Cryogenic Refrigeration for Quantum Voltage Standards

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Abstract.

Currently the world maintains the voltage standard using a Josephson junction which makes use of the properties of superconductors and quantum tunneling. Current technology requires liquid He to cool the Josephson junctions to ~4 K to allow them to function as superconductors. He (l) is expensive and price is geographically dependent. Here we investigated using a cryocooler, modeled after a Gifford-McMahon Refrigerator, that could run on 120V (or a standard outlet) and used gaseous He as the working fluid—a less geographically dependent and inexpensive alternative to He (l). We found that indeed a standard outlet gaseous He compressor could reach temperatures of 4 K and that temperatures did not fluctuate with compression cycles of the cold head. It was also determined that indium metal is an effective contact interface to allow heat to be withdrawn from a surface.

Chapter 1: Introduction.

1.1 Superconductivity

Superconductivity is a state found in, among other substances, transition metals and transition metal alloys when they are cooled to temperatures near 0 K. A superconducting state is characterized by zero DC resistance and the expulsion of a magnetic flux from within the superconducting material (Meissner effect).

The transition from conducting metal to superconductor occurs at a temperature known as the critical temperature ($T_c$). At and below this critical temperature it is theorized, by the BCS theory of superconductivity (Bardeen, Cooper, and Schrieffer)$^1$, that free electrons within the metal lattice pair up and become bound. These bound electron pairs are referred to as Cooper pairs and are no longer spin ½ fermions but rather are spin 0 bosons. Because they are bosons an infinite number of these Cooper pairs are capable condensing into this lowest energy state because bosons can share the same quantum numbers.
Electrons can be represented by their wave-like nature as a superposition of plane waves. A property of plane waves is their ability to pass through a perfectly periodic structure without experiencing any scattering (resistance). No perfect crystalline structure exists, even at 0 K, and hence all conductors exhibit some amount of resistance. The time evolution of the electron plane waves causes their wave functions to be coherent only over short distances. Cooper pairs, on the other hand, have wave functions that remain coherent over indefinitely long distances and therefore show no electrical resistivity.

When a DC constant current is sent through a superconductor no electrical resistance is measured. Experiments have been conducted setting an initial current in a conduction loop of superconducting material and at later times measuring the current decay. An early experiment done by Gallop showed the resistivity of the superconductor to be $10^{-26} \, \Omega m$ (eighteen orders of magnitude less than the room temperature resistivity of Cu). A more accurate study was undertaken by File and Mills, using precision nuclear magnetic resonance methods, to show that the decay time of a superconducting current was not less than 100,000 years.

When an AC current is passed through a superconductor the electric current is no longer completely carried by the Cooper pairs. The alternating current passing through the superconductor produces an electric field in the material. The Cooper pairs (the superconducting electrons) have a greater inertia than that of the normal electrons and therefore their response trails behind the changes in the alternating field. This lagging of the current in the superconducting electrons allows the normal electrons to hold a portion of the current and therefore there is a measurable resistance.

1.2 Superconducting Materials and Characteristics

In addition to temperature being a defining parameter of a superconductor phase transition, magnetic field and current also have a crucial role. As graphically displayed in Fig 1.1, above a critical temperature ($T_c$), critical magnetic field ($H_c$), and critical current/current density ($I_c/J_c$) a superconducting material will no longer superconduct. Temperature plays a crucial role in superconductivity because of the formation of Cooper pairs. For a particular metal, Cooper pairs can only form at temperatures below $T_c$; above $T_c$ there is enough energy from thermal vibrations to release bound Cooper pairs into normal electrons. It is experimentally known that superconductors have no internal magnetic field. Large shielding currents form within the superconductor to negate an external magnetic field. When the current density within the superconductor goes above that of the
critical current density ($J_c$) the external magnetic field in the metal breaks the superconductivity of the material. The magnetic field strength at which the superconductivity is broken is known as $H_c$. The final parameter, critical current density is explained in detail in section 1.3. 

