Instrumentation/Controls/Design Overview

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&

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Tentative Schedule

Chapter	Duration (min.)
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Cryogenic Instrumentation, Controls and Electrical Power

Jonathan Creel

Overview

Today's discussion topics include

- **Power Distribution System Design**
- **Control System Architecture**
- **Cryogenic Sensor Installation**
- **Power conductors in a vacuum**

- **Research and Development**

Main Site Power Feed

- Redundant independent main power feeds.
- Redundant independent main substations.
  - Site can be powered from either substation or power feed during failures or maintenance.
  - Allows continued accelerator operation during power company maintenance actions.
  - Protection against major helium loss.
  - Protection against thermal cycle.

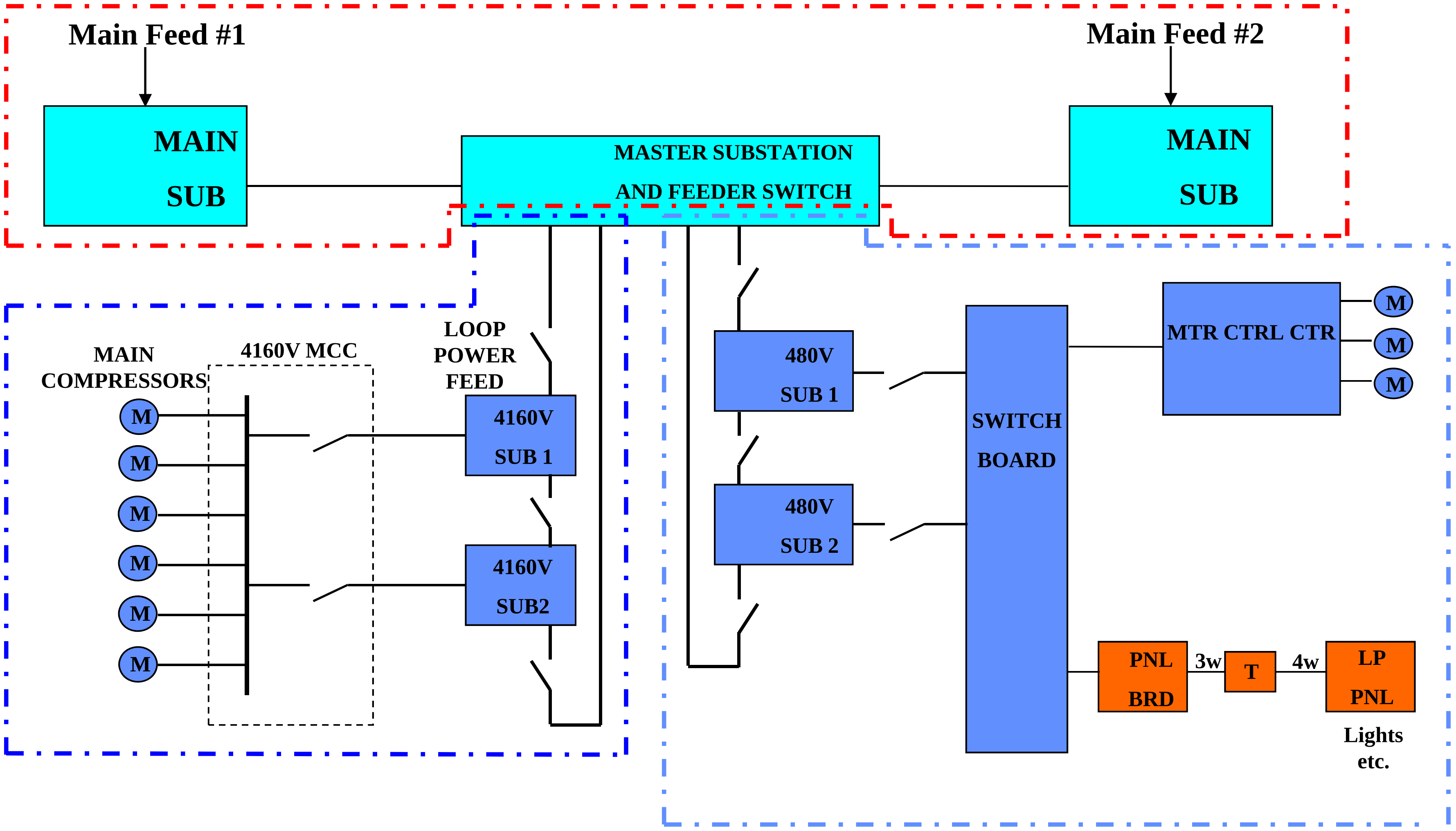
Equipment Feeders

- Dual unit substations feeding a common bus.
  - — Provides continued operation during substation or cabling failures or during maintenance.
  - Substations supplied using loop-feed concept.
  - — Allows full rated power to be supplied through either loop leg during failures or maintenance.
  - Circuit breaker between bus and substation.
  - — Protects bus against substation failures.
  - — Protects bus against substation to bus wiring failures.

480V Equipment Verses Lighting Power

- Use independent 480V 3-wire for equipment.
- Use separately fed 480V 3-wire to 480V 4-wire transformer to provide power for air-conditioning, 277V lighting, etc.
  - De-couples ground fault protection trips for items like lighting from 480V equipment circuits.

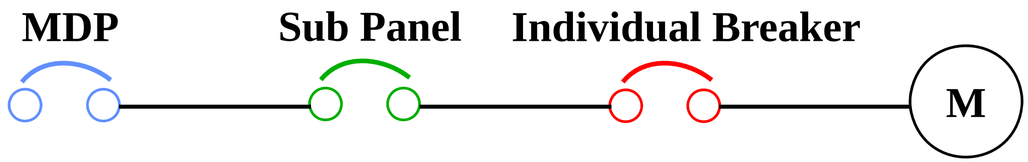
Conceptual


Main Feed #1
Main Feed #2
MAIN SUB
MASTER SUBSTATION AND FEEDER SWITCH
MAIN SUB
MAIN COMPRESSORS
4160V MCC
LOOP POWER FEED
M
M
M
M
M
M
4160V SUB 1
4160V SUB2
480V SUB 1
480V SUB 2
SWITCH BOARD
MTR CTRL CTR
M
M
M
PNL BRD
3w
T
4w
LP PNL
Lights etc.

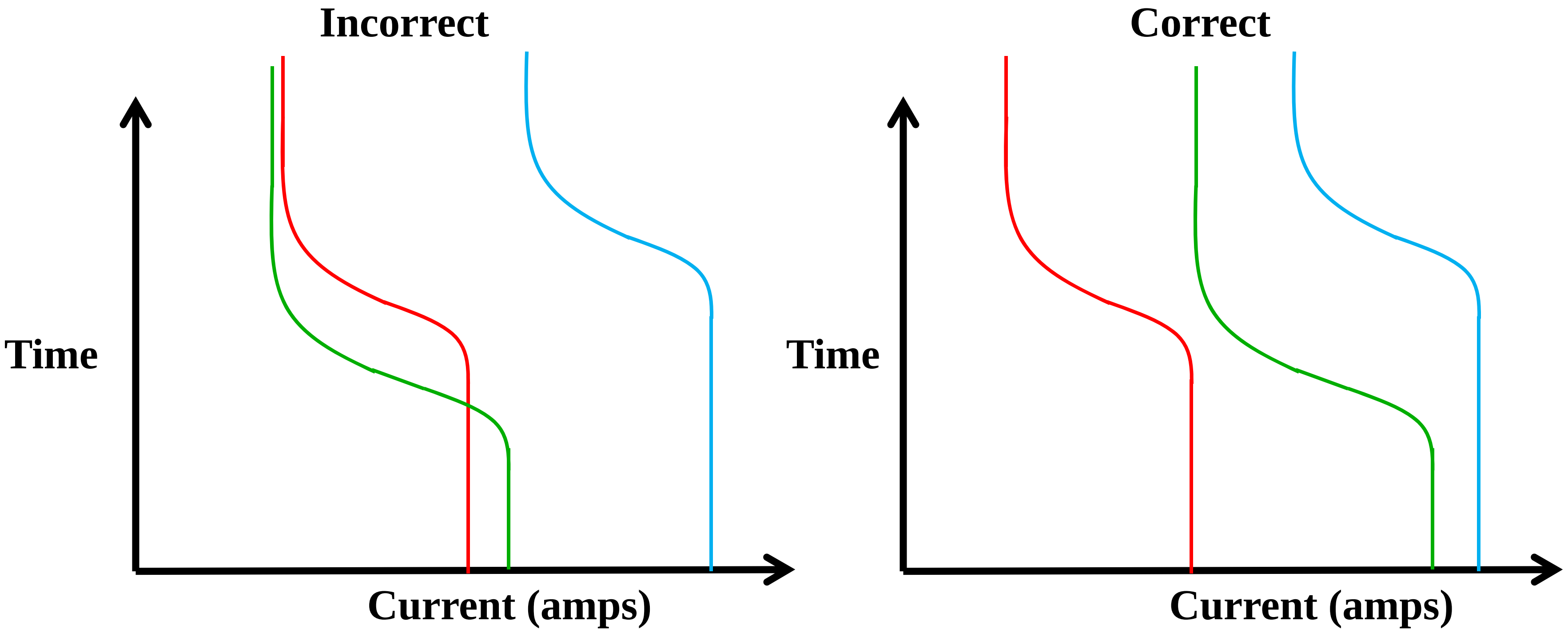
Circuit Breaker Coordination

- Ensure proper coordination study's are done
  - Trip curves for various breakers can have overlapping regions
  - Can result in main distribution panel tripping before a subpanel or individual breaker
  - Set up propagation of breaker trips
  - Keep trips at lowest possible level

Circuit Breaker Coordination



Time Current Curves



Control Systems (Cont.)

