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Revision History

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<th>Revision</th>
<th>Issued</th>
<th>Changes</th>
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Authorizing Document
None.

Authorized Documents
None.

Authorized Committees and Boards
None.
1 Scope

1.1 Introduction
This specification details the technical requirements for the design, fabrication, and factory testing of helium cryogenic (or cold) centrifugal compressors to be used in the Continuous Electron Beam Accelerator Facility (CEBAF) located in Newport News, Virginia and operated by Jefferson Lab (JLAB); also known as the Buyer. These compressors are in series, but do not share the same shaft. The scope of this contract does not include the cold box where these are physically mounted near the supervisory control system. The remote operation of this system shall be through the vendor-supplied interface to the JLAB control system. The vendor shall meet all of the requirements of this specification.

This proposed refrigeration system that incorporates these compressors does not utilize sub-atmospheric warm (ambient) compression. The cold compressor system delivers a positive pressure (nominally, 1.2 bar return flow) to the main 4.5-K cold box and the warm (ambient) compression system does not process any sub-atmospheric flow.

1.2 Hardware and Engineering Deliverables

(1) Cold compressors; turbo-machinery, bearings, thermal isolators, vacuum shell mounting fixture, motor, instrumentation, equipment safety protection.
(2) Motor (variable frequency) drive units.
(3) Active magnetic bearing control and back-up power (if applicable).
(4) All interconnecting hardware; including electrical-instrumentation cables and connectors/feedthroughs and any mating hardware of proprietary connections.
(5) The following deliverables shall be provided as preliminary documents with the proposal (W/P) and as final documents (to be approved by JLAB prior to proceeding with manufacture) at the final design review (FDR) unless stated different by notation. Detailed monthly progress reports shall be provided by the 5th day of each month with an up-to-date project schedule unless substituted by bi-weekly status meetings as agreed upon between parties at the kickoff meeting. The final operation and maintenance manuals and installation instructions shall be provided with the delivery of the equipment.

<table>
<thead>
<tr>
<th>Item</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly progress reports (5th day of each month)</td>
<td>1.2</td>
</tr>
<tr>
<td>Operation and maintenance manuals (with equipment delivery)</td>
<td>1.2</td>
</tr>
<tr>
<td>Installation instructions</td>
<td>1.2</td>
</tr>
<tr>
<td>Drawings, diagrams, schematics and parts lists</td>
<td>1.3</td>
</tr>
<tr>
<td>Project schedule</td>
<td>1.4</td>
</tr>
<tr>
<td>Spare parts list (and pricing)</td>
<td>1.7</td>
</tr>
<tr>
<td>Pump-down process path and control philosophy/configuration (d)</td>
<td>3.1</td>
</tr>
<tr>
<td>Mechanical and electrical design (basis, data, calculations)</td>
<td>3.2</td>
</tr>
<tr>
<td>Fluid and material property standards</td>
<td>4</td>
</tr>
<tr>
<td>Compressor technical data</td>
<td>5.2</td>
</tr>
<tr>
<td>Motor technical data</td>
<td>6.2</td>
</tr>
<tr>
<td>VFD and Magnetic Bearing technical data</td>
<td>7.2</td>
</tr>
<tr>
<td>Cabling/Connectors technical data</td>
<td>8.2</td>
</tr>
</tbody>
</table>
Instrumentation technical data (a) | 9.2
---|---
Repair plan | 11.1
Maintenance plan | 11.2
Past performance history (similar design) (WFP only) | 12
Testing procedures and reports (done at vendor’s facility) (b) | 13.1
Final acceptance test – equipment operation procedure (c) | 13.2
Final acceptance test report (done at JLAB’s facility) (d) | 13.2
Packaging and shipping plan (e) | 15

(a) Calibration sheets shall be provided with equipment or prior to shipment
(b) Due within 2 weeks of test completion and prior to shipment
(c) Due 4 weeks prior to acceptance testing
(d) Due within 2 weeks of final acceptance test completion
(e) Due at FDR