It is not known why some metals superconduct and others do not. Some elements, namely the alkali and alkali-earth metals do not exhibit superconductivity down to the lowest temperatures tested. Other metals show no superconductivity but alloys including these elements do. The highest transition temperature for an elemental superconductor is Niobium (Nb) at 9.3 K but higher transition temperatures have been achieved with compounds such as Nb$_3$Ge (23 K). Matthias's theory shows that $T_c$ is dependent on the number of valence electrons present in the element or alloy. Fig 1.2 His theory accounts for the high $T_c$ of Nb and its alloys. In 1986 the first high temperature superconductor LaBaCuO was discovered with a $T_c$ of 30K by IBM researchers Bednorz and Müller. Their initial discovery led to the synthesis of a family of cuprate-perovskite ceramic materials with high $T_c$ values, the highest $T_c$ being HgBa$_2$Ca$_2$Cu$_3$O$_{8+6}$ with a temperature of 135 K under atmospheric pressure. The high $T_c$ values for these superconductors
Figure 1.2 Critical temperature ($F(n)$) as a function of valence electrons. As the number of valence electrons increases, $T_c$ of the superconductor increases reaching a maximum at 5 and 7 valence electrons. Between 5 and 7 valence electrons there is a local minimum in $T_c$.

allow them to be cooled to superconducting temperatures in liquid nitrogen, 77 K, as opposed to liquid He.

1.3 The Josephson Effect

A unique property of superconductors is known as the Josephson effect. The Josephson effect arises when a superconducting material (or two different superconducting materials) are separated by a thin insulator or non-superconducting metal. From quantum mechanics it is known that not only electrons but also Cooper pairs tunnel through the insulator. Such a setup of superconductor, insulator, superconductor is known as a Josephson junction.

A Josephson junction that is not superconducting exhibits three distinct tunneling behaviors. First, if no bias voltage is applied to the junction no net voltage is detected. Electrons and Cooper pairs have equal probability of tunneling in either direction. Fig 1.3(a) Second, when a small voltage on the order of $10^{-4}$ V is applied to one side of the junction a slight current flows as electrons tunnel from higher to lower energy states. Fig 1.3(b) Third, if a voltage of $2\Delta/e$ or greater, where $\Delta$ is the energy of the band gap between the Cooper pairs and the electron conduction band and $e$ is the charge of an electron, is applied net current flow increases due to splitting Cooper pairs. Fig 1.3(c)

Tunneling for a superconducting Josephson junction occurs slightly differently. When no bias voltage is applied across a superconducting Josephson junction a resistant-less current passes through the junction. This current can flow up to a maximum current above which a voltage step is seen across the junction. The current where a voltage step is first observed is known as the critical current, $I_c$. If
**Figure 1.3.** Possible tunneling transitions of normal electrons, ●, and Cooper pairs, ○○, at various energy levels. (a) $V = 0$ When no bias voltage is applied both metals are at the same Fermi level and no net current flows. (b) $V \sim 10^{-4}$ When a small bias voltage is applied to one of the metals a slight net current flows as electrons tunnel from higher to lower energy states. Net current does not increase as bias voltage increases (c) $V = 2\Delta/e$, where $\Delta$ is the energy gap between the Cooper pairs and the conduction band. When a bias voltage equal to or greater than $2\Delta/e$ is applied Cooper pairs have enough energy to split and the splitting Cooper pairs cause the net current to increase.

**Figure 1.4.** Current vs voltage plot showing the characteristic constant voltage steps of a Josephson junction. A current can be applied to bias the voltage to a particular step, $n = 1$ shown in the figure. If $x$ Josephson junctions are placed in series voltage steps of up to 10 V can be obtained. $I_c$ denotes the critical current of the junction.\(^{11}\)

an AC current is set across the junction a bias voltage will be present and the junction will not be resistance-less. Uniquely, the Josephson junction will show step increases in current as the voltage is increased. Fig 1.4 A DC current can be used to bias the junction to a particular voltage step and that voltage step can be related to the frequency of current oscillation.\(^{12}\)

$$f = \frac{2eV_{dc}}{h} \quad (1.1)$$
Figure 1.5. (a) Josephson junction circuit equivalent. A DC or AC current, $I$, is sent through a set of three elements in parallel with a bias voltage, $V$, across them. The first element, the capacitor, represents the junction’s capacitance like function as charge can build up on each side of the junction before tunneling through it. The second element, the resistor, represents the resistance to current flow caused by the insulator of the junction. The third element represents the non-resistive superconducting current that is a function of the critical current, $i_c$, and the phase difference of the voltage on each side of the junction between and (b) pendulum analogue.