Problem Areas

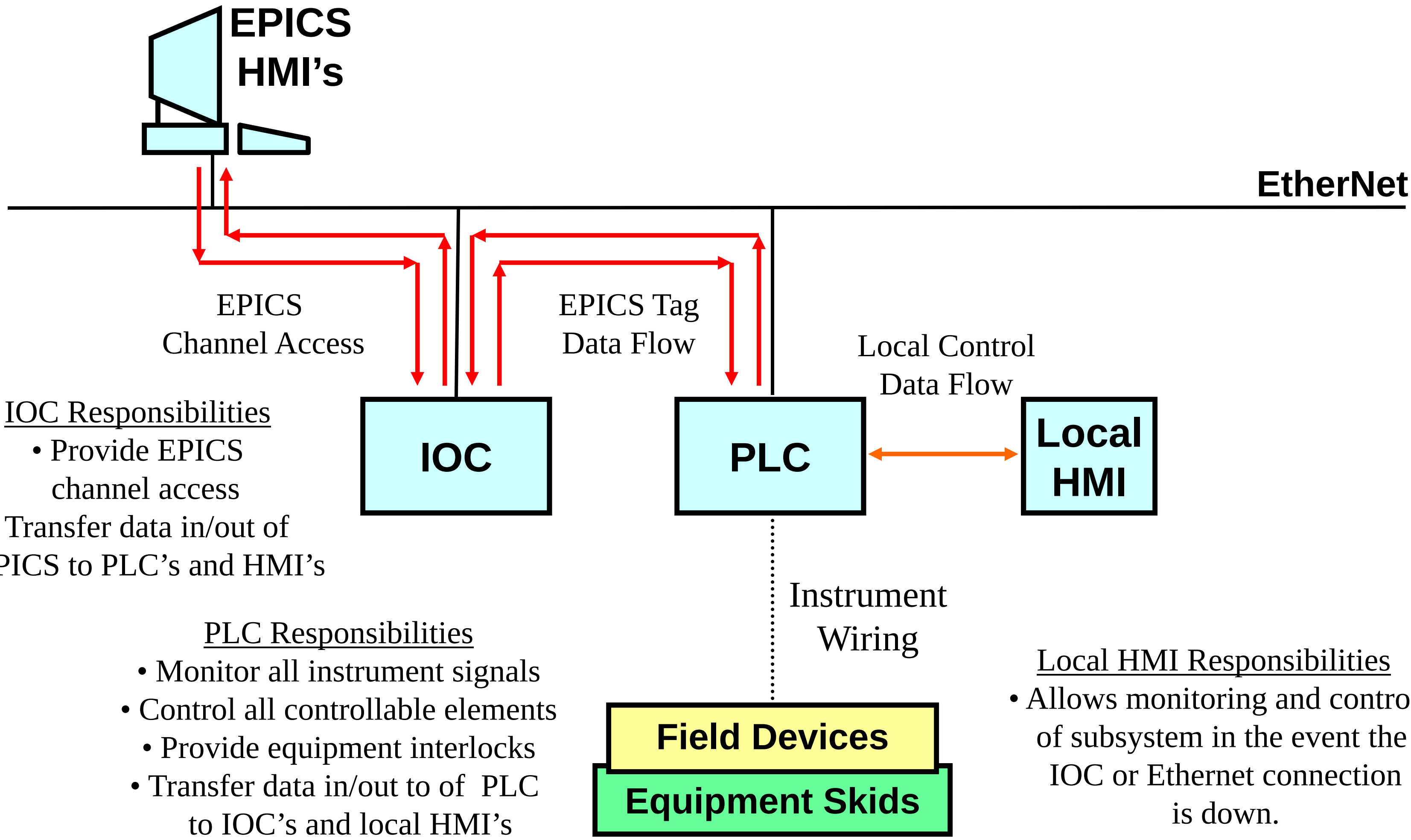
- **Use of non-industrial or laboratory-grade control system components.**
  - **CAMAC**
    - Old technology, large, consumes a lot of power, and generates a lot of heat. Failures increase as ambient temperature rises
    - Not designed for industrial environment
    - Difficult to maintain as parts become more scarce
    - Highest failure rates in control system
      - Crate controllers and power supplies
  - **VME**
    - Large
    - Not designed for industrial environment
    - Total System can be expensive

Control Systems (Cont.)

Problem Areas (Cont.)

- **PLC**
  - Best choice.
  - Specifically designed for industrial environment.
    - Robust, small foot-print, low power consumption.
    - Meant for continuous processes such as plant operation.
    - Many levels of system redundancy available.
  - Low component failure rates.
  - Provides signal conversions, equipment protection, and control of system components.
  - Implementation of control loops at this level allows the plant to continue operating normally even if the EPICS, IOC, or Ethernet systems are down.

Control Systems (Cont.)



EPICS HMI's

EtherNet

EPICS
Channel Access

EPICS Tag
Data Flow

Local Control
Data Flow

IOC

PLC

Local HMI

Instrument
Wiring

Field Devices

Equipment Skids

<u>IOC Responsibilities</u>

- Provide EPICS channel access
- Transfer data in/out of EPICS to PLC's and HMI's

<u>PLC Responsibilities</u>

- Monitor all instrument signals
- Control all controllable elements
- Provide equipment interlocks
- Transfer data in/out to of PLC to IOC's and local HMI's

<u>Local HMI Responsibilities</u>

- Allows monitoring and control of subsystem in the event the IOC or Ethernet connection is down.

Cryogenic Sensors

Temperature Diodes

- **Normally used ambient to 2 Kelvin.**

  For good performance:

  1. Maximize coupling between fluid and sensor.
     - — Proper materials and placement.
  2. Minimize influences of stray thermal conduction and radiation effects on sensor.
     - — Proper heat stationing.
     - — Good shielding.
  3. Minimize influences of stray electromagnetic interference on sensor and signal wiring.

     i.e. Don’t run power conductors near signal wiring.
  4. Backup / robustness.

Cryogenic Sensors (Cont.)

Temperature Diodes (Cont.)

- **Maximize thermal coupling between process fluid and sensor.**
  1. JLAB designed in-process-flow thermal-well specifically for our diode installations.
  2. Thermal-well-tip machined from copper and centered in process pipe for maximum thermal coupling to process fluid.
  3. Diodes are mounted to brass standoff that is screwed into thermal-well-tip for good thermal coupling to fluid.
  4. Thermal-well-tube made from thin wall stainless steel to minimize thermal conduction effects from outside process pipe.
  5. Tube is socket welded inside Cu tip to ensure joint gets tighter when cooled because of differing contraction rates.

Cryogenic Sensors (Cont.)

Temperature Diodes (Cont.)

- **Minimize stray thermal convection effects on sensor**

    — Careful heat stationing

1. Diodes purchased with 3-foot lead wires.
2. Approximately 2’8” are wrapped and bonded to thermal-well to process pipe weld adapter.
    1. Anchors diode lead temperature very close to the process flow temperature.
    2. Intercepts unwanted convective heat flow through signal leads from warmer sources in the vacuum space and through the vacuum shell instrumentation feed-thru.

Cryogenic Sensors (Cont.)

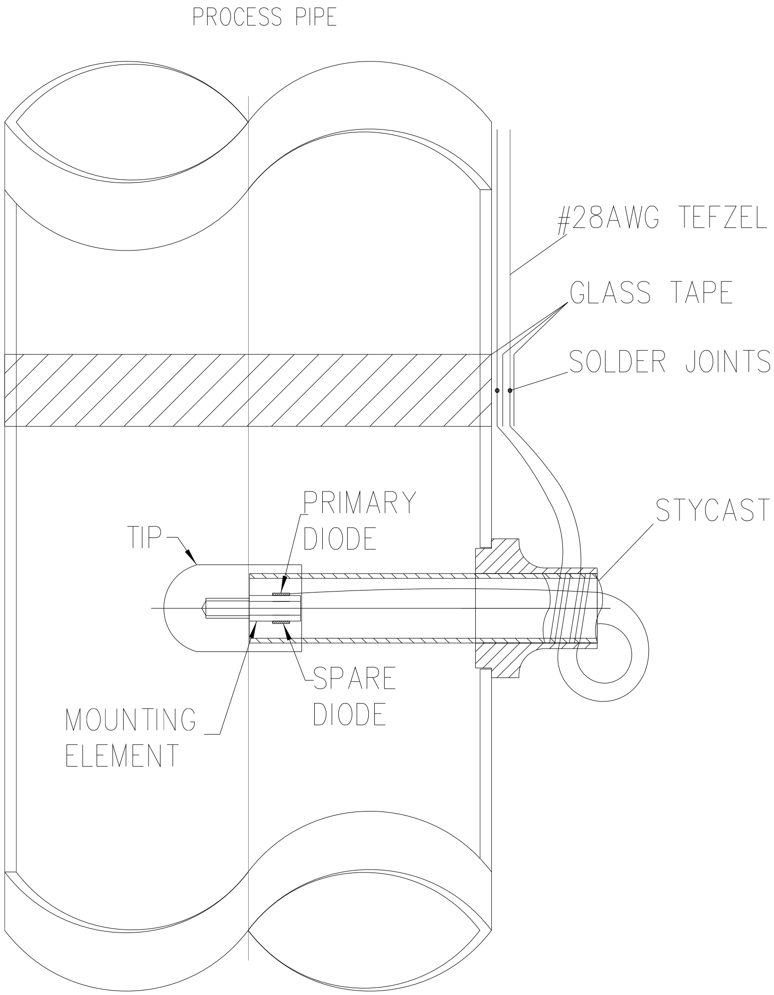
Temperature Diodes (Cont.)

