mm bore diameter UHP vessel weighs more than 1 MN (110 tons). Further, the space frame defines a volume "foot print" for the module, which can be used to house such infrastructure components as the low pressure

* The MSHWT module three perpendicular axis geometry, strictly speaking, does not have octahedral symmetry. Nevertheless, it is convenient to describe the geometry as "octahedral."

vessels that store the process energy.

Figure 3 shows how multiple modules may be joined to provide the required UHP volume for the process gas. Although each module is force neutral (except for gravitational forces), thermal and elastic strains result in large displacements that require a degree of freedom along the line of modules.

B. Transfer Module

Adjacent air supply modules join at the ends of their respective manifolds. (The manifolds are UHP pipes that transfer the working fluid from one UHP module to another, then to the nozzle.) This means the assembly of modules required to provide the total gas mass must be linear or, at least, have linear segments that must be connected at right angles because of the octahedral cross bore geometry. This geometry constraint becomes important when laying out the MSHWT facility, since it precludes arrangements that make better use of floor space and reduce the cost of the building housing the UHP gas supply. If the air mass requirement results in more than one air UHP module, a "transfer module" directs the flow from the arrangement of air modules to a "nozzle module," described in Section C. The transfer module, shown in Figure 4, functions primarily as a right angle connection (a 2100 MPa "cross") that changes the direction of the UHP air flows. In this module, which is smaller than a UHP gas supply module, two hydraulic ram components provide the forces along two of the six octahedral directions. UHP manifolds provide the forces in the four remaining directions, and the tie rod geometry of the external load frame adjusts distribution of the forces from the rams. The low pressure supplied to the hydraulic rams is the same as to the UHP gas supply modules, so the normal stresses that provide the stress balance and sealing functions at the octahedral junction of the module are the same as in the gas module.

At least two of the four manifolds in the transfer module are used for gas flow. The remaining can be used to connect one or two other linear arrays of UHP modules or for other purposes. These include 1) bringing to ambient the electrical signals from diagnostics in the UHP environment, 2) pressurize or de-pressurize the UHP volume in normal and off-normal conditions, and 3) pass a mechanical linkage from ambient to the UHP environment. All of these functions are necessary in the complete MSHWT design, although some may be satisfied using the single free manifold at the terminating UHP gas supply module in a linear array.

C. Nozzle Module

The "nozzle module," shown in Figure 4, is the second, special purpose octahedral module in the MSHWT UHP gas supply. Its three functions are to 1) combine the flows from the UHP nitrogen modules, 2) join this nitrogen flow coaxially to the core air flow, and 3) connect the UHP gas supply system to the downstream section of the wind tunnel. This third requirement is extraordinarily challenging since the space within a distance of about 50 cm of the nozzle throat must accommodate a 2100 MPa, 750 K, 160 kg/s coaxial fluid flow; a nozzle that supports a flow with a unit Reynolds Number of the order of 10^8 m^{-1}; and a multi-Tesla magnetic field that focuses the counter flow electron beam into the core air flow. One of the design assumptions for the MSHWT nozzle is that no existing material or surface treatment for the nozzle wall can sustain the high temperature, high fugacity oxygen in the air flow. The present solution to this problem is to surround the hot, core air flow with a cooler flow of nitrogen, which has a lower recovery temperature at the nozzle wall, significantly less reactivity with candidate nozzle materials, and will quench oxidation ignition events at the nozzle wall. The latter feature is particularly useful, since it is likely that some oxygen will diffuse from the core air flow to the nozzle wall and that perturbations in the electron beam entering the nozzle throat from the downstream portion of the nozzle will result in collision of high energy electrons with the wall.

The nitrogen mass flow is about the same as the air mass flow, so the arrangement shown in Figure 4 satisfies these functions. The manifold from the transfer module connects to a nozzle module manifold along the nozzle (and wind tunnel) axis. The connection, which uses pressure seals similar to others in the UHP subsystem, constrains the air flow to a central pipe. The nitrogen flow comes through the two manifolds orthogonal to the air flow manifold into the coaxial region outside the pipe. It stagnates at this point, then flows coaxially and joins the air flow at the nozzle converging section, as shown in Figure 6. Minimizing the mixing of the converging air and nitrogen flows upstream of the throat implies keeping their pressures equal, so that the central pipe separating them does not have to sustain a high differential pressure. However, the temperatures of the two flows may differ by as much as 100 K, so the pipe must support as large a radial thermal gradient as possible.