A simple analogy of these effects is made by comparing a Josephson junction circuit to a pendulum. Fig 1.5 shows the representative circuit for a Josephson junction and next to it the pendulum analogue.

The circuit has a voltage drop across the junction, $V$. Because of this voltage a tunneling current of normal electrons will flow through the junction and this is represented by the resistance, $R$. $C$, denotes the capacitance caused by the proximity of the two superconducting metal surfaces and $i_s$ is the Cooper pair tunneling current.

$$i_s = i_c \sin \Delta \phi$$  \hspace{1cm} (1.2)

where $\Delta \phi$ is the phase difference of the current on both sides of the junction and $i_c$ is the critical current, the maximum current a superconductor can carry before superconductivity is lost. It can also be shown that the voltage across the Josephson junction is related to the phase difference by the relationship,

$$2V \cdot e = \hbar \frac{d}{dt} \Delta \phi$$  \hspace{1cm} (1.3)

The resulting current through this circuit equivalent of a Josephson junction is equal to the sum through each branch of the circuit.
\[ I = C \frac{dV}{dt} + \frac{V}{R} + i_s \]  

(1.4)

Substituting in the values calculated in Eq 1.2 and Eq 1.3 we find

\[ I = \frac{Ch}{2e} \frac{d^2}{dt^2} \Delta \phi + \frac{h}{2eR} \frac{d}{dt} \Delta \phi + i_s \sin \Delta \phi \]  

(1.5)

Using the pendulum analogue with a rigid rod of length, \( l \), mass, \( m \), angle of deflection, \( \theta \), applied torque, \( T \), and viscous dampening, \( \eta \) the relationship can be established

\[ T = M \frac{d^2}{dt^2} \theta + \eta \frac{d\theta}{dt} + mgl \sin \theta \]  

(1.6)

Similarities between Eq 1.5 and Eq 1.6 are immediately evident, and so the pendulum analogue can be used to understand a Josephson junction. A summary is given of all of the variables and their junction/pendulum analogue:

**Junction**

<table>
<thead>
<tr>
<th>Phase Difference ( \Delta \phi )</th>
<th>Deflection ( \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Current across junction ( I )</td>
<td>Applied torque ( T )</td>
</tr>
<tr>
<td>Capacitance ( C )</td>
<td>Moment of inertia ( M )</td>
</tr>
<tr>
<td>Normal Tunneling Conductance ( 1/R )</td>
<td>Viscous damping ( \eta )</td>
</tr>
<tr>
<td>Cooper pair tunneling current ( i_s = i_c \sin \Delta \phi )</td>
<td>Horizontal displacement of bob ( x = l \sin \theta )</td>
</tr>
<tr>
<td>Voltage across junction ( V = \frac{h}{2e} \frac{d}{dt} \Delta \phi )</td>
<td>Angular velocity ( \omega = \frac{d\theta}{dt} )</td>
</tr>
</tbody>
</table>

If a small constant torque is applied to the pendulum the mass is displaced a fixed distance \( x \). \( x \) remains a fixed variable until the horizontal displacement is equal to the length of the rigid rod (a 90° deflection). A torque of greater magnitude would cause a non static system to result and the pendulum mass would begin a periodic orbit. In the junction equivalent a current is set across the junction and a constant Cooper pair current is measured. The current can increase, causing the superconducting current to increase until the critical current is reached. At applied currents greater than this an oscillating current is measurable. The constant superconducting current (aka constant horizontal displacement) is the DC Josephson effect.

The AC Josephson effect is due to the oscillating current (or varying horizontal displacement) which is a result of currents greater than \( i_c \) (large torques). The average phase difference or frequency
of the oscillations, $f$, is related to the voltage across the Josephson junction as shown in Eq 1.1. This relationship between frequency and voltage is known as the AC Josephson effect.\(^{13}\)

