FINAL PROGRESS REPORT

National Nuclear Security Administration Stewardship Stockpile Academic Alliance Research Grant #DE-FG52-03NA00068

This grant, entitled "Experimental investigation of magnetic, superconducting and other phase transitions in novel f-electron materials at ultrahigh pressures," spanned the funding period from May 1st, 2003 until April 30th, 2006. The major goal of this grant was to develop and utilize an ultrahigh pressure facility—capable of achieving very low temperatures, high magnetic fields, and extreme pressures as well as providing electrical resistivity, ac susceptibility, and magnetization measurement capabilities under pressure—for the exploration of magnetic, electronic, and structural phases and any corresponding interactions between these states in novel f-electron materials. Realizing this goal required the acquisition, development, fabrication, and implementation of essential equipment, apparatuses, and techniques. The following sections of this report detail the establishment of an ultrahigh pressure facility (Section 1) and measurements performed during the funding period (Section 2), as well as summarize the research project (Section 3), project participants and their levels of support (Section 4), and publications and presentations (Section 5).

1. ULTRAHIGH PRESSURE FACILITY

a. Dilution Refrigerator System

As many f-electron materials exhibit structural, magnetic, and superconducting phase transitions at low temperature, a dilution refrigerator proves to be an extremely useful experimental tool for the investigation of these materials. We purchased our Oxford Kelvinox MX-100 dilution refrigerator during the first year of this grant and it arrived at our laboratory near the end of that year. Before installing and operating the refrigerator, it was necessary to construct a structure to support the weight of the refrigerator and the associated liquid helium dewar as well as to vibrationally isolate the refrigerator system from the floor and the pumps that would be used to operate the system. Air springs were chosen as vibrational dampers for this structure and have proven more than capable of supporting the weight of the system while virtually eliminating heating due to external vibrations. An additional hoisting structure was fabricated for the purpose of raising and lowering the dilution refrigerator insert, which is equipped with a sliding seal to prevent excessive liquid helium boil-off, into the dewar. When used with the sliding seal, this hoisting structure provides a quick cooling time for the insert, which takes approximately six hours to cool from 300 K down to liquid helium temperatures, while keeping liquid helium boil-off below 20 liters. With the ancillary structures completed, the dilution refrigerator was tested and certified by an Oxford technician who successfully operated the refrigerator down to ~ 13 mK. An experimental tail was fabricated and attached to the mixing chamber of the dilution refrigerator, the source of the cooling power of the system, on which a variety of high-pressure cells could be attached. The experimental tail provides a thermal link to the mixing chamber while placing the pressure cells and their associated samples in the center of the magnetic field produced by the 9 T superconducting magnet contained in the liquid helium dewar.

b. Diamond Anvil Cells

We have designed and fabricated a screw-type diamond anvil cell (DAC), in which two diamonds are used as anvils to compress a sample located inside of a gasket, for use at pressures in excess of 1 Mbar and temperatures down to the mK range. The DAC was constructed from non-magnetic beryllium-copper, permitting its use in high magnetic fields. Pressure is applied to the diamonds via a piston that is translated in a direction perpendicular to the culets of the diamonds by a fine thread screw. As misalignment of the diamond anvils can result in premature failure of an experiment and subsequent destruction of the diamonds, orientation of the diamond anvils is crucial to achieving high pressures. The screw-type DAC was designed to provide two types of alignment: horizontal alignment is accomplished by translating the bottom diamond within a plane parallel to the table (and culet for appropriately cut and polished diamonds) by means of four set screws; angular alignment is achieved by adjusting a hemispherical rocker plate, to which the top diamond is affixed, with three set screws. The DAC provides ample optical access to the sample space through holes along the centerline of the DAC as well as four windows on the sides of the DAC.

c. Diamonds

We have purchased six 1/3-carat diamonds for use as diamond anvils. Three of the diamonds were exchanged with Sam Weir at (LLNL) for two designer diamonds with resistivity microprobes and one designer diamond with a multiloop coil to be used for ac susceptibility measurements. A blank diamond and designer diamond make a pair of anvils that can be used in a DAC.