All submittals shall be electronic, clearly legible and in English. Final drawings and documents shall include up-to-date changes and not be red-lined or marked-up. If changes occur, as specifically approved by JLAB, between FDR and the delivery of the equipment, the affected documents shall be updated and re-sent to JLAB immediately after the change has been approved and prior to equipment delivery. It is the vendor’s responsibility to ensure that the provided document can be properly read/viewed. Unless other approved by JLAB, the format shall be as follows:
(a) 2D Drawings: DXF and PDF (both)
(b) 3D Drawings: STP and PDF (both)
(c) Documents: Microsoft Word (DOCX) and PDF (both)
(d) Lists and calculations: Microsoft Word (DOCX) or Microsoft Excel, and PDF (both)

1.3 Drawings
Complete mechanical and electrical/instrumentation/control system drawings shall be provided. Mechanical drawings shall show outline dimensions, all interface/connection dimensions and sizes, a complete parts list. Electrical drawings shall provide details of all wiring and cabling connections and a complete parts list. Modification details shall be provided for commercially obtained parts that have been modified by the vendor.

1.4 Reviews and Schedule
Significant documentation is required with the proposal. Potential vendors are expected to supply preliminary details that are close to the same level expected at the final design review (FDR). The only design review prior to beginning manufacture is the FDR to be conducted 60 days after the receipt of order (ARO). Only, after FDR documentation is approved by JLAB, manufacture of the equipment may commence. All hardware deliverables will be shipped according to an agreed upon milestone delivery schedule that is part of the RFP package. Vendor shall submit a design, manufacturing, inspection and test schedule detailing not only major tasks/milestones but also all sub-tasks/sub-milestones. An updated schedule shall be provided immediately upon a change affecting a major task/milestone.
1.5 Utilities
(a) Electrical power will be supplied as 120 V/208 V/60 Hz and 480 V/3 phase/60 Hz; 480 V/3 phase/60 Hz should be used for loads larger than approximately 1 kW.
(b) For motor cooling, water (if used) will be supplied at maximum temperature of 38 °C from closed loop cooling system and shall be returned at a maximum temperature of 49 °C (11 °C differential temperature) to the cooling system given a maximum pressure drop of 1 bar.
(c) Instrument air will be supplied at a dew point of minus (-) 30 °C and a supply pressure of 5 to 7 barg.
(d) For sealing intercept, helium gas (if used) will be supplied at approximately 3 bar and ambient temperature.
(e) For sealing intercept, vacuum (if used instead of helium gas) will be provided at less than 0.2 mbar.
(d) For a thermal intercept, liquid nitrogen (if used) will be supplied at approximately 4 bar and near saturated liquid condition.

1.6 Certifications
Vendor shall submit welding/brazing procedure qualifications (WPQ’s/BPQ’s), welding/brazing procedure specifications (WPS’s/BPS’s) and procedure qualification records (PQR’s) in accordance with ASME BPVC Sec. IX. Personnel conducting testing of welds shall be certified in accordance with ASME BPVC Sec. V. Personnel conducting other tests required by the specification shall be qualified by the appropriate industrial organization that is recognized by JLAB.

1.7 Spare Parts
Vendor shall provide a complete list of all spare parts with pricing. Description of each spare part shall exactly match the description of the corresponding item on the (required) parts list.

1.8 Exceptions
All the exceptions to the specifications shall be identified by the section number and gathered together and listed in one place under the title “Exceptions” in the proposal. Items that are actually exceptions but are listed elsewhere (i.e., not listed under “Exceptions”) will be ignored. However, all technical data (applicable) must be provided to be considered meeting the specification. It is understood that many of the technical details provided may be considered proprietary and such information will remain confidential and accessible to only those directly involved in the procurement and evaluation.

2 Applicable Documents
American Petroleum Institute (API)
API Standard 617 – Axial and Centrifugal Compressors and Expander-Compressors for the Petroleum, Chemical and Gas Industry Services
American Society of Mechanical Engineers (ASME)
Boiler and Pressure Vessel (B&PV) Code, Sections II, V, VIII (Division 2), IX
National Electrical Manufacturer’s Association (NEMA)
ICS – Industrial Control and Systems Standards
MG-1 – Motor and Generator Standard
State Codes – In addition to the requirements shown or specified, the vendor shall comply with all applicable National codes. However, the vendor shall comply with the requirements shown or specified in this document when Codes, Rules, Regulations, Standards, and Ordinances are not in excess of these requirements. The vendor should also list all the codes the equipment(s) are complied with.