The relationship shown in Eq 1.1 can be used in reverse if a current of microwave frequency is applied to the Josephson junctions and a voltage is measured. The only variables in Eq 1.1 are the frequency, $f$, and the voltage, $V_{dc}$. Because frequency (time) can be measured with extreme accuracy this relationship allows for precision voltage measurements. This voltage measurement is much more accurate than the Weston and wet cells of the past.\(^{14}\) The measured voltage across each Josephson junction is proportional to the input frequency (Eq 1.1) and can be biased to a different step level (-1, 0, 1...) with a dc current. On an oscilloscope showing Josephson junction current over a time sweeping voltage characteristic “voltage steps” can be seen. Fig 1.4 The current or input frequency can be set to a vertical region of the steps and a constant output voltage is generated.\(^{15}\)

Precision voltage measurements of up to 10 V have been achieved by putting many Josephson junctions in series. To cool the Josephson junctions to superconducting temperatures liquid He is used; liquid He is expensive, price is geography dependent, and is not a sustainable method of maintaining a voltage standard. Liquid He dewars required constant refills as the He evaporates into the atmosphere. Using a compressor that plugs into a standard wall outlet running on gaseous He as the working fluid is an economic, eco-friendly, and feasible alternative to liquid He voltage standards.

**Chapter 2: Experimental Apparatus and Technique.**

In our research we used a compressor using highly purified gaseous He as the working fluid in conjunction with a cryogen free vacuum chamber to maintain temperatures of \(\sim 4\) K. Sumitomo CNA-11 compressor units were used with an RDK-101D Janis/Sumitomo cold head system. The compressor units were modeled after a Gifford-McMahon cooler, detailed in Fig 2.1 High pressure gas enters the expansion space which is initially at a minimum volume. The expansion space then increases while the high pressure gas is still allowed to enter thus keeping the pressure constant in the chamber. The high pressure valve is then closed and the chamber is opened to the low pressure exhaust valve. The gas cools as it expands and the pressure of the gas decreases. The cooled gas can be used to absorb heat from its surroundings. The displacer/regenerator of the compressor forces the gas out of the expansion chamber, returning to the minimum expansion space and the idealized cycle can be repeated.\(^{16}\)
Figure 2.1 An idealized Gifford-McMahon cycle (a) High pressure gas enters the expansion space which is at a minimum (b) The expansion space increases while the high pressure gas is still allowed to enter the chamber therefore keeping the pressure constant (c) The high pressure gas valve is closed and the low pressure exhaust valve is opened. The gas cools as it expands into the exhaust value and the pressure decreases. The cooled gas can be used to absorb heat from its surroundings (d) The displacer/regenerator forces the gas out of the chamber and the expansion space is again at a minimum.

Figure 2.2. (a) Vacuum Jacket (b) Internal radiation shield of the gaseous He cryocooler system. The two shields reduced the temperature at the cold head. The external shield separates room temperature from a ~30 K vacuum. The internal shield intercepts room temperature radiation.
Figure 2.3. (a) Cold head (b) Wire with a 50 Ω resistance coiled underneath the Pb thermal ballast (c) Pb thermal ballast and cold head top stage

Figure 2.4. (a) Pb thermal ballast (b) Ni plated Cu (c) Si-Diode temperature sensor (d) Epoxy resin prepreg (similar to that of printed circuit boards) to provide structure for where the Josephson junction chip sits (e) Au plated Cu platform where the chip makes contact with the cold head (f) Thin indium metal providing the malleable contact between the Au/Cu platform and the back of the Josephson junction chip
Josephson junction chip set onto the indium metal contact site (b)(c) Compression apparatus

The parts of the cold head apparatus are detailed in Fig 2.2 to Fig 2.5. Fig 2.2 shows the external and internal cold head shields. Fig 2.3 shows the overview of the cold head and top stage. Fig 2.4 details the pieces of the cold head top stage and Fig 2.5 shows how the compression apparatus and the Josephson junction chip mount on the top stage.

Josephson junction chips were designed and manufactured by Paul Dresselhaus and Samuel Benz of the National Institute of Standards and Technology (NIST), Electronics and Electrical Engineering Laboratory, Quantum Devices Group in Boulder, CO. National Instruments LabVIEW software was run with LakeShore Temperature Controller models 332 and 218 and Si-Diode temperature sensors (SiDTNs).