d. Ruby Fluorescence Pressure Calibration

Pressure calibration in a DAC is usually achieved via ruby fluorescence, wherein a laser is used to excite a pressure-dependent emission line of ruby (694.2 nm at ambient pressure), which is situated inside of the sample chamber of the DAC, that is detected using a spectrometer. A typical pressure measurement setup consists of a laser, spectrometer, and microscope, all of which we have acquired or fabricated. In our setup, we use a solid-state blue laser (CrystaLaser, 473 nm), a spectrometer consisting of a CCD camera and SPEX 500M monochromator (Jobin Yvon), and a specially designed microscope equipped with a stage on which the DAC rests. The laser light enters the microscope and is reflected inline with the microscope optics towards the ruby in the sample chamber by a dichroic mirror, which reflects wavelengths below 550 nm (i.e., the blue laser light) and passes longer wavelengths (i.e., the red ruby fluorescence). White light can be used in conjunction with the laser light to center and focus the sample chamber by adjusting the stage. The ruby fluorescence is gathered by a 20X long working distance objective, which is necessary to focus through the diamond that is contained within the cell, and passes back through the dichroic mirror and a red filter, used to eliminate any scattered laser light, towards a beamsplitter that directs half of the signal to a 10X eyepiece for viewing and half of the signal to a fiber optic bundle. The fiber optic bundle directs the light into the aperture of the spectrometer, where the resulting spectrum provides information on the pressure and its homogeneity in the sample chamber.

The CCD camera is an area detector that, when combined with the appropriate diffraction grating of the monochromator, is capable of recording a window of wavelengths that easily encompasses the pressure-dependent portion of the ruby fluorescence spectrum. Furthermore, the spectrometer system is computer controlled, permitting quick analysis of the pressure distribution in the DAC such that precise pressure steps may be taken when conducting an experiment.

e. *In situ* Pressure Calibration

We have previously constructed a ruby fluorescence microscope for calibrating the pressure inside the sample chamber of the diamond anvil cell at room temperature. In addition to room temperature measurements of the pressure, we would also like to be able to calibrate the pressure at low temperatures to account for pressure losses due to differential thermal contraction with changing temperature. To that end and in conjunction with RoMack Fiber Optics, we have designed a custom fiber-optic patch cord for use at the low temperatures and the moderate vacuum associated with our measurement apparatus. This patch cord will gather laser light from a 473 nm solid state laser and direct it along the multimode fiber into the cryostat directly at the ruby within the diamonds. The same fiber will collect the fluorescence spectrum and direct it out of the cryostat to the spectrometer. This system should allow pressure calibration as a function of temperature down to 1 K. With this information, we will attempt to minimize the pressure losses due to differential thermal contraction by using additional materials or components with different coefficients of thermal expansion such as Delrin or Belleville springs.

f. Micro EDM

The successful use of a DAC can be very dependent upon the quality of the gasket and thus the sample space used in the experiment. A gasket must be pre-indented and a hole must be drilled in the center of that indent to provide a sample chamber. The drilling of the gasket is extremely important, because burrs or deformations can result in failure of the DAC at relatively low pressures. The preferred technique for preparing the sample chamber of a DAC is to use a micro Electric Discharge Machine (EDM) to electrically cut the hole in the gasket. Using an EDM has two distinct advantages over micro drilling: the drilled holes have no burrs, and the lack of physical contact between the bit and the gasket yields a strong, deform-free chamber. Our EDM, purchased from Hylozoic Products, has several different wire attachments for drilling various sized holes in the gasket. In addition, we have created cutting plates and disk borers to further shape the samples used in the high-pressure experiments. A Nikon SMZ-660 stereoscopic microscope is used to visually align the object to be machined.

g. Magnetization Pressure Cell

With magnetic and superconducting systems, it can be illuminating to explore the magnetic behavior of these phenomena as a function of pressure, magnetic field, and temperature. To that end, we have designed and fabricated a pressure cell for use in a commercially available Quantum Design Superconducting Quantum Interference Device

(SQUID) Magnetic Properties Measurement System (MPMS), which is capable of measuring small moment dc magnetization as a function of temperature (2 K up to 340 K) and field (up to 5.5 T). The cell is constructed of non-magnetic beryllium-copper. The internal bore of the cell, which is 2.5 mm, houses a Teflon capsule (1 cm long) in which the sample under scrutiny is enclosed along with a pressure-transmitting medium. The cell was designed to be significantly longer than the distance between the SQUID detection coils in order to provide the smallest background possible. Based on the yield strength of the material and the dimensions of the sample space relative to the outer diameter of the cell, the cell should be capable of reaching pressures of approximately 12 kbar. The relatively low pressures achievable are confined by the constraints of the magnetometer measurement chamber. Preliminary results on a sample of lead, which can be used to calibrate the pressure-force dependence of the cell owing to the well-known pressure dependence of the superconducting transition temperature, indicate a large signal-to-noise ratio. Pressure is applied to and maintained in the Teflon capsule by means of a hydraulic press and a locking screw on the cell, respectively.