Environmental Conditions – The table below presents the dry and wet bulb temperatures ($T_{db}$, $T_{wb}$) for the Newport News, Virginia area. In the summer, the temperature would be at or above the listed temperature. In winter the temperature would be at or above the listed temperature.

<table>
<thead>
<tr>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{db}$[1]</td>
<td>$T_{wb}$[2]</td>
</tr>
<tr>
<td>99%</td>
<td>97.5%</td>
</tr>
<tr>
<td>-3 °F</td>
<td>1°F</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{wb}$[2]</td>
<td></td>
</tr>
<tr>
<td>1%</td>
<td>2.5%</td>
</tr>
<tr>
<td>90°F</td>
<td>87°F</td>
</tr>
<tr>
<td>73°F</td>
<td>72°F</td>
</tr>
</tbody>
</table>

Notes: Ref. ASHRAE Handbook – Fundamentals
[1] Design dry-bulb temperature and frequency (out of 2160 winter hours in northern hemisphere) which temperature is above the listed value.
[2] Design dry-bulb and mean coincident wet-bulb temperatures with frequency (out of 2928 summer hours in northern hemisphere) which temperature is below the listed value.

3 General

Five stages of cold compression shall be implemented. Each of these stages shall have a vertical shaft orientation and, except for the cold (cryogenic) housing, they shall be capable of being installed (and removed) externally to/from the cold box to which they are a part. That is, once the housing is welded to the cold box shell and to the internal suction and discharge piping, the wheel-bearing-motor assembly shall be able to be installed and removed without affecting the cold box vacuum.

3.1 Basic Process Control Concept

The speed of the first four stages of cold compression will be controlled by the fourth stage’s speed through a (changeable) proportionality constant (i.e., “gear ratio”). The speed of the fourth stage is adjusted via a process control loop to maintain a specified (input) cold compressor mass flow. The fifth stage seeks to maintain either a specified pressure difference (discharge minus suction) or a specified suction pressure (which is normally slightly sub-atmospheric). During the pump-down, the “gear ratios” are adjusted in a manner that ensures zero or positive compressor wheel acceleration (minimal deceleration). The set-point mass flow (for the fourth stage) generally increases to a maximum then decreases to a specified value determined by the anticipated cryogenic load.
Before starting or re-starting cold-compressors, the first stage cold compressor suction volume, which is common to the sub-atmospheric load volume, is re-pressurized to a positive pressure (approx. 1.2 bar), either by ‘back-filling’ (i.e., reverse-flowing) from a main cold box injection port, which can vary from a 5 K to 35 K temperature level or by ‘forward-filling’ (i.e. forward-flowing by vaporizing liquid baths at the load) from the load, which is typically at ~4.5K. There are generally two kinds of pump-downs. A “cold” pump-down is one where the cold compressors are re-started quickly after a back-fill/forward-fill has been accomplished (i.e., sub cooled liquid helium is at the load). A “warm” pump-down is typical if the system has been operating at (nominally) 4.5-K for more than 8 hours; that is, there is little or no sub-cooled helium liquid warming from 2 K to 4.5 K.

Vendor shall provide a proposed pump-down process path for both a “cold” and “warm” pump-down (described above) to reach any given steady operating condition - nominal or maximum capacity (see below) at the FDR. Vendor shall provide complete process path details and complete control philosophy/configuration details. JLAB may choose to implement the proposal (in its entirety), or certain specifics of the proposal, or not implement it at all; and, this decision (by JLAB) shall have no bearing on the vendor’s equipment warranty.

### 3.2 Mechanical and Electrical Design

Compressor mechanical design shall conform to the most conservative interpretation of the intent and guidelines/rules of the ASME BPVC Sec. VIII and API Standard 617. Design values for allowable material strength and fatigue properties shall not be less conservative than set forth in ASME BPVC Sec. II. Vendor shall provide the basis for the mechanical design and all supporting calculations (that verify the integrity of the design) for the components including the inlet and outlet nozzles to the compressor volute / casing. The electrical design shall conform to the NEC. All supporting data and calculations shall be submitted by the vendor that verify conformance to the NEC.

### 4 Process Design and Required Operating Modes

The compressors, motors, bearings and VFD’s shall be designed for the following four modes. A couple of these “modes” are process paths; i.e., the process parameters are changing with time and the starting condition is very different from the ending condition.