- **Backup/robustness**

  1. We install two diodes in each thermal-well at each measurement point, a primary and a spare.
  2. Both sets of diode signal wires brought outside vacuum shell.
  3. If primary diode fails we can switch to backup without entering vacuum shell.
  4. Both primary and backup diodes are tested at each installation step.

Cryogenic Sensors (Cont.)

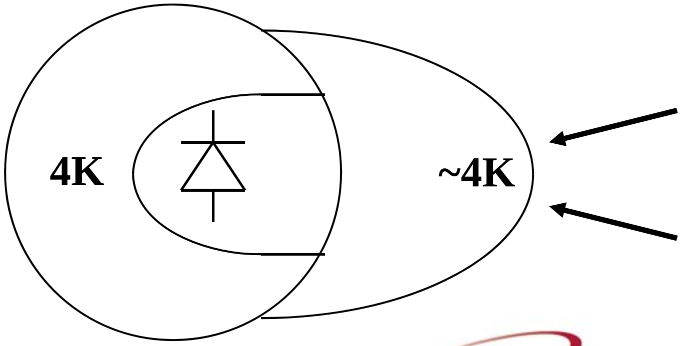
Temperature Diodes (Cont.)



Cryogenic Sensors (Cont.)

Temperature Diodes (Cont.)

- **Minimize stray thermal radiation effects on sensor.**
  - — **Provide good thermal shielding.**
  - **1. JLAB designed diode thermal-well shield.**
    - — Made of copper for maximum heat conduction.
    - — Firmly fixed to bare process piping.
    - — Covers end of diode thermal-well.
      1. Anchors shield temperature very close to process flow temperature.
      2. Intercepts unwanted line-of-sight thermal radiation effects from influencing diodes measurement.



Thermal Radiation from surfaces warmer than the process flow.

i.e. 30K, 80K, 300K

Cryogenic Sensors (Cont.)

Temperature Diodes (Cont.)

- Utilized in
  - JLAB
    - SCN 2K Cold Box
    - SCM 2K Cold Box
    - ESR/CTF transferline
    - CTF upgraded reciprocating expansion engine skids (3)
    - CTF calorimeter
  - SNS
    - 2K Cold Box
    - Linac Transferline System
    - Commissioning heaters (3)
  - MSU
    - Cryogenic Distribution Box
    - Transferline Cans

Cryogenic Sensors (Cont.)

Pressure Instrument Tubing

- **Used to for process pressures from subatmospheric to high pressure.**
- **Installation priorities for maximum performance.**

1. Sized to minimize plugging from process contamination.
    - Contaminates freeze out as solids at cryogenic temperatures.
    - Solids accumulate in small tubing, effecting measurements.
    - Critical in systems like JLAB that make long runs between warm ups.
2. Connections are resistant to leaks (in or out of system).
    - In-leaks supply contaminates during upsets in low pressure streams.
    - Out-leaks waste helium leading to higher operating costs.
3. Installed to resist thermal-acoustic-oscillations (TAO’s).
    - AKA “Density Gradient Oscillations**“.**
    - Visualized as oscillations in the transmitters measurements.
    - Increases overall system heat leak.

Cryogenic Sensors (Cont.)

Pressure Instrument Tubing (Cont.)

- **Sized to resist plugging from process contamination.**
  - Use only 0.25"O.D. 0.035" W. stainless steel tubing.
    - Provides sufficient cross sectional area to reduce chance of full plugging by contaminates accumulating over long periods of time.
- **Connections must be leak resistant.**
  - Use only bellows seal valves for instrument lines.
    - Reduces chance of system contamination and leaks through stem.
  - Weld joints or use VCO or VCR fittings. No swaged fittings.
    - Reduces chance of leaks into or out of process.
    - Allows joints near instruments to be reused indefinitely by simply replacing a o-ring or copper gasket.
    - Swaged connections have a limited number of open/close cycles before they will leak.

Cryogenic Sensors (Cont.)

Pressure Instrument Tubing (Cont.)

- **Thermal-acoustic-oscillations.**
  - **Simplified explanation.**
    - Typically found in long tubes with one end open to a cold source and the other end extended out to a closed end warm boundary (i.e. like pressure instrument tubing).
    - As cold gas enters the warmer tube the temperature increases causing the gas inside the tube to expand.
    - Expanding gas increases the pressure in the tube and forces the colder gas near the open end of the tube back out into the cold source.
    - 'Burping' action lowers the pressure in the tube which draws in cold gas again.
    - Oscillations will continue if there is no mechanism to balance the temperature gradient.

Cryogenic Sensors (Cont.)

Pressure Instrument Tubing (Cont.)

- **Thermal-acoustic-oscillations.**
  - **Control System Impact.**
    - Pressure transmitters will sense the oscillations within the instrument tubing and measurements will suffer.
    - Can cause operational instabilities as control system attempts to compensate for oscillations in real-time (valves move, speeds change, etc.)
  - **Heat Leak Impact.**
    - Oscillations serve as an effective heat-pump process conducting heat from the warm boundary down to the cold source, increasing the overall system heat-leak.
    - Results in higher operational costs for additional capacity needed to maintain process conditions.

Cryogenic Sensors (Cont.)

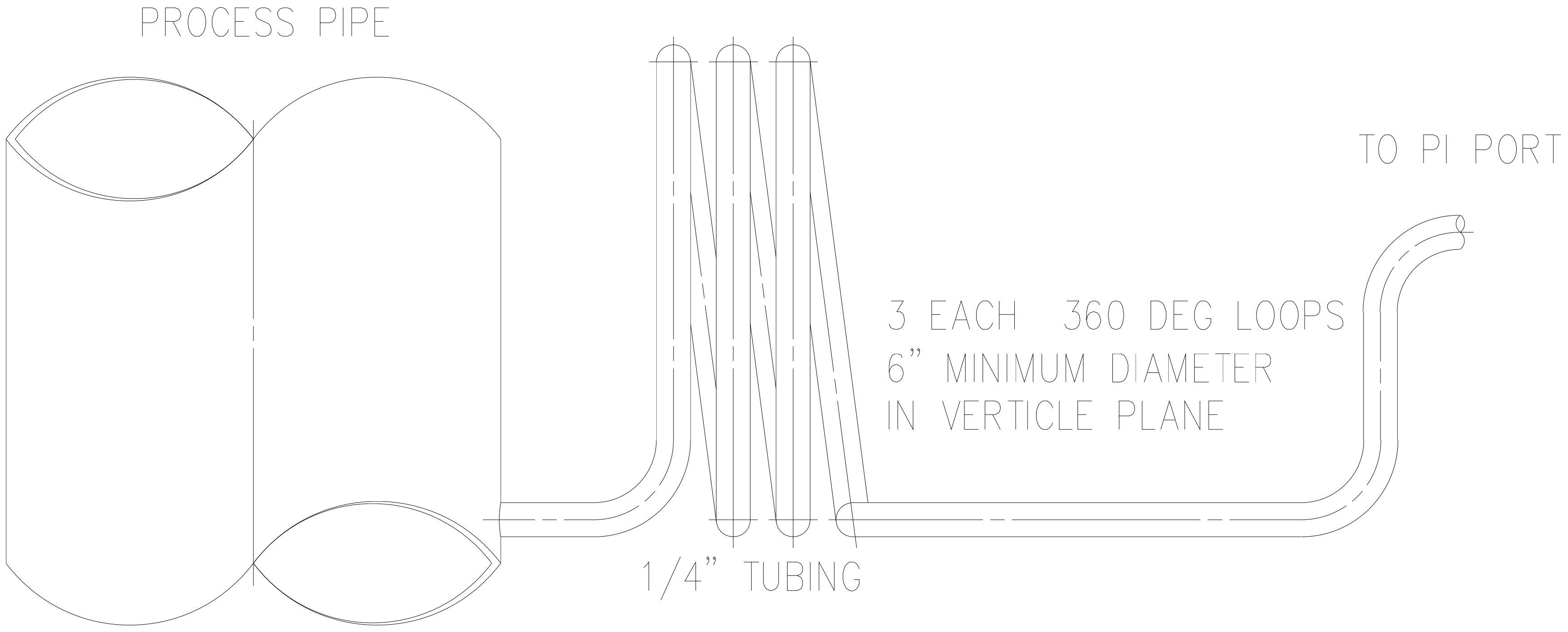
Pressure Instrument Tubing (Cont.)

- **Installed to resist thermal-acoustic-oscillations.**
  - As soon as the instrument tubing exits the process piping tap it is formed into three 6-8” close-coupled vertical loops before making the run to the instrument flange exiting the vacuum shell.
    - Provides a proven mechanism to minimize density gradient oscillations by allowing each loop to reach stable intermediate values between the cold and warm end temperatures.
    - Temperature gradient distributed over the vertical sections of tubing help stratify gas densities using gravity.
    - Multiple small vertical loops function like one large vertical run with out using up a lot of real-estate.
    - Horizontal loops will not provide any resistance to TAO’s..
    - Don’t fight nature, use it to your advantage.

Cryogenic Sensors (Cont.)