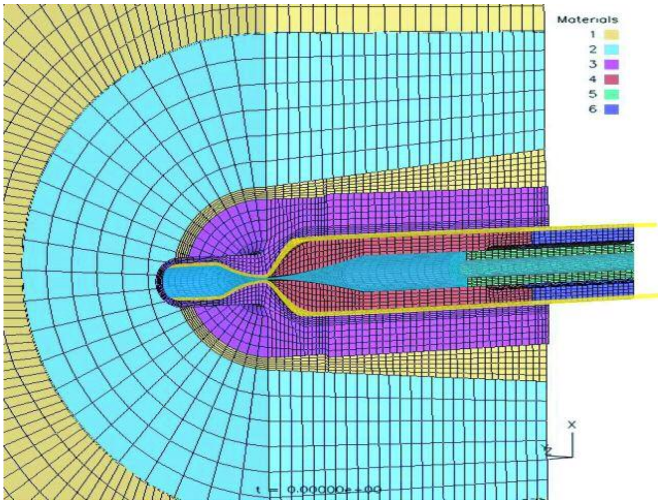

Figure 6 UHP coaxial nozzle. The core air flow and coaxial nitrogen flow join upstream of the nozzle throat. The upstream pressure is 2100 MPa, and the nitrogen and air flows are at different stagnation temperatures. A multi-Tesla magnet provides a solenoidal field at and downstream of the throat.

The third major function of the nozzle module is to connect the UHP gas subsystem to the downstream section of the wind tunnel. This is another area of high complexity resulting from conflicting requirements. The first of these arises from providing a strong focusing magnetic field for the electron beam in a UHP gas at the nozzle throat. The gas pressure in the converging section of the nozzle is 2100 MPa and then falls to about 550 MPa at the nominal 1.2 cm-diameter nozzle throat and remains at about 200 MPa for about 20 cm in the downstream energy addition region. The confining magnetic field in this region is solenoidal and coaxial to the nozzle, with a maximum strength of several Tesla near the throat. It likely will be generated using a superconducting magnet with a limit on the magnet core open space of about 10-15 cm. This means the pressure vessel containing the 2100 MPa, 750 K flow has a marginal outside diameter/inside diameter ratio of near 10. Fortunately, use of paramagnetic materials for the nozzle is permitted, since the saturation time for the field is short compared to the flow time. The second conflicting set of requirements owes to the high unit Reynolds number of the flow and the assumption that the nozzle will have to be serviced frequently. The high Reynolds number requires exceptional nozzle surface smoothness (a figure of merit is a few tenths of a micrometer) and servicing implies removing the nozzle from the wind tunnel. Additionally, since the nozzle represents one "end closure" termination of the pressure manifold, the design must provide for reaction of an axial pressure force of about 20 MN (4 (10^6) lbf). Further, present schemes to contain the air and nitrogen at about 300 MPa before the operating cycle to 2100 MPa involve a flow starting valve either immediately upstream or downstream of the throat. The connections on the upstream, UHP end to the nozzle module and the downstream end to the remainder of the wind tunnel must meet these requirements with acceptable operating costs.

IV. UHP Technology Demonstration Experiments

The high symmetry inherent in UHP design and state-of-the-art FEA codes significantly reduce the risk in the UHP subsystem design. However, none of the high risk components has been demonstrated at 2100 MPa and 750 K in air, even on a laboratory scale. The RDHWT/MARIAH II research plan provides for several technology demonstration experiments that reduce risk in the specification for the MSHWT:

1. A2 LITE. A single UHP intensifier, having a bore diameter of 63.5 mm (about 0.3 of the MSHWT intensifier) and operated to 2000 MPa and 750 K. It demonstrates the compound cylinder design, a moving UHP seal, and control of the energy flow from the low pressure nitrogen storage to the gas flow through the nozzle. Its primary function is to provide a 1 s flow of air for the development of the MSHWT nozzle. [7]
2. MSHWT Component Experiment. Two, MSHWT full-scale manifold sections and end closure that demonstrate, at room temperature, the stationary gland seal, the triangle seal used at the connection between two UHP octahedral modules, the end closure used to introduce the process gas, and the clamping shells used to join octahedral modules and to react the manifold end forces.
3. Subscale Octahedral Module Experiment. An approximately 1/8th scale octahedral intensifier module that demonstrates the UHP seals at the cross bore region and the mechanics of the octahedral geometry.
4. A2 LITE Modified. Addition of a second A2 LITE system to provide steady flows of air and nitrogen through a coaxial nozzle at 900 MPa and 750 K for 1 s.
5. Integrated Test System. A Mach 10 facility operating at 900 MPa and 750 K for 1 s with a q = 2000 psf in a 380 mm test section.