2. MEASUREMENTS PERFORMED

a. $PrFe_4Sb_{12}$

We have synthesized and measured single crystals of the filled skutterudite compound $PrFe_4Sb_{12}$, a heavy fermion, weak ferromagnet with an ambient pressure Curie temperature of T_C = 4.1 K, as determined by neutron diffraction and modified Arrott plot analysis. A broad peak in the specific heat centered at ~ 4 K, a shoulder in the resistivity data at ~10 K (with an inflection point at T ~ 4.8 K), lack of saturation in M(H), and large value of μ_{eff} / M_{sat} all suggest the presence of an itinerant Fe moment. The electrical resistivity of $PrFe_4Sb_{12}$ has been shown to be very weakly dependent upon magnetic field and pressure. The Curie temperature of $PrFe_4Sb_{12}$ decreases only slightly with applied pressure, evolving from an ambient pressure value of T_C = 4.8 K (defined as the inflection point in the electrical resistivity as a function of temperature) to a minimum value T_C = 3.9 K at the maximum pressure of 23 kbar. A preliminary estimate of the critical pressure at which ferromagnetism is suppressed in $PrFe_4Sb_{12}$ was performed and results suggest a critical pressure of approximately 100 kbar, a pressure well within the range of diamond anvil cell technology.

b. $NdOs_4Sb_{12}$

We have also synthesized and measured another filled skutterudite compound similar to $PrFe_4Sb_{12}$. $NdOs_4Sb_{12}$, like its relative $PrFe_4Sb_{12}$, is a heavy fermion compound with a large $\gamma \approx 435$ mJ/mol-K^2 corresponding to an effective mass $m^* \sim 82\ m_e$. Weak, mean-field-type ferromagnetism was also observed in this compound with an ambient pressure Curie temperature of T_C ~ 1 K. Electrical resistivity measurements indicate the presence of both s-f exchange coupling and aspherical coulomb scattering. Low temperature electrical resistivity measurements also suggest the existence of spin-wave excitations below T_C. It was found that the ferromagnetic transition in $NdOs_4Sb_{12}$ increases with pressure up to a value of T_C = 1.8 K at 28 kbar. The pressure dependence of the Curie temperature, however, displays a reduction in the rate of increase indicating the possible existence of a maximum at a pressure of approximately 35 kbar and a subsequent suppression of magnetism for higher pressures.

c. $PrOs_4As_{12}$

Single crystals of the filled skutterudite compound $PrOs_4As_{12}$ were obtained from Z. Henkie (Polish Academy of Sciences) and were characterized via measurements of bulk magnetization, electrical resistivity, and specific heat. In collaboration with S. McCall and M. W. McElfresh (Lawrence Livermore National Laboratory), specific heat measurements were extended to high field. In this heavy fermion compound, two bulk phase transitions are observed at ~2.2 K, below which the material shows behavior consistent with antiferromagnetic order. Specifically, magnetization measurements in field demonstrate a lack of magnetic hysteresis and provide evidence of a Pr^{3+} crystal field-split magnetic ground state, while the low-temperature electrical resistivity shows behavior consistent with the opening of a magnon energy gap. In applied magnetic field, the antiferromagnetic phase is suppressed by ~1.7 T and makes a transition into another ordered phase, currently speculated to be quadrupolar in nature, that is suppressed by ~3.2 T. In the paramagnetic state of $PrOs_4As_{12}$, both resistivity and specific heat measurements show clear signs of single-ion Kondo behavior. The electrical resistivity was measured at several pressures up to 23 kbar, between 1 K and 300 K, and no significant pressure dependence was found. However, it is expected that at higher pressures, the low-temperature ordered phases of $PrOs_4As_{12}$ will be suppressed, and we plan to measure the electrical resistivity at pressures exceeding 30 kbar.

d. $CeRh_{1-x}Co_xIn_5$

We have performed hydrostatic pressure measurements on the f-electron material $CeRh_{1-x}Co_xIn_5$ using a piston-cylinder clamp. Pressure measurements up to 28 kbar were made on samples with Co concentrations x = 0.1, 0.2, 0.4, and 0.6. Co concentrations of x = 0.1 and 0.2 display antiferromagnetism at ambient pressure and pressure-induced superconductivity at pressures of 6.9 kbar and 8.8 kbar, respectively. Antiferromagnetism and superconductivity coexist until magnetic order is suppressed toward a QCP at approximately 24 kbar for both concentrations. Samples with Co concentrations of x = 0.4 and 0.6 exhibit ambient pressure superconductivity; however, x = 0.4 shows signs of antiferromagnetism at ambient pressure while one at x = 0.6 shows no signatures of antiferromagnetism in electrical resistivity. For x = 0.4, antiferromagnetism is quickly suppressed toward a quantum critical point at $P_c \sim 6$ kbar, after which superconductivity persists to the highest pressures measured. For x = 0.6, superconductivity exists at ambient pressure and persists to the highest pressures measured. Unlike other heavy fermion compounds where superconductivity exists in a small region surrounding the QCP, $CeRh_{1-x}Co_xIn_5$ exhibits superconductivity over a broad region that is not necessarily centered upon the QCP. It was found that all concentrations measured display non-Fermi liquid behavior even to the highest pressures measured, consistent with other heavy fermion materials near a QCP.