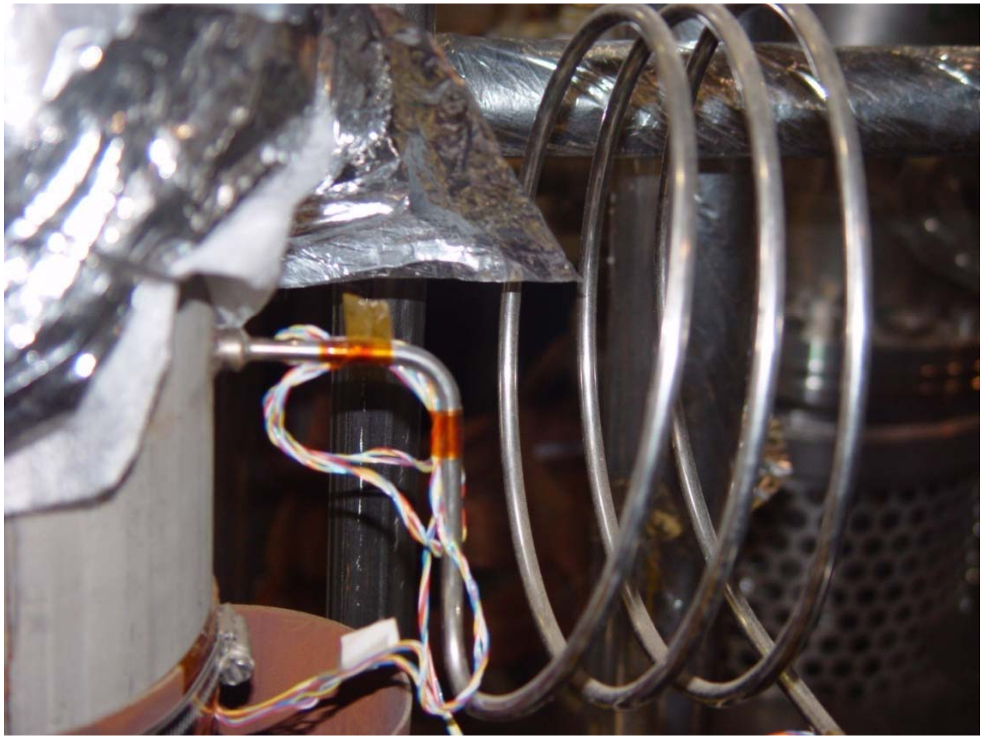
Pressure Instrument Tubing (Cont.)

- **Installed to resist thermal-acoustic-oscillations.**



Cryogenic Sensors (Cont.)

Pressure Instrument Tubing (Cont.)



- Utilized in systems at
  - JLAB
  - SNS
  - MSU
  - JSC

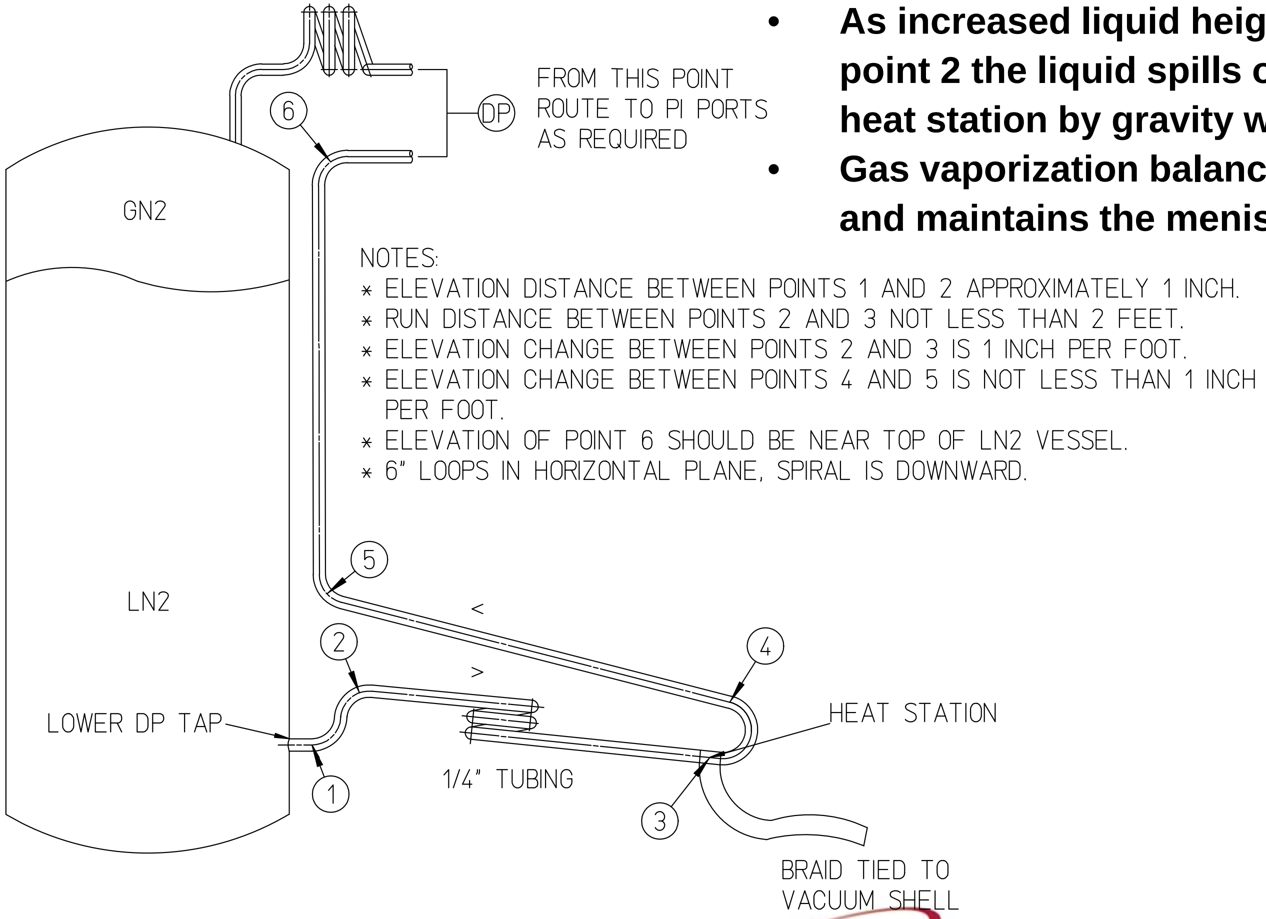
Cryogenic Sensors (Cont.)

DP Instrument Tubing for Liquid Level Measurement

- **Low pressure tap installed similar to single pressure measurement instrument tubing.**
- **High pressure tap instrument tubing must be installed to control the vaporization point (meniscus) and minimize heat input oscillations to the liquid.**
  - When liquid is in the dewar, the high pressure instrument tube entrance will always contain liquid but will transition to a gas at some point along the length before the transmitter.
  - Location of the meniscus point must be well planned to ensure accurate level measurement.
  - JLab designed a specific tubing configuration for these types of installations.

Cryogenic Sensors (Cont.)

- As liquid fills the vessel, it covers the lower tap and traps gas within the sensing tube.
- As height of liquid increases, trapped gas is compressed, which moves meniscus point further into the tube.
- As increased liquid height pushes meniscus beyond point 2 the liquid spills over and flows toward the ambient heat station by gravity where the liquid is vaporized.
- Gas vaporization balances the pressure within the tubing and maintains the meniscus between points 2 and 3.



NOTES:
* ELEVATION DISTANCE BETWEEN POINTS 1 AND 2 APPROXIMATELY 1 INCH.
* RUN DISTANCE BETWEEN POINTS 2 AND 3 NOT LESS THAN 2 FEET.
* ELEVATION CHANGE BETWEEN POINTS 2 AND 3 IS 1 INCH PER FOOT.
* ELEVATION CHANGE BETWEEN POINTS 4 AND 5 IS NOT LESS THAN 1 INCH PER FOOT.
* ELEVATION OF POINT 6 SHOULD BE NEAR TOP OF LN2 VESSEL.
* 6" LOOPS IN HORIZONTAL PLANE, SPIRAL IS DOWNWARD.

Power Conductors in a Vacuum

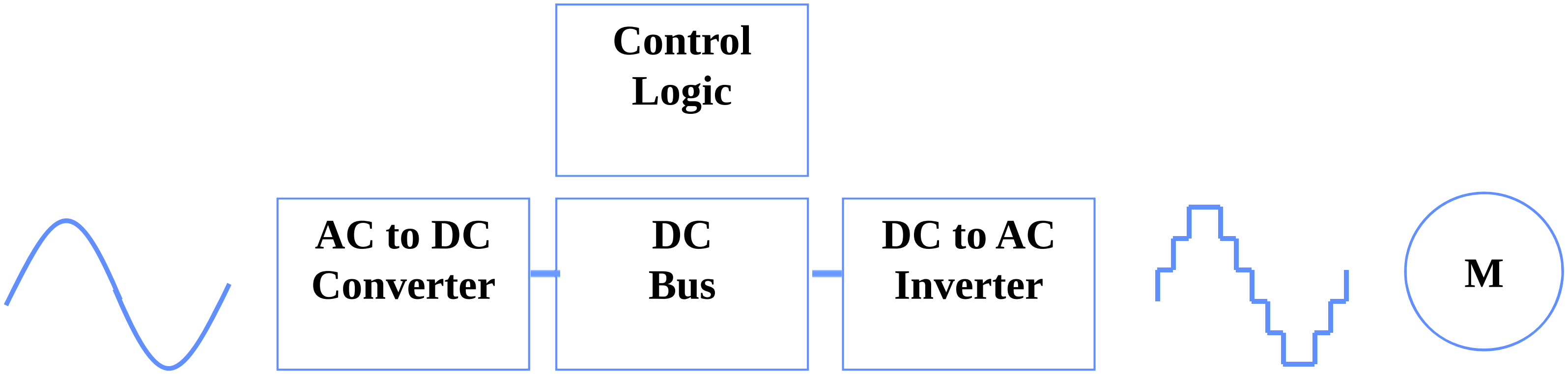
- **Conductors used to supply power within a vacuum space must be specified with care.**
- **Examples are power conductors to supply 80K/20K beds, subcoolers, or commissioning heaters.**
  - — Normal convective cooling mechanism for conductors is not present due to the lack of air within the vacuum space.
    - i.e. Nothing to transfer normal heat away from wire.
  - — If conductor is marginally sized for the actual load, the I^2R losses will be high and will result in excessive conductor heating.
  - — If conductor has a non-heat-resistant covering it will likely melt during some phase of initial operation.
    - Can lead to damaged wires, short circuits, and damage to other components inside the vacuum space such as super-insulation or other wires used for instrumentation signals.