NIST Technical Note 1334 shall be used for the evaluation of helium thermo-physical properties. Other required/pertinent fluid and material properties shall be obtained from NIST (or an acceptable equivalent agency). All such standards for fluid and material properties used in the design shall be submitted.

#### 4.1 Maximum Capacity

Helium, 250 g/s, 3.6 K suction, 1.20 bar final (cold compressor train) discharge. The suction pressure shall be less than or equal to 28 mbar and the final discharge temperature shall be less than 30 K. This condition forms the basis for the maximum volume flow and maximum operating speeds.
4.2 Nominal Capacity
Helium, 200 g/s, 31 mbar, 3.8 K suction, 1.20 bar final discharge. The final discharge temperature shall be less than 30 K. This is the nominal turn-down condition and forms the basis for the maximum pressure ratio and safe operating point away from the surge condition.

4.3 Start of Pump-Down
Compressors are initially at a minimum speed (idling), and the suction pressure has been equalized with the discharge pressure at ~1.2 bar, typically by forward filling (from load) with up to 6 K helium. Start of pump-down begins as the compressor’s speed begins to steady increase from this condition until the maximum capacity condition is reached. Note: The individual speed of each compressor will be adjusted to accomplish the pump down, in such a manner that the speed (for each) steadily increases.

4.4 Pump-Down Peak
The compressor suction is sub-atmospheric, but still above the operating level; and, the suction temperature is below ~6 K. The mass flow rate is at a maximum condition and the compressor speed begins to increase more rapidly. Note: The individual speed of each compressor will be adjusted to accomplish the pump down, in such a manner that the speed (for each) steadily increases.

5 Compressors
5.1 Requirements
(a) Each compressor shall have a pressure rating of 4.1 bar differential (process to external/vacuum) between 4 K and 310 K.
(b) Each compressor shall be designed for individual speed control from zero to its maximum speed.
(c) The rotor critical speed shall be at least 30% greater than the speed required for any operating mode, including any condition during pump-down.
(d) A thermal shield may be employed to meet the performance requirements. Liquid nitrogen is preferred as the shield fluid.
(e) Compressors shall be designed and instrumented for efficient operation and control during steady state, transient and process upset conditions; including a pump down.
(f) Compressors shall be designed with all the required safety interlocks, protection devices and instrumentation to protect the compressors and motors from all anticipated equipment failures, utility failures and process upset conditions. Only those failures that will imminently damage the compressors, motors, bearings, VFD’s, etc., shall shut-down the compressors. Although, the shutdown mechanism may be the PLC system (supplied by others), the VFDs shall independently shut down if they detect a failure or (if applicable) a magnetic bearing fails. This includes but is not limited to the following:
   (i) Instrument failure
   (ii) Supervisory control system (PLC) failure
   (iii) Motor bearing failure
   (iv) Compressor imbalance
   The vendor should also provide a list of process conditions (pressure, temperature at inlet and outlets as a function of compressor speeds) at which the equipment needs to shut down.
5.2 Technical Data

Vendor shall provide the following technical data:

(i) Total number of compressor stages
(ii) Pressure rating (from 4 K to 310 K) [bar]
(iii) Impeller, shroud and hub diameters [mm]
(iv) Wheel height (impeller exit width) [mm]
(v) Ratio of rotor maximum design speed to critical speed [percent]
(vi) Maximum rotor design speed [rpm] or [rps]
(vii) Thermal intercept (i) type, (ii) fluid, (iii) process interface requirements (flow, pressure, temperature)
(viii) Complete list and description of all safety interlocks with the related failure (whose occurrence that safety is intended to protect), corresponding process set-points, and associated transducers/switches.

Vendor shall provide the following technical data for each compressor at each required operating mode:

(1) Mass-flow [g/s]
(2) Suction pressure [bar] and temperature [K]
(3) Pressure ratio [non-dim.]
(4) Temperature ratio [non-dim.]
(5) Adiabatic (isentropic) efficiency [non-dim.]
(6) Rotational speed [rpm] or [rps]
(7) Shaft power (to compressor wheel) [kW]
(8) Required motor torque [Nm]
(9) Input power (to motor) [kW]
(10) Heat in-leak [W]
(11) Flow coefficient (provide definition used) [non-dim.]
(12) Velocity triangles for wheel inlet and outlet (diagrammatically with values for velocities and angles); include both no slip and with slip conditions)

At least four significant figures and the units used shall be provided for all numbers/data.