e. URu_2Si_2

The f-electron compound URu_2Si_2 is a very interesting material that displays many novel properties including: moderately heavy fermion behavior with $m^* \sim 25\ m_e$; a "hidden order" transition at $T_{HO} \approx 17.5$ K, which coincides with a small-moment antiferromagnetic transition at the same temperature; and a superconducting transition at $T_c \approx 1.3$ K. Previous experiments from our laboratory suggest that the "hidden order" and the superconductivity both occupy a fraction of the Fermi surface. Upon the application of pressure, it has been shown that the "hidden order" gives way to bulk antiferromagnetism at $P_c \approx 15$ kbar a pressure near where the superconductivity extrapolates to zero temperature. We have performed electrical resistivity measurements as a function of temperature, pressure, and applied magnetic field. Preliminary results of the evolution of the upper critical field H_{c2} for the superconductivity reveal a change in curvature at low fields. The results of these measurements indicate that the superconductivity and $H_{c2}(0)$, the upper critical field at zero temperature, are indeed suppressed at $P_c = 15$ kbar. Furthermore, the upper critical field lines, when plotted as $H_{c2}/H_{c2}(0)$ vs. T/T_c, scale to lie atop each other for the different pressures measured, suggesting that the superconducting state is not fundamentally altered with pressure and that pressure is acting as a pair-breaking mechanism only. Measurements of the T_{HO} as a function of applied pressure reveal a distinct change in slope near 15 kbar, with T_{HO} more than doubling from a slope of approximately 0.10 K/kbar at low pressures to a high-pressure slope of approximately 0.23 K/kbar. Much of the data obtained in this study, as well as data previously reported, indicate a distinct change in either the electronic or magnetic structure of the system, implying an intimate link between the "hidden order" state and superconductivity that could be used to understand the nature of the "hidden order" state.

f. Dilute $Au_{1-x}V_x$ Alloys

In an effort to understand the dramatic increase in the Curie temperature—and likely the magnetic exchange interaction—of Au_4V, we have synthesized low V concentration $Au_{1-x}V_x$ alloys with x = 0.1, 0.05, 0.02, 0.01, 0.005, and 0.0025. Electrical resistivity measurements of the alloyed samples exhibit characteristic signatures of the presence of local moments in the Au host with the concentrations below 1% (x = 0.01) displaying an upturn in the electrical resistivity at low temperature, a classic hallmark of the Kondo effect. A sample with 0.5% vanadium was mounted in a hydrostatic pressure cell and electrical resistivity measurements were performed from 1 K – 300 K. The characteristic minimum is seen to increase slightly with increasing pressure. Analysis of the data reveals an increase in the Kondo temperature T_K of the sample from ~180 K at ambient pressure to ~200 K at almost 30 kbar. Like the Curie temperature in Au_4V, the increase in the Kondo temperature of $Au_{0.995}V_{0.005}$ suggests an increase in the magnetic exchange interaction. The change in the Kondo temperature of this sample was used to estimate the change in the magnetic exchange coupling J_K as a function of pressure.

g. Au_4V

We have measured the electrical resistivity of the ferromagnetic compound Au_4V under hydrostatic pressure up to 25 kbar. The electrical resistivity of Au_4V as a function of temperature displays a characteristic kink corresponding to ferromagnetic ordering in the system at approximately $T_C = 45$ K. With applied pressure, the Curie temperature of a single-crystal sample increases to a value of $T_C = 52$ K. A crystalline sample of Au_4V was filed into a fine powder and, with our collaborator Sam Weir, loaded into a DAC at

LLNL. High-pressure electrical resistivity measurements were performed on the Au_4V powder at LLNL up to a pressure in excess of 200 kbar. The results are in excellent agreement with the lower pressure hydrostatic cell data taken at UCSD. The high-pressure diamond anvil studies indicate that the Curie temperature of Au_4V continues to increase to a value of $T_C \sim 90$ K at a pressure of approximately 180 kbar. Above 180 kbar, no resistive transition due to the onset of ferromagnetism could be resolved. In collaboration with Yogesh Vohra of the University of Alabama, Birmingham, X-ray diffraction measurements were performed in a diamond anvil cell. These diffraction measurements revealed a gradual structural phase transition from the body-centered-tetragonal crystal structure of Au_4V to the disordered face-centered-cubic structure of $Au_{1-x}V_x$ between 180 and 270 kbar. Combining the data from Au_4V and the experiment on $Au_{1-x}V_x$ as mentioned above, we have posited that the strong increase in the Curie temperature for Au_4V is due to an increase in the number of vanadium ion nearest neighbors. Furthermore