Power Conductors in a Vacuum (Cont.)

- **Good practices**
  - Conductors should be generously sized to minimize the I^2R losses to minimize heating. Generally use one or two wire size steps up from what you would normally use in air.
  - Ensure that the conductors insulation will support the expected temperature rise which is eventually dissipated into the support structure at the tie points.
  - Generally you should use only conductors with coverings rated for high temperatures and low out-gassing for use in a vacuum.
  - Carefully plan wiring routes to stay away from danger areas such as super-insulation and to avoid routing power conductors near instrumentation signal wiring to reduce EMI.

Research and Development

- Variable Frequency Drives
  - Background
    - Provide speed control for AC motors
    - Convert AC to DC then invert DC back to AC at variable frequencies and voltages (VVVFD) using PWM
    - Typical frequencies are 0-60 Hz
    - Cold Compressor frequencies are 0-640 H



Control Logic

AC to DC Converter

DC Bus

DC to AC Inverter

M

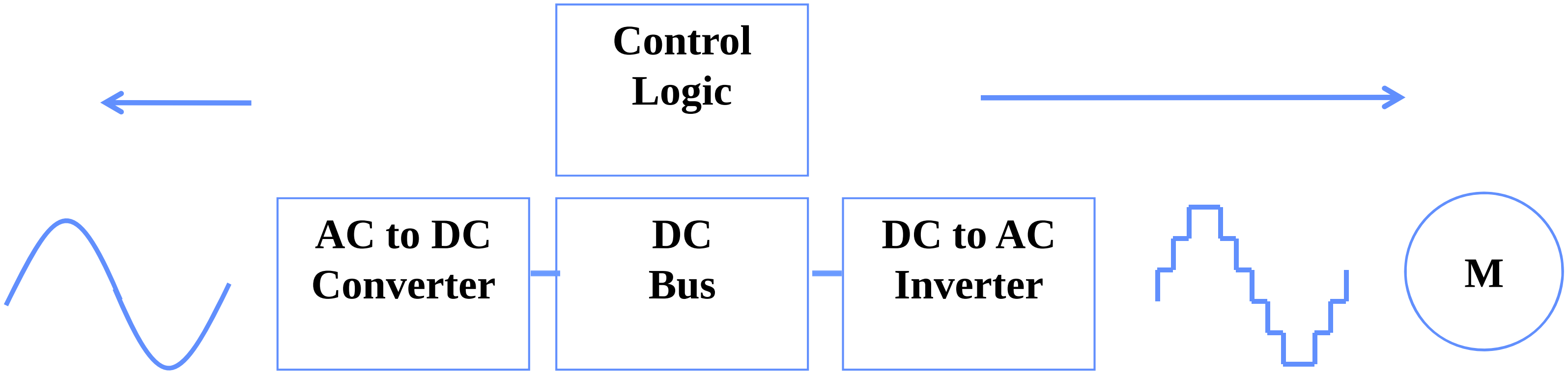
Research and Development (Cont.)

— Beliefs

- **VFD’s deliver high power factor**
  - Ratio of real power to apparent power

— Reality

- **High power factor is between power system and VFD**
- **Power factor between VFD and motor not constant**



Control Logic

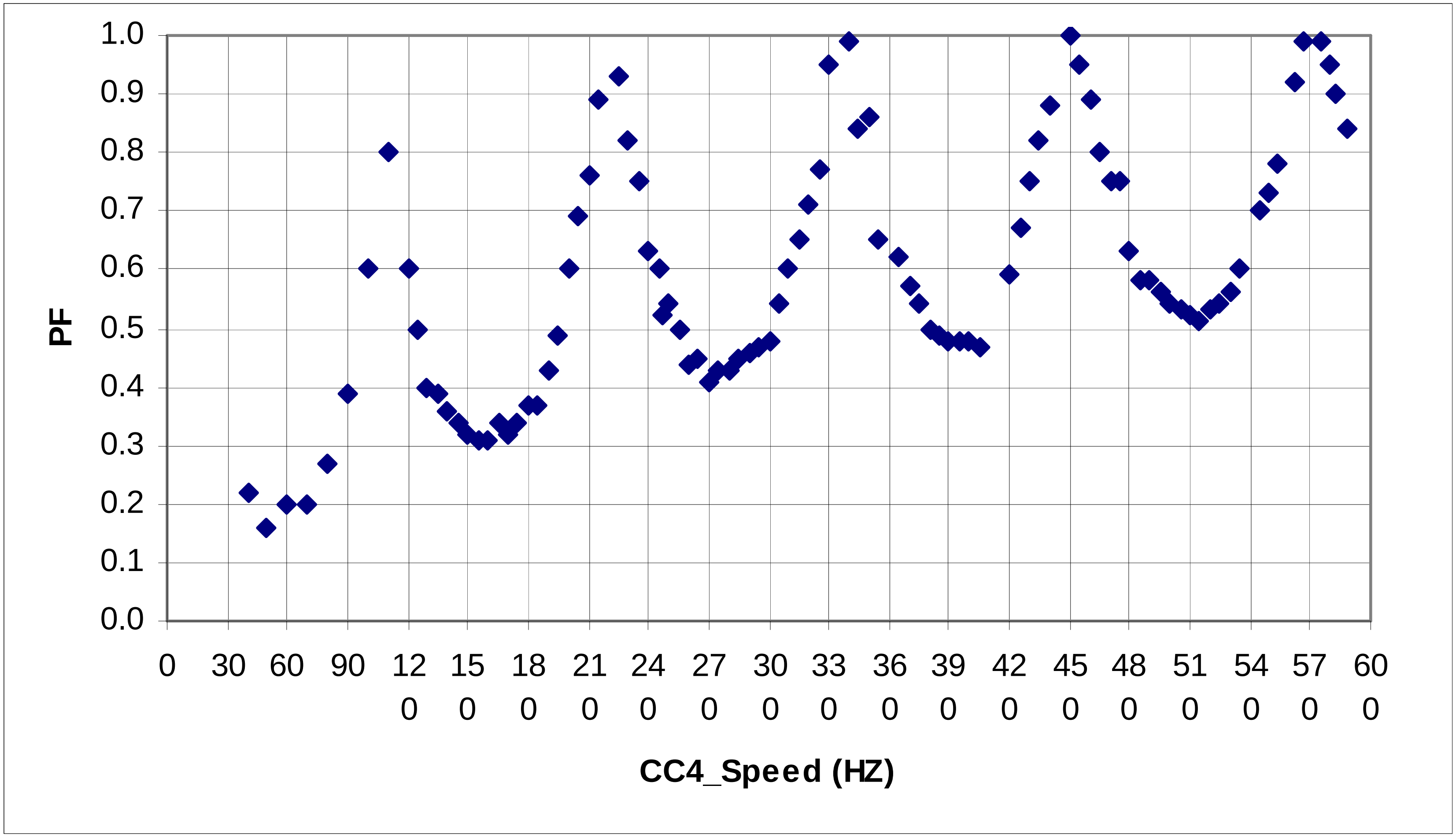
AC to DC Converter

DC Bus

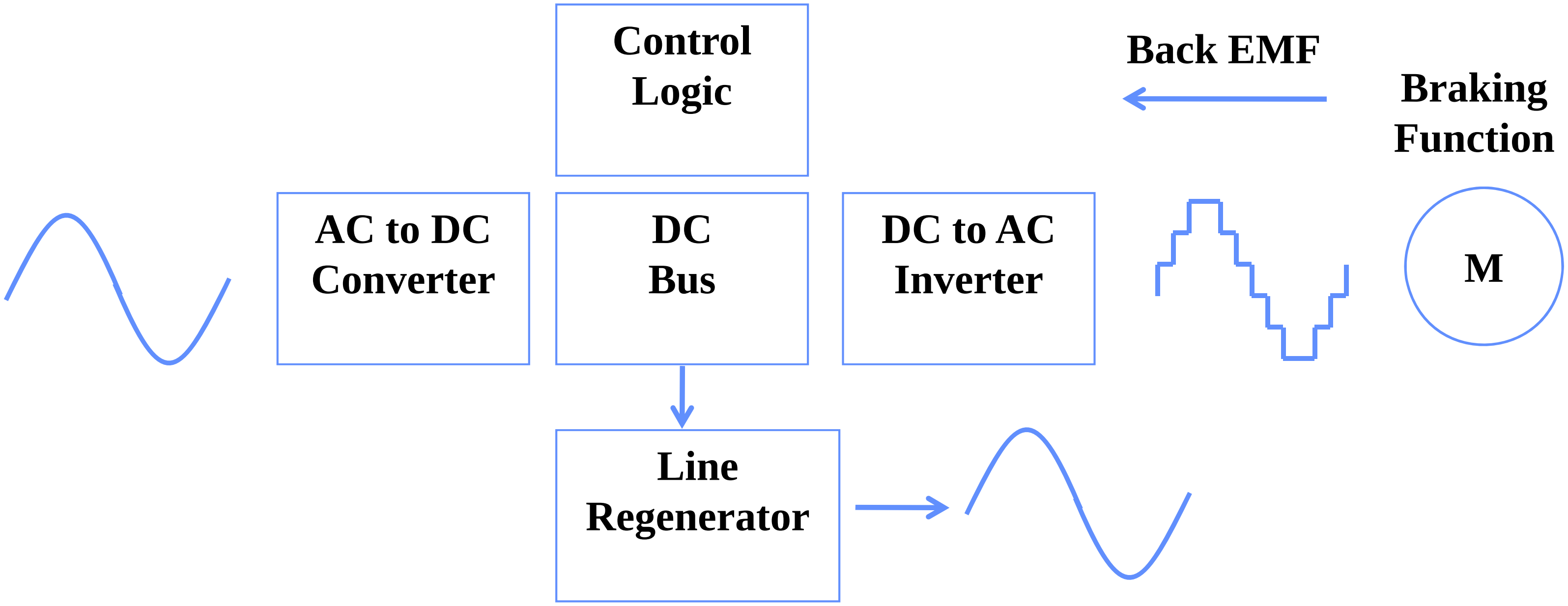
DC to AC Inverter

M

Research and Development (Cont.)