Vendor shall provide a pressure ratio vs. normalized (reduced) exit volume flow diagram with constant normalized (reduced) speed and constant adiabatic efficiency curves; including surge line, choke line, design point(s), with each required operating mode superimposed.

6 Motors

6.1 Requirements

1. Motors

(a) Motors shall be in accordance with NEMA MG-1 and the NEC (NFPA 70).
(b) Motors shall be mounted externally to the vacuum space at ambient temperature and preferably cooled by water. Any other means of cooling shall be approved by JLAB. An intercept guard vacuum and/or helium sealing gas to prevent air in-leak to the sub-atmospheric process shall be provided.
(c) Motors shall be designed with a 30% minimum margin above the required torque for any required operating mode; including the entire pump-down path.
Motor power factor shall be greater than 0.8 from zero to the maximum speed and for all operating conditions.

2. Connectors

Fluid and electrical connections shall be disconnectable (on the ambient air side). They shall be a proven type and tested by the manufacturer at their actual operating conditions.

3. Bearings

(a) It is preferred that motors use a proven oil-free non-contact type primary bearing design; principally, active magnetic bearings (AMB). However, a ceramic ball bearing design used for a comparable application (in load and speed) that has a demonstrated successful operation of more than 5 years, 40,000 hours of MTBF, and less than 8 hrs for MTTR may be considered as acceptable.

(b) Primary bearings shall provide five-axis support (three translational and the two rotational axes perpendicular to the compressor axis of rotation).

(c) For both AMB and ceramic ball bearing designs, the compressor/motor shall be instrumented to detect an imbalance.

(c) AMB power supply shall utilize standard U.S. voltages such as 120 VAC, 208 VAC, 480 VAC etc. and be capable of filtering and smoothing normal variations in the power supply voltage, current imbalance and frequency. AMB shall be equipped with a standard commercially available back-up battery power supply (UPS) or have suitable means of ensuring safe ramp-down of cold compressors upon a power loss.

(d) If AMB’s are used, the motors shall include backup (mechanical) bearings capable of withstanding fifteen (“hard”) landings from their maximum speed due to complete power loss (including back-up batteries) or other malfunction without damage to any parts of the compressor or motor.

6.2 Technical Data

The vendor shall provide the following technical data for each motor.

(a) Motor rated (i) input power, (ii) voltage, (iii) current and (iv) service factor

(b) The following parameters vs. rotational speed: (i) input power, (ii) current, (iii) torque, (iv) power factor and (v) efficiency

(c) Bearing (i) type/size, (ii) stiffness and (iii) life

(d) For a ceramic ball bearing design, the comparable (i) load, (ii) speed, (iii) hours of continuous operation (without failure)

(e) Back-up bearing (i) type/size, (ii) rating (number of landings)

(f) Back-up battery (if applicable) (i) type, (ii) manufacturer, (iii) complete model/part number, (iv) specification

(g) Cooling (i) type, (ii) fluid, (iii) process interface requirements (flow, pressure, temperature).

(h) Connector (i) manufacturer, (ii) type/size, (iii) complete model/part number, (iv) specification.

(i) Intercept (i) connection type/size, (ii) fluid, (iii) process interface requirements (flow, pressure, temperature).
Variable Frequency Drive (VFD)

7.1 Requirements
(a) VFD’s shall conform to the NEC and utilize standard U.S. voltages such as 120 VAC, 208 VAC, 480 VAC etc. and be capable of filtering and smoothing normal variations in the power supply voltage, current imbalance and frequency.
(b) VFD’s shall be capable of operating the cold compressor motors over the entire speed and power range for all motor load conditions and regulating the motor speed to within 0.5% of the VFD output request.
(c) VFD’s shall be capable of continuous output to the motor, even if there is an interruption of incoming power lasting several cycles.
(d) VFD’s shall be capable of quickly bringing compressors to a stop; i.e., “brake” to an idle speed
(e) VFD’s shall be designed to prevent power factor distortion at motor harmonics.