2.1 Josephson Junction Chip Mounting

During the experiment various Josephson junction chips were mounted onto the cold head. The following process was followed for the dismounting and replacement of a chip at the cold head: the cold head was heated to room temperature using the 50Ω heater then the vacuum destroyed by opening the closed system to the atmosphere. The vacuum jacket and radiation shield surrounding the cold head were removed and the compression apparatus was carefully detached. The solder joints on the currently mounted chip were unsoldered and the chip was removed and stored. Before mounting the new Josephson junction chip it was soldered such that a voltage and current measurement could be made for each Josephson junction array. Fig. 2.6

The contact site on the cold head and new chip were cleaned with acetone and ethanol. A thin (0.005”) layer of indium metal or thermal grease was applied to the cold head contact site and the
new Josephson junction chip placed above – such that the two contact sites directly overlapped. The compression apparatus was re-assembled, the shields replaced and the chamber put under vacuum. A vacuum of $\sim 10^{-8}$ torr was restored and the compressor started to lower the temperature to $\sim 4$ K.

In this experiment we used chips 80904a-33, 60420-43, 60119-43, Y50907b-54, and 80904a-34 which had schematic layouts of NIST PV5, PV9, PV9, PV7 and PV5 – respectively. The schematic for NIST PV9 is shown in Fig 2.6.

![Figure 2.6. PV9 Josephson junction chip schematic. Labeled 1-9, A-G are each of the 16 arrays present on this chip design. The white squares at the top of the diagram are the locations of the soldering joints used in the experiment. The rectangular and triangle shaped boxes at the bottom of the figure mark the microwave input locations](image-url)
2.2 Josephson Junction Chip Calibration

Each Josephson junction chip required calibration before it could be used to take accurate temperature readings at the chip's surface. The 50 Ω heater was used to obtain temperatures between 2.8 K and 5.2 K with an increment step of 0.4 K. At each temperature a LabVIEW program was used to determine the critical current, or current where the array transitions from the superconducting to normal state, for each array present on the chip, see Fig 1.4. For each array the known temperature given by the Si-Diodes was plotted against the I_c measurements and fitted with a second order polynomial. That calibration was used to convert latter measurements of I_c into temperatures. Calibrations were only valid for the current chip mounting and had to be repeated for different chips or the remounting of a previously calibrated chip.

2.3 Thermal measurements

We created various temperature schemes to test the effectiveness of different chip backings and thermal interfaces between the chip and the mounting platform. The three schemes were (1) a DC bias on one or more Josephson junction arrays (2) a DC bias on the 50 Ω heater and (3) microwaves (AC). For schemes (1) and (3) temperature measurements were made by taking I_c measurements for each array and converting them into temperatures. Temperature measurements were recorded as distance from the array(s). For scheme (1) measurements were not taken on arrays directly adjacent to that of the biased array(s) because of the chip pin-out pattern. For scheme (2) measurements were taken using the Si-Diode temperature sensors (SiDTSs). These measurements were reported as the temperature present over the entire Ni plated Cu cold head surface. Fig 2.4b. Unless otherwise noted, temperature measurements were recorded using the SiDTSs at the Ni plated Cu cold head (2 sensors) and underneath the Pb thermal ballast (1 sensor) for all temperature schemes. Fig 2.4ab

Chapter 3: Experimental Results.

3.1 Thermometer Calibration

As mentioned in chapter 2.3, SiDTSs were used to measure the temperature at several locations on the top stage of the cold head. Due to the needed sensitivity of the thermometers they all required an initial calibration. At the beginning of the project all the thermometers were calibrated against a standard thermometer which had, in turn, been calibrated by the manufacturer. The 4 temperature sensors were placed directly next to each other on the Ni plated Cu partition of the cold
head. **Fig 2.4b.** Several data runs where conducted ramping the temperature from ~3-10 K. (An additional run from ~3-300 K was also conducted to provide some data points at higher temperatures.) The temperature was incremented in the vacuum chamber through the 50Ω heater (located underneath the Pb thermal ballast). SiDTS readouts were recorded in voltage across the diode (sensor units) and temperature (K) derived from the calibrated thermometer. A plot of both the low temperature and high temperature calibration runs can be seen in **Fig 3.1** and **Fig 3.2.** **Fig 3.1** shows a 2.5 – 11 K short calibration plotting the temperature against the voltage for each SiDTS. The calibrated SiDTS is shown in pink asterisks while the other three SiDTSs are shown in the remaining shapes. The figure clearly shows that the voltage versus temperature calibration differs for the sensors. **Fig 3.2** shows a 2.5 – 350 K long calibration with temperatures corrected as shown in **Fig 3.1.** The long calibration took fewer data points over the large temperature range because high precision temperature measurements are not needed at temperatures above 10 K. The short calibrations took many measurements at short intervals to build a precise calibration in the 2.5 – 10 K range.