Research and Development (Cont.)



Control Logic

Back EMF

Braking Function

AC to DC Converter

DC Bus

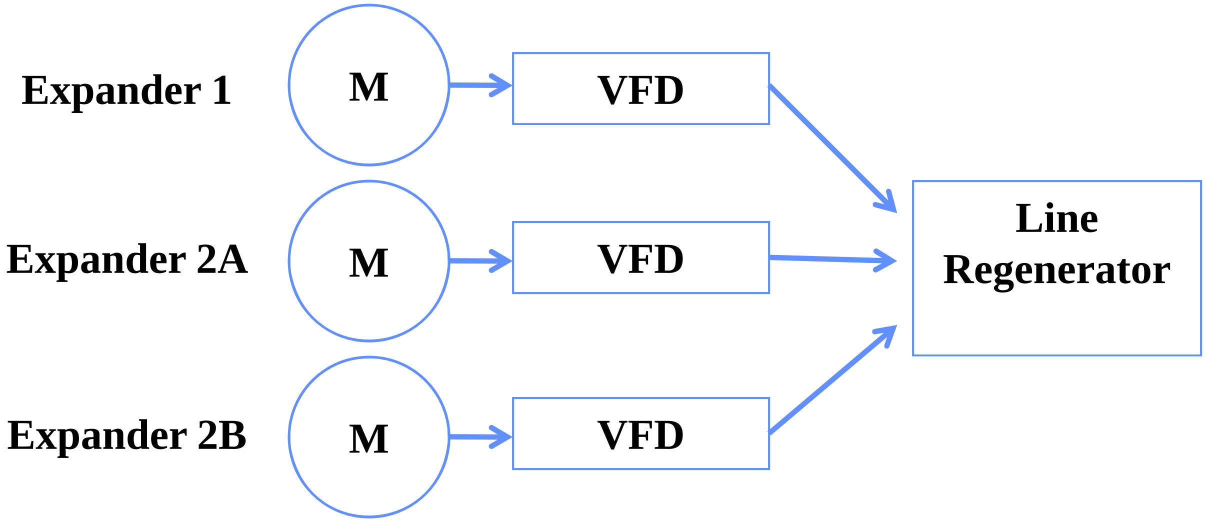
DC to AC Inverter

M

Line Regenerator

- **Line Regenerators**
  - Employed when VFD/motor used to provide braking function
  - Braking energy transfers to DC bus as overvoltage
  - Absorbs excess voltage and converts it to line power
  - Offsets energy consumption

Research and Development (Cont.)



- **CTF**
  - One line regenerator receives excess power from three VFD’s
  - Provides approximately 5 kW of offset power

The End

Thank You

Acronyms

- AC (Alternating Current)
- CAMAC (Computer Automated Measurement System)
- CC4 (Cold Compressor #4)
- CTF (Cryogenic Test Facility)
- DC (Direct Current)
- DP (Differential Pressure)
- EMF (Electro-Motive Force)
- EPICS (Experimental Physics Control System)
- HMI (Human Machine Interface)
- IOC (Input Output Controller)
- M (Motor)
- PF (Power Factor)
- PLC (Programmable Logic Controller)
- PWM (Pulse Width Modulated)
- VFD (Variable Frequency Drive)
- VME (VERSA Module Eurocard)
- VVFD (Variable Voltage & Frequency Drive)

11. System Design Overview

For a new refrigeration system specifications development, carefully analyze:

- **system *capacity* and**
- ***pressure rating* (relief) requirements**

Both strongly influence capital and operating costs.

System Design Overview (Cont.)

System Capacity Specification and Margin Allocation:

Specification of the system capacity is a combination of science and art (experience)

- **Conservative (over-specified) load estimations may result in a significant system excess capacity**
- **A large excess capacity wastes capital investment and continuously operates off-design at a reduced efficiency**
- **On the other hand, a system capacity set too small can endanger the entire project**

System Design Overview (Cont.)

The specification should encourage the vendor to be conservative in components selection that operate well over a wider range of operating conditions, rather than a maximum capacity point to mitigate some of the concerns.

The monetary incentives to the vendor for

(a) capacity range ability

(b) efficiency

(c) or a combination with reasonable bounds on the above two parameters

System Design Overview (Cont.)

Capacity or Carnot capacity and Carnot Efficiency for the following six operating cases is generally of interest:

- **Maximum System Capacity**
- **Nominal operating case**
- **100% liquefaction**
- **100% refrigeration**
- **50% liquefaction and 50% refrigeration**
- **Minimum capacity (e. g. : ~30% of the maximum system Carnot capacity, say ~15% liquefaction and ~15% refrigeration) operation**

If the capacity is less than 80% of the maximum Carnot Capacity in any of the modes (except the minimum capacity mode), that mode needs to be closely examined before finalizing the system design

System Design Overview (Cont.)

Some of the factors to be considered in the capacity margin allocation (or allowance) are:

- **Uncertainty of the primary load estimates**
- **Uncertainty of the heat leak into distribution system load estimates**
- **Capacity for system and load control (~4%)**
- **Uncertainty of instrumentation (~1%)**
- **System degradation with time due to contamination and allowance for valve leakage before requiring a system shut down and maintenance (~3%)**
- **Cool down and bringing the loads to steady state conditions (cool down heat exchangers with LN2 and/or additional cool down lines and valves)**
- **Critical reduced-capacity operation with some component failures (make sure each major component failure is analyzed)**

In general, the sum of all these factors often add to *50% or more (margin)* to the primary steady state load capacity requirement.

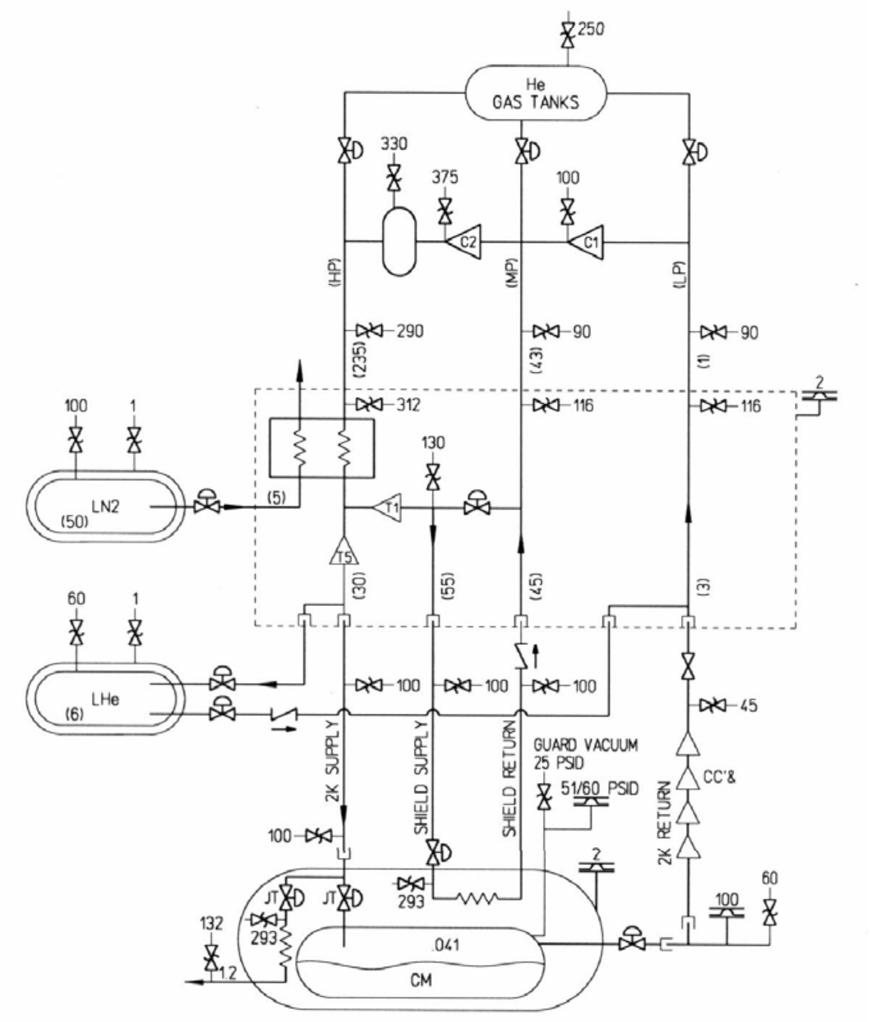
System Design Overview (Cont.)