D. MSHWT Component Experiment

The MSHWT Component Experiment consists of three major components: a) two 2100 MPa, three layer, compound cylinder UHP vessels; b) a hydraulic ram; and c) an end closure containing a 2100 MPa valve. The connection between the two UHP vessels is the same as for the MSHWT full-scale design connection between the manifolds of adjacent gas supply modules. The remaining opening for one vessel contains a gland seal that permits relative motion between the UHP piston and the vessel. The remaining opening for the second vessel contains a MSHWT full-scale, 2100 MPa valve. The valve is a "brute force" design, in which a commercial hydraulic ram forces a tungsten carbide stem into a tungsten carbide seat. It permits isolation of the UHP volume during the operational cycle after pre-charging with the process gas. It also provides a means of releasing the process gas in off-normal conditions. The hydraulic ram provides a MSHWT-design 100:1 pressure intensification through a tungsten carbide UHP piston having a MSHWT-design length/diameter ratio. Four MSHWT full-scale "clamping shells" connect and align the three components; and react the pressure-related forces at the ends of the assembly.

The UHP seal at the connection between the two vessels is a "triangle" seal, which has been demonstrated to 1500 MPa in laboratory-scale fluid systems,[8] and which permits easy separation of an octahedral gas supply module from adjacent modules. This addresses an essential element of the MSHWT design strategy of controlling the operational costs of the wind tunnel UHP subsystem. Since UHP operations at the extremes of material properties in an industrial environment demand a rigorous surveillance and maintenance program, there must be cost effective access to the UHP components, such as pressure vessel bores, seals, and the nozzle. The modular design of the gas supply system permits efficient maintenance and replacement, but is possible only if there exists a reliable UHP seal that connects modules.

Operation of the MSHWT for steady, 2100 MPa flows greater than 1 s requires some means of keeping the plenum pressure constant as mass passes through the nozzle. This is accomplished using a moving piston in each UHP intensifier, which implies a UHP seal that supports relative motion. A classic Bridgman "mushroom" seal, used in the A2 LITE, is reliable, but requires a moving contact with a smooth pressure vessel bore. Since thermal barrier coatings are not likely to survive the more than 1% radial strain of the bore, use of the Bridgman seal implies bore wall temperatures equal to the gas process temperature, degrading the bore material properties and contributing an unwelcome thermal compressive stress at the end of an operational cycle. A "gland seal" is a static seal at the end of the UHP bore that permits use of a bulk insulator between the process gas and the bore, at the cost of an increased bore diameter. One geometry for the seal has been demonstrated on a laboratory scale using a fluid pressure medium,[9] but has not been used with a gas medium. The gland seal in the Component Experiment is a variant of this geometry, suggested by Prof. S. M. Stishov, the Director of the Russian Academy of Sciences Institute for High Pressure Physics.[*] The gland seal in the MSHWT Component Experiment is smaller in outside dimension than the MSHWT design, but has approximately the same annular (outside diameter – inside diameter) and height dimensions.

E. Subscale Octahedral Module Experiment

The fundamental feature of the MSHWT UHP subsystem design is using forces having an "octahedral" symmetry to manage the deviatoric stresses in a cross bore connection. This scheme simultaneously connects UHP volumes and solves the cross bore stress concentration problem. The primary risk is the six UHP "brute force" pressure seals at the contacts between the four UHP intensifiers and two manifolds. The probability of failure owing to this risk is proportional to the total number of seals which, for a baseline Mach 12, 10 s facility, is seventy-two. Demonstration of the sealing concept which underlies the MSHWT UHP subsystem design therefore seems prudent. Risk reduction using a full scale MSHWT octahedral gas supply module is beyond the resources of the RDHWT/MARIAH II research plan, so a subscale module having identical stress fields suffices.

The experiment also addresses the second, somewhat lesser risk of static mechanical stability in normal and off-normal operation. The basic idea of the octahedral geometry is to use an external load frame to convert the four forces owing to pressure in the UHP intensifiers to uniform compressive stresses in the cross bore region. Although static and buckling analyses indicate both stability and self-alignment for the octahedral geometry, further risk reduction, especially in off-normal events such as a catastrophic pressure release, is prudent.

The Subscale Octahedral Module Experiment is a room temperature, stand-alone, approximately 1/8th MSHWT-scale UHP gas supply module. One manifold termination permits pre-charging the working fluid and discharging the fluid in normal and off-normal operations. The second manifold termination is for pressure and temperature diagnostics. The device initially is operated quasi-statically under manual control, although it can be modified for closed loop, dynamic control with an operational cycle time of the order of seconds. Finally, certain off-normal

[*] S.M. Stishov, Private Communication. 6 September 2000.

events, such as a catastrophic loss of pressure owing to a seal failure or fracture of a UHP piston, can be simulated to assess their effects on mechanical stability, noise, and blast.

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This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.