For each data point in the plots, the 50 Ω heater was set with a particular DC bias voltage and the system allowed to reach thermal equilibrium. At equilibrium a set of voltage and temperature measurements were taken simultaneously on all four temperature sensors. The temperature readouts for the 3 sensors being calibrated were replaced with the temperature given by that of the standard. At any given temperature each sensor, having minute manufacturing differences, will read a different voltage but that voltage is characteristic of the same temperature. The calibration voltage and temperature points were loaded into the LakeShore instrument software. The software uses interpolation through a Chebyshev polynomial fit to the discrete data points.

### 3.2 Temperature Stability

The Gifford-McMahon expander in the coldhead runs at a frequency of 1.2 Hz. (See chapter 2 and **Fig 2.1** for more on Gifford-McMahon coolers.) Heat is extracted from the coldhead during approximately half of the cycle leading to an oscillation of the temperature at the coldhead which is partially damped by the lead thermal bias. To evaluate the effectiveness of the ballast the amplitude of the 1.2 Hz temperature oscillations were measured as a function of temperature. Temperature measurements taken using a SiDTS located on Ni coated Cu surface and the 50 Ω heater. The 50 Ω heater ramped the temperature at 1 K intervals from 2.5 – 7.5 K. Variations in temperatures measurements were assumed to be caused by compression and expansion of the compressor cold
**Figure 3.1.** Short calibration run from 2.5 – 11 K without temperature correction. Temperature is plotted against the voltage for each SiDTS. Because only the pink asterisk data has been calibrated for a simultaneous temperature reading (each horizontal data set) the temperature values do not match.

**Figure 3.2.** Long calibration run from 2.5 – 350 K with temperature correction. The pink asterisk data was used as the calibrated standard and the three other thermal sensors were calibrated to its temperature reading. Each horizontal data set has the same temperature reading.
Figure 3.3. Plot of the fluctuation in temperature caused by compression and expansion of the gaseous He working fluid in the compressor. The fluctuation measurements were taken at mean temperatures from 2.5 – 7 K with an interval step of 1 K. Fluctuations are seen to be small averaging less than 0.1 K between compression cycles.

Figure 3.3 shows those variations measured by the difference between the peak and the trough temperature. Those variation measurements were taken at mean temperatures of 2.5 – 7 K at 1 K intervals.

The temperature fluctuations at the cold head were shown to be minimal, averaging less than 0.1 K between compression cycles. The small fluctuation in temperature signifies that a gaseous He cryogenic compressor system can be used to achieve low and stable temperatures in the operating range of a Josephson junction chip (2-10 K, ideally 2-6 K). The appearance of highs and lows in between the 2.5-7.5 K temperature range were most likely caused due to the PID (proportional–integral–derivative) settings used on the LakeShore device.

3.3 Compressor Units in Parallel

The goal of this work was to show that we could use compressors in parallel to achieve lower temperatures than using one compressor. Temperature measurements were taken on chip 80904a-33 while slowing increasing the power across the 50 Ω heater; measurements were first taken using one
compressor then repeated using two compressors, connected in series. Fig 3.4 shows that the addition of a second compressor lowered the temperature at the cold head by ~0.5 K at targeted operational chip power of 200 mW.

3.4 Josephson Junction Chip Packaging

Two different substrate materials were evaluated for the chips, Standard Si and High Purity Si. In addition, some chips were coated with PdAu on the back/contact side in an attempt to decrease the interface thermal resistance. Chips with backings made of Pd/Au, High Purity Si (Si-Pure), and Standard Si (Si) were tested along with contact interfaces of indium metal and thermal grease.