Integrated safety relief system coordination

The relief system is designed for supporting a set of loads. The pressure rating and the relief choices for the system are to be carefully evaluated in order that the system is self-protecting.

Helium flow path and prioritized location(s) venting during load upset and emergency shutdown must be carefully planned in the design stage. The strong interaction of isolation especially in subsystem relief coordination is an essential part of these design considerations.

System Design Overview (Cont.)



Example: Integrated safety relief system for SNS

System Design Overview (Cont.)

The pressure rating design for loads, refrigeration and compressor systems need to be coordinated in an operational pressure profile of their system relief set points and relief capacity with the isolations (including critical failures) for the following cases:

- Normal operating condition and the relief pressure rating margin
- Shutdown of each subsystem
- Total system shut down (power outage, etc.)

The goals of the relief system are first protection of personnel and equipment and then helium loss during planned and unplanned shut downs

12. Design Verification and Acceptance Testing

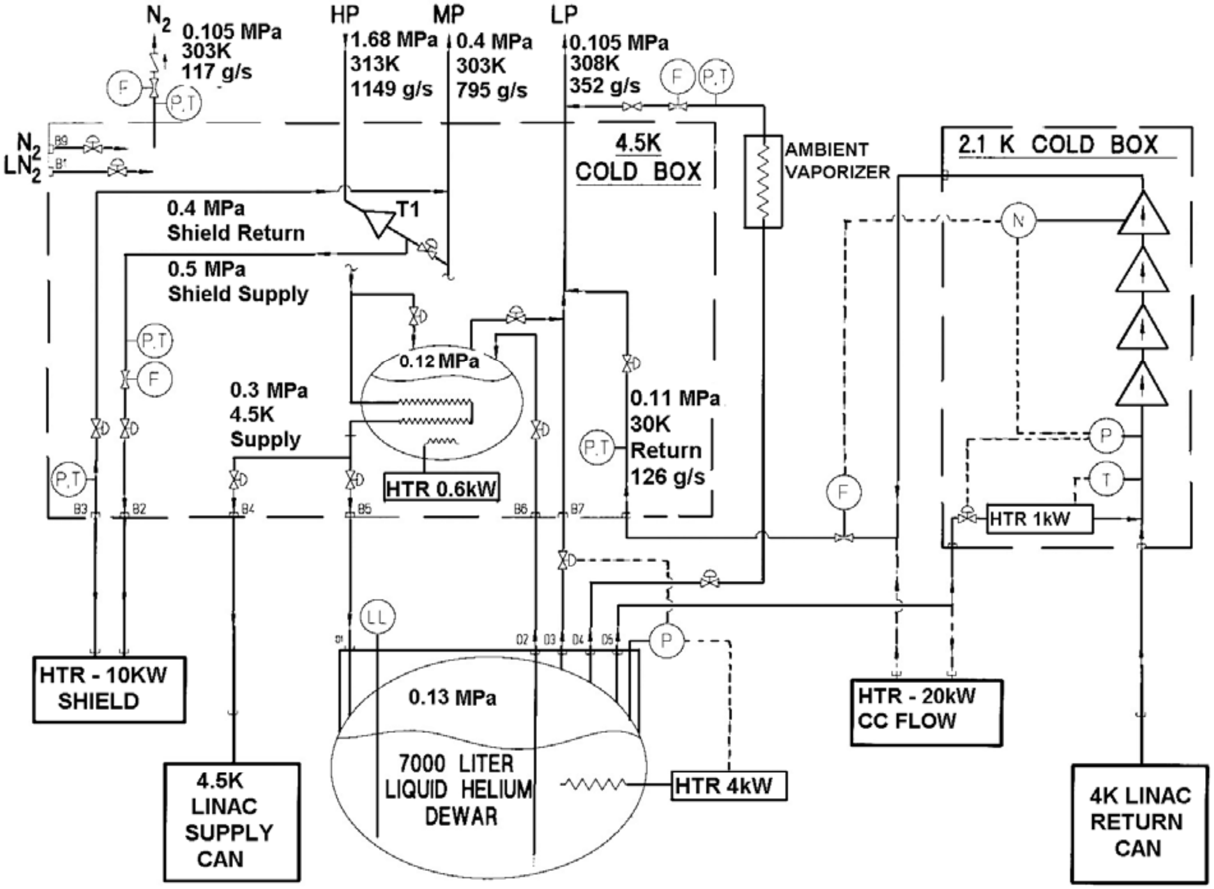
The need for devices necessary to quantitatively verify the system capacity is often unrecognized or underestimated.

Such an oversight creates a system capacity uncertainty for intended operational modes and can lead to the misidentification and modification of the wrong component(s) due to a lack of understanding of the under-performing component(s) in the system.

Usually electric heaters are used for capacity testing

Careful test boundaries should be defined

Design Verification and Acceptance Testing
(Cont.)



SNS 4K System Test Configuration

Design Verification and Acceptance Testing
(Cont.)

They will help to:

- **Verify the initial system, vendor supplied, performance**
- **Operate at partial loads as required**
- **Occasionally demonstrate the system capacity; especially after major maintenance and major component replacement periods**
- **Handle the load and system transients by providing a basis for the capacity modulation**
- **Justify the small additional capital investment for permanent test devices built into and integral with the system, instead of as a part of temporary "commissioning only" jumpers.**

A procedure outlining the required performance calculations for generally encountered helium system loads is provided in Appendix-G.

13. Some of the Lessons Learned over the Years

A great deal can be learned from the existing operating systems and they can be good, bad or even ugly

Analyze the data carefully before reaching any conclusions

Too often the *perceptions of the problems* are *different* or even very very different from the realities

For new projects, extreme care is required in developing specifications and assuring that the scope-of-supply includes all the required items

The success of the project depends upon its organization; cost estimates based on current data, schedule planning and project execution

Some of the Lessons Learned over the Years (Cont.)

Compressors:

- **Oil removal equipment under-sizing in general and in particular for minimum capacity or reduced pressure (reduced capacity) operation**
- **Improper selection of compressor frame sizes**
- **The number of compression stages**

Some of the Lessons Learned over the Years (Cont.)

Cold Box

- Designed to a single mode operation and not addressing all aspects (potential modes) of operation
- Undersized surface area and high pressure drop HX’s
- Overestimated turbine efficiencies
- Inadequate cool down and warm up connections
- Nonfunctioning 80K and 20K beds (leaky isolation valves)
- Oil contamination

Some of the Lessons Learned over the Years (Cont.)

Sub atm Cold box design

- Undersized surface area and high pressure drop HX’s
- Overestimated cold compressor efficiencies and pressure ratios
- Underestimated torque requirements by the compressor or overestimated torque performance of the CC motors specially during pump down
- Poor power factor and its variation with speed for variable frequency CC motors

Some of the Lessons Learned over the Years (Cont.)

Auxiliary Systems

- Inadequate helium purifier flow capacity
- Excessive purifier bed regeneration time
- Inadequate LN2 storage to allow for weather related (summer and winter) or other delivery issues

Some of the Lessons Learned over the Years (Cont.)

Helium Storage

- Dewar(s) size requirement estimates
- Operable dewar specification including calorimeter heaters, accurate level gauge(s)
- Warm gas storage sizing, location, connection and subdivision

Some of the Lessons Learned over the Years (Cont.)

Distribution System

- High heat leak to transfer lines and distribution system components (lines, bayonets, valves etc.)

Instrumentation & Controls

- Some of the problem areas are listed in chapter 9

14. Some Areas of Interest for Future Developments

The *Floating Pressure* gas management scheme for system capacity modulation should be implemented for all helium refrigeration / liquefaction systems. This approach has saved many MW's of electric power for JLab, MSU, SNS and BNL (Linde has license from Jlab)

Test the *Screw Compressor system* to establish the effect of built-in volume ratio on the pressure ratio, rotor tip speed, oil helium mix during the compression process and oil choice choices on the efficiency for helium system applications. Also establish the other process parameters like operating temperature to minimize input power and to increase the maintenance interval.

Some Areas of Interest for Future Developments

(Cont.)

Bayonet design improvements:

More and more labs are using large multiples of bayonet type connections between the systems that are similar to those originally developed at Fermilab. The thermal load of these components significantly exceeds the load estimates based on longitudinal conduction. Industry has used tight clearances or end seals to minimize the convective loops effects in the annular gap. It is also questionable how well the heat intercepts on these bayonets are working.

Some Areas of Interest for Future Developments
(Cont.)

Mass flow meter:

Develop a mass flow meter to measure the vapor flow from a load with very low pressure drop and also for supercritical helium flow

Software models for operating helium cryogenic systems with the real system components to help them operate closer to the realizable maximum efficiency for the operating modes and load conditions and to help diagnosing the problems when arise

Some Areas of Interest for Future Developments
(Cont.)

Expanders:

Develop turbo expanders that can utilize commercially available magnetic bearing technology and that operate with larger pressure ratios and higher efficiencies

Develop a multi-cylinder reciprocating expansion system utilizing the mass produced parts of the auto industry

Some Areas of Interest for Future Developments

(Cont.)