7.2 Technical Data
Vendor shall provide the following technical data:
(a) VFD manufacturer, model/part number, and options
(b) VFD rated (i) power, (ii) input voltage, (iii) input current
(c) VFD output speed vs. power factor (with motor as the load)
(d) Number of supply power cycle drop-outs that can be tolerated for uninterrupted operation.

Cabling and Connectors

8.1 Requirements
All cabling and connectors shall be provided to form a fully functional system. Vendor shall furnish mating connectors for any proprietary cabling and/or connectors (i.e., those made by the subcontractor). If the cabling and/or connectors are obtained from another manufacturer and modified by the vendor, the complete details of the modifications and the manufacturer’s item shall be provided.

8.2 Technical Data
Vendor shall provide the following technical data:
(a) Manufacturer
(b) Part/model number
(c) Dimensions
(d) Specifications
(e) Details of modifications (if applicable)

Instrumentation

9.1 Requirements
(a) Instrumentation and control equipment shall be in accordance with NEMA ICS requirements.
(b) Calibration sheets shall be provided for all instruments.
Any PLC system or components provided by the Vendor shall utilize components from the JLAB PLC standard components list (see below), or shall be specifically approved by JLAB.

1. Processor: 1756-Lxxx (Any Logix L7 Series)
2. Ethernet: 1756-EN2TR
3. Chassis: 1756-A10
4. Power Supply: 1756-PAR2
5. Digital In: 1756-IB16D
6. Digital Out: 1756-OB16D
7. Analog In: 1756-IF16
8. Analog Out: 1756-OF8
9. I/O Cables/Termination Modules: 1492-TBCN, 1492-TBNH
10. Touchscreen: AB2711PT15C4A8

Minimum instrumentation for each compressor stage -
1. Speed (measured)
2. Speed (requested by VFD)
3. Motor winding temperature(s)
4. VFD output voltage, current and frequency
5. Bearing (measured) voltage and current (for AMB’s)
6. Rotor/bearing displacement indication (for AMB’s)
7. Rotor/bearing imbalance indication

**Note:** compressor suction and discharge, pressure and temperature, as well as, utility supply and return conditions are not in the subcontractor’s scope.

### 9.2 Technical Data

(a) For every transducer, provide (i) manufacturer (name, address), (ii) complete model/part number, (iii) specifications.

(b) Calibration sheets (with equipment).

### 10 Quality and Inspection

#### 10.1 Witness Points

JLAB reserves the right to designate selected manufacturing, inspections and/or test as "witness" points. Vendor shall provide key/critical hold and/or inspection points for JLAB and/or JLAB’s representative(s). These hold and/or inspection points shall be submitted and incorporated into the project schedule. At least 4 weeks advance notice shall be given by the Vendor to JLAB.

#### 10.2 Inspection / Surveillance / Audit

The Vendor shall afford JLAB and/or representative(s) designated by JLAB access to the subcontractor’s facilities and those of the vendor’s suppliers for the purpose of inspection, surveillance and audit in order that JLAB’s representative(s) may assure that items are being furnished in accordance with subcontract requirements. The vendor’s and the vendor’s suppliers records and documentation necessary for this function shall be made available for review by JLAB’s representative(s).
10.3 Nonconforming Material or Items
When an article or material is found to depart from the drawing, specifications, tests or other subcontract requirements, and cannot be readily resolved by rework of the item or by scrapping it (at the vendor’s expense), JLAB shall be contacted for written approval of alternative disposition.

11 Reliability and Maintainability

11.1 Repair Plan
The vendor shall provide an expected meantime between failure (MTBF) and meantime to repair (MTTR) for all components. The vendor shall indicate the length of time required to repair a malfunction or to replace the component. This information is required to plan for the downtime required for repair of the system. The vendor shall identify times to repair failures where equipment is in place and/or where equipment is removed to a repair shop. The vendor shall identify and provide complete information for all special tools, equipment and process materials to affect repairs. Vendor shall provide all special tools required for typical repairs and normal maintenance.

11.2 Maintenance Plan
The vendor shall identify all preventive maintenance requirements for the provided equipment, including the frequency, number and skill level of personnel required, as well as, the tool and test equipment required, and process materials required. This shall be organized in groups according to frequency, e.g. daily, weekly, and monthly. Preventative maintenance requirements shall be those necessary to maintain the cold compressors at a reliability of greater than 99.9%. The vendor shall identify and provide complete information for all special tools, equipment and process materials to affect maintenance. Vendor shall provide all special tools required for preventive maintenance.