The indium metal and thermal grease (Fig 3.5) were applied to the Au plated Cu platform on the cold head (Fig 2.3a)

A 120mW DC bias was applied to an edge array and temperature measurements were taken using the adjacent arrays to determine the effectiveness of each contact interface. The tests were performed on chip 80904a-33 and we found the thermal grease to be completely ineffective at 4 K. \(I_c\) measurements could not be taken on the chip with that interface because so little current or heat was
The two thermal interfaces we experimented with were indium metal and thermal grease. (a) shows the paper thin indium metal layer still adhered to the Josephson junction chip after dismounting and (b) shows a thin layer of thermal grease applied to the Au plated Cu platform.

required to cause the array to stop superconducting. The extremely poor performance of the thermal grease was thought to be caused by the freezing of the thermal grease followed by shearing of the contact as the Au coated Cu contracts at a slightly different rate than that of the Josephson junction chip. Mounting a chip with no interface produces results similar to or worse than those seen with the thermal grease because few points of contact would exist to allow the heat to transfer from the chip to the cold head base.

Indium metal was previously used as the standard contact interface and therefore showed no unexpected results. Indium is an extremely soft and malleable metal that can press into the surface imperfections on the Au/Cu platform and the chip backing. This creates more points of contact between the two surfaces allowing heat to flow more quickly from the chip to the cold head base.

Fig 3.6 shows the effectiveness of the three different chip backings (Si, Si-Pure, and Pd/Au with Si-Pure) in their ability to remove heat from the Josephson junction chip. The figure shows the difference between the array temperature and the coldhead temperature as a function of distance from the array used as a heater. Thermal interfaces that are more effective at removing heat from the chip will have lower $\Delta T$ values while those that are less effective will have larger values. Temperatures decrease as distance from the heater array increase because there have been more modes for the temperature to be absorbed, through the cold head or through other arrays.

Unfortunately, the measurements shown in Fig 3.6 do not yield strong conclusive evidence that one chip backing is more effective at removing heat from the Josephson junction arrays than another.
Figure 3.6. Temperature change between the Josephson junction arrays and the cold head as a function of distance from the heated array. The orange data represents a chip with a silicon backing (Si). Its comparatively elevated position in comparison to the other curves shows that Si is the least effective of the three materials tested in removing heat from the chip to the cold head. The pink dashed data represents a pure silicon backing (Si-Pure) and the green data represents a Si-Pure with Pd/Au backing (Pd/Au with Si-Pure). The Si-Pure and Pd/Au with Si-Pure data differ by less than the uncertainty in their measurements so neither material was seen conclusively to be more effective at removing heat from the chip than the other. Temperature difference decreases as distance from the heated array increases because the heat has had more modes through which to dissipate the heat – other arrays, the thermal interface, and the cold head.

The Si chip was the poorest heat conductor of all three backings as marked by its high position in Fig 3.6 but the Si-Pure and the Pd/Au (with Si-Pure) showed temperature variances that were within the noise of the measurements making it impossible to distinguish one as being more effective than the other. It appears that Pd/Au could allow greater heat conduction because its curve is lower in Fig 3.6 but experimentation is still required.

Initially we assumed that calibrations for a particular chip were valid, even during different mountings. Unfortunately it was not fully discovered until late in the experiment that calibrations were sensitive to the mounting process and needed to be performed after every mounting (including a re-mounting). Building more accurate calibration curves and comparing chips of the same array layout could help narrow the ±0.1 K variance in the temperature measurements shown in Fig 3.6.
3.5 ANSYS Finite Thermal Analysis

In addition to determining which chip backing and contact interface materials were most effective at removing heat from the Josephson junction arrays we also calculated the thermal conductance of several of the interfaces. Calculations were carried out using the thermal finite analysis program ANSYS. Experimental temperatures of Josephson junction arrays at various distances from the heated array (data such as is shown in Fig 3.6) were compared to ANSYS models of how the arrays would function under particular thermal conductances.

In the model all heat was assumed to exit only through the bottom face of each layer used in the model. The model only accounted for the materials present above (and including) the Au coated Cu platform to (but not including) the compression apparatus. Each model array was assumed to have the same temperature over the entire array. Thermal conductance values (G) that were obtained from the program were those for the indium metal interface (G_{interface}) and the Si present in the chip (G_{Si}). The indium metal represented the ability of heat to leave the chip to the cold head and the Si represented the ability of heat to flow laterally from the heated array to those adjacent – prior to leaving the chip through the indium metal. Fig 3.7 shows temperature output from the program by color, red indicating the highest and dark blue the lowest, while Table 3.1 shows the calculated thermal conductance values.

![Figure 3.7](image)

Figure 3.7. A visual representation of the thermal conductance fitting completed through ANSYS. The red array marks where heat is entering the system (the heated array) and in color contours it can be seen how heat dissipated through the chip
Table 3.1. Thermal Conductances

<table>
<thead>
<tr>
<th>Chip</th>
<th>Chip Model</th>
<th>Chip Backing</th>
<th>$G_{Si}$ (W/K·m)</th>
<th>$G_{interface}$ (W/K·m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80904a-33</td>
<td>PV5</td>
<td>Pd/Au with Si-Pure</td>
<td>80 ± 5</td>
<td>0.030 ± 0.002</td>
</tr>
<tr>
<td>Y50907B</td>
<td>PV7</td>
<td>Si</td>
<td>55 ± 5</td>
<td>0.012 ± 0.002</td>
</tr>
<tr>
<td>60420-43</td>
<td>PV9</td>
<td>Si-Pure</td>
<td>20 ± 5</td>
<td>0.022 ± 0.002</td>
</tr>
<tr>
<td>60119-43</td>
<td>PV9</td>
<td>Si-Pure</td>
<td>20 ± 5</td>
<td>0.028 ± 0.002</td>
</tr>
</tbody>
</table>

The values obtained for $G_{Si}$ showed unexpected characteristics. A lower thermal conductance should be measured for the Si when compared to the Si-Pure. The PV9 model chips with Si-Pure show a lower $G_{Si}$ than the Si in the PV7 model but the Si-Pure in the PV5 model shows a much higher $G_{Si}$ than all other measurements. The source of these large variances in thermal conductances remains unclear.

After a multitude of measurements were taken we concluded that the ANSYS fits were bimodal, consistently producing different results for PV9 chips than PV5 or PV7. It is possible that the ANSYS model used was too simple and a more complex model could correct for the bimodal discrepancy and the irregularity in the $G_{Si}$ values. Since the PV5 PV7 and PV9 chips have different number of arrays and different number of junctions in each array, it is also possible that there is an additional thermal conductance between the arrays and the chip that is not considered in the models used here.

Chapter 4: Conclusion.

Using gaseous He as the compressor working fluid is an effective way of obtaining stable temperatures as low as 2.8 K in a 4 K closed cycle refrigerator system. It was found that gaseous He compressors used in parallel are effective at removing the heat from a Josephson junction chip and can do so without large temperature fluctuations in between compression cycles.

This allows for a more cost effective way to maintain a voltage standard. The cost savings increase dramatically for those countries that do not have a natural source of He. Liquid He at the time of this publishing sells for $\sim$500 per 100 L (the smallest purchasing quantity) but is at least 10 times that price for countries such as Australia that do not have a natural He source. Further, the use of gaseous He is more ecologically sustainable than that of liquid He. Liquid He is lost into the atmosphere after evaporation and has a short and limited shelf life. Gaseous He, too, can leak out of
closed systems and be lost to the atmosphere but does so at a much slower rate than liquid He.

The use of indium metal and a contact interface between the Josephson junction chip and the cold head platform was found to be highly effective at allowing heat to flow away from the chip to the cold head. Indium metal was found to yield greater reductions in temperature on the Josephson junction chip than thermal paste or no material at the contact interface.

No conclusive evidence was found to determine whether a Si-Pure or Pd/Au with Si-Pure chip backing was better able to remove heat from the Josephson junction arrays. Further testing is required to determine any possible advantage using Pd/Au in addition to Si-Pure.

Finally, we found that running two compressors in parallel is an effective way to reduce the temperature at the cold head by ~0.2 K. The apparatus used in this experiment could maintain temperatures of 4–5 K with input at the design power of 200 mW. Because the maximum allowable temperature under the design parameters was 6 K the addition of a second compressor is not necessary, but there is a lower chance of quantum impurities such as fluxons – quantum units of electromagnetic flux – from entering the system at lower temperatures.
References

9. Chu, C. W. "Superconductivity above 150 K in HgBa2Ca2Cu3O8+δ at high pressures". Nature 1993 365, pp. 323