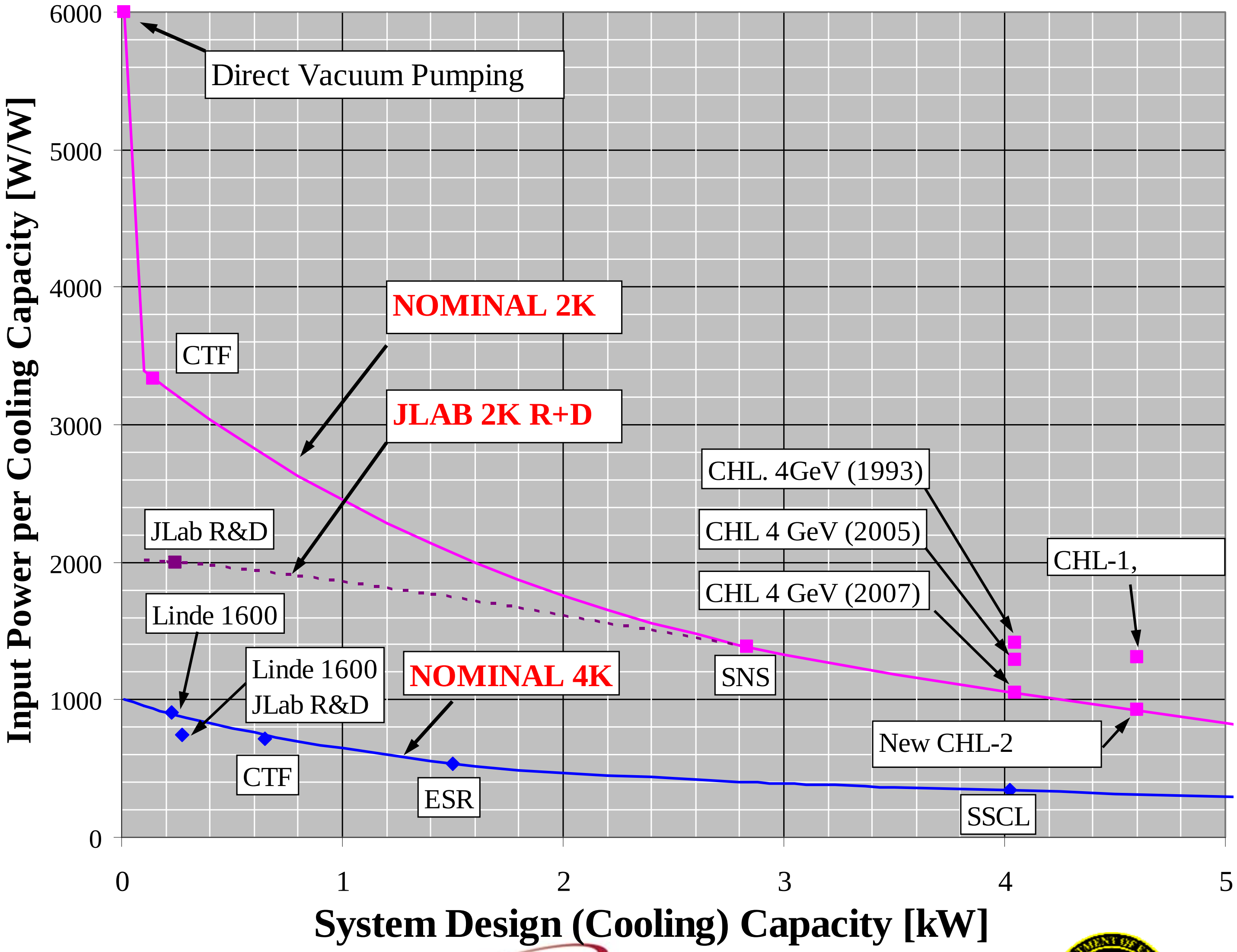
High efficiency, small helium refrigerator/liquefier:

High efficiency, small helium refrigerator/liquefier systems for both 4.5K and 2K applications

Driver Development:

Improved power factor designs for the variable frequency motors used, especially for Ln2 cooled motors for cold compressors

2K and 4K JLab Research Development Areas



15. Conclusions

Carefully develop new system requirements that consider loads including all anticipated transients while allowing for the practical strengths and weakness of all system components

Make sure that the design goals are carried through the selection of all components and into the detailed system design and construction

If the *user has difficulty defining the requirements* or how to achieve them in the specification, then it certainly *can not be assumed that the vendor will be able to provide them*

Conclusions (Cont.)

What is an optimum system? Does it result in the:

1) Minimum operating cost?
2) Minimum capital cost?
3) Minimum maintenance cost?
4) Maximum system capacity?
5) Maximum availability of the system?

Or, A combination of some or all the above

Or, Some other factors?

What do you think?

Conclusions (Cont.)

Hopefully the information presented in these notes and other information available will help you to design and operate cryogenic systems at optimal conditions and to answer the above questions. Floating pressure-Ganni Cycle is a step in that direction

The central theme of these classes is to minimize the utilities (e.g.: input power) for all required operating conditions. This will help to save our natural resources; an objective that is worth pursuing

Hope you saw the

"Need for understanding the fundamentals"

Conclusions (Cont.)

We need to treat

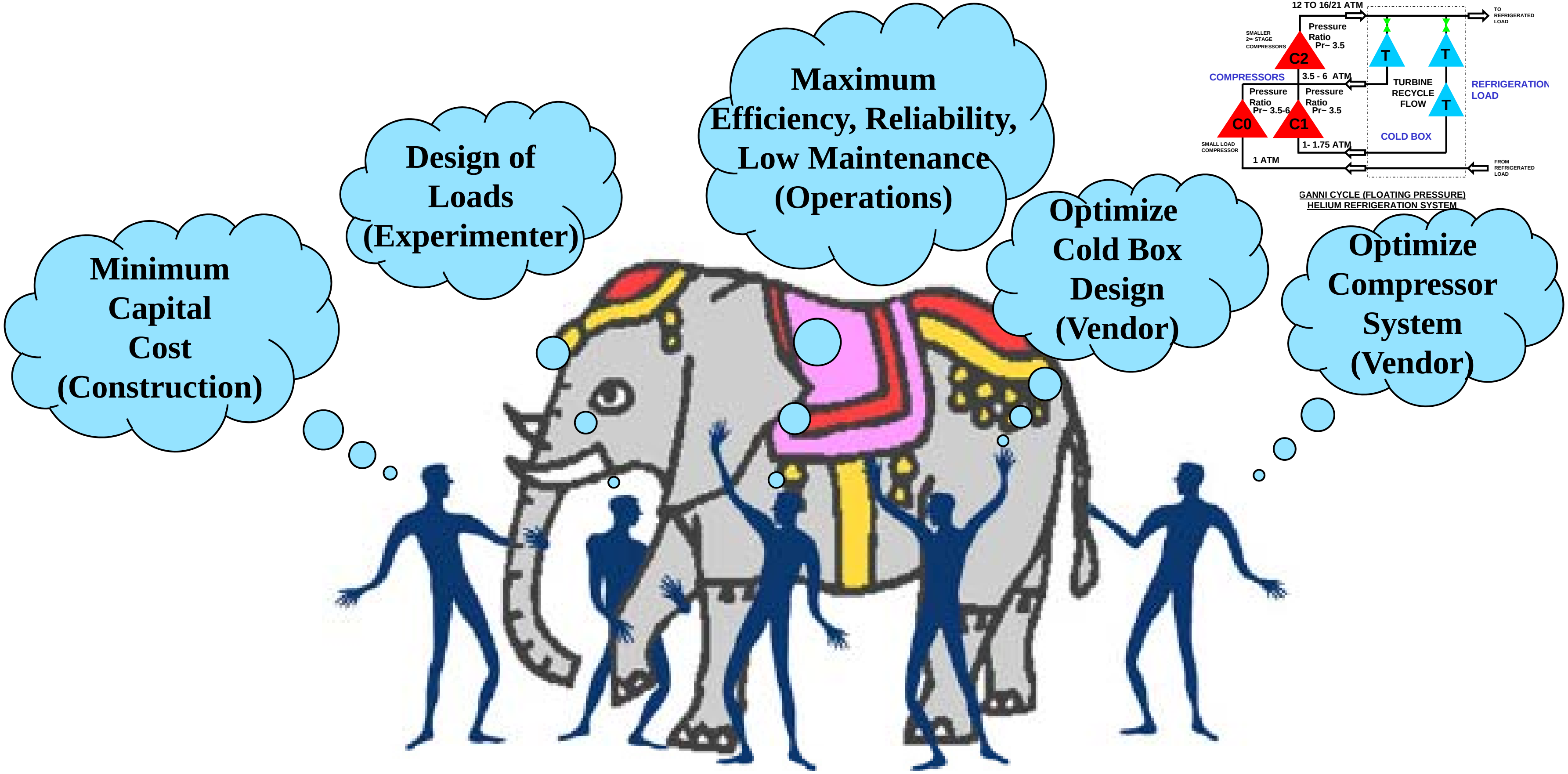
the Natural Resources

not as Inheritance **from our parents**

But

as *barrowed* from our children

What is an “Optimal” System



GANNI CYCLE (FLOATING PRESSURE)
HELIUM REFRIGERATION SYSTEM

- One’s viewpoint can be based only on their role and focus within a project
- Easy to believe that one’s goals are mutually exclusive of others
- Many believe that maximum system efficiency occurs only at one set of fixed operating conditions

Conclusions (Cont.)

We like to see all of us to take personal interest

in how we use the precious commodity

energy

in accomplishing the end goal !!!

Conclusions (Cont.)

My special thanks to the members of JLab Cryo Department and especially to *Peter Knudsen* for making substantial contributions and all the other reviewers for helping me develop the notes.

Thank you all for your interest in this course

VenkataRao Ganni

Note: **All suggestions to correct any errors and to improve this manuscript will be greatly appreciated.**

Conclusions (Cont.)

Discussions & Remarks

Open Session