12 Past Performance History
Vendor shall supply technical data demonstrating past performance for a similar design in both size and process conditions. References of users of such equipment shall be provided; i.e., contact name, phone number, mailing address and (if available) email. This information is required with the proposal (i.e., not at FDR).

13 Testing

13.1 Requirements
The following tests shall be performed by the vendor:
(a) Rotational speed and balance check of compressors from zero the maximum design tip speed. This test shall ensure the mechanical integrity of the all rotating parts and demonstrate that there are no vibrational harmonics adversely affecting the compressor or process stability over the entire operating speed.
(b) Code and sensitive leak (helium) leak check. The process and utility lines/components shall be tested at 10% above their design pressure and (concurrently) leak checked using a helium mass spectrometer with no leaks found at a sensitivity better than $10^{-9}$ mbar-l/s. As applicable below, all fluid lines/components shall be checked:
   (i) Process lines/components to other process lines/components
   (ii) Process lines/components to the (insulating) vacuum
   (iii) Process lines/components to ambient air (as applicable)
(c) Resistance of motor windings and the windings to ground shall be checked.
(d) Resistance of all cabling/connector wires shall be checked end-to-end and from each wire to ground.

13.2 Final Acceptance Tests
Final acceptance testing is to occur at JLAB’s facility. Equipment provided by the vendor is to be integrated into vendor’s sub-system (by others). After completion of installation and when both vendor and JLAB signify that all is ready to proceed, the vendor shall participate in commissioning the system at JLAB’s facility.

A complete, descriptive, chronological and detailed log shall be maintained by the vendor from the beginning of the system startup. Pertinent process data, such as temperatures, pressures, mass flows, and gas purity will be recorded by JLAB’s archival system. The entire system shall operate stably at each of the operating conditions described in sec. 4 for 24 hours.

1. The vendor shall submit all final operational test procedures to JLAB at least 4 weeks prior to the start of acceptance testing for review and approval.
2. The vendor shall provide the services of competent engineers and technicians to participate and conduct the initial startup and operations for the acceptance tests.
3. JLAB will provide competent and qualified support personnel to man stations as required during operations and testing for the purpose of training. JLAB may also assign additional engineers and/or technicians to observe and evaluate the testing.
4. JLAB will supply all helium, electrical power and other utilities for the initial operations and tests.
5. The vendor shall verify that all remote signals associated with the provided equipment are properly indicating throughout each portion of the acceptance test.
6. The vendor shall provide a written report to JLAB no later than 2 weeks after the acceptance testing is complete. The report shall contain the log kept by the vendor, the results of the required testing and the disposition of any anomalies or malfunctioning equipment discovered during the testing.

14 Submittals
Final procedures shall be submitted at FDR for approval, except those for the final acceptance test. Procedures shall clearly indicate the data expected to be obtained (form/format, independent and dependent variables, variable units, calculations/formulas used). Test reports shall be clearly documented, showing actual procedure used, details of auxiliary test equipment used, deviations/abnormalities encountered, actions taken in resolution of deviations/abnormalities, data collected (tabulated and/or plots with all units and variables clearly defined), analysis of data (showing all calculations/formulas) and result summary (supporting the data collected). Test reports shall be professionally written and assembled and shall be provided within 2 weeks after completion of test and before the equipment delivery. Procedures and test reports shall be submitted for:
(a) Rotational speed and balance check
(b) Code and sensitive leak check
(c) Motor winding test
(d) Cabling/connector test
(e) Final acceptance test
15 Packaging and Delivery

All hardware shall be packaged in a manner that precludes damage during shipment and degradation from the environment. This includes precautions and verifications such as hermetic sealing, shipping supports and accelerometers. Cold compressor volutes / casings should be able to be shipped horizontally while installed in a Cold Box (along with associated piping). Vendor shall provide additional support structures (based on mechanical loading – as provided by JLAB) to prevent damage of the volutes/casings during shipping. Packaging and shipping plan shall be provided at FDR (i.e., it is not required with the proposal) and approved by JLAB prior to packaging and shipping. Vendor is responsible for correcting/replacing damage to hardware as a result of packaging and/or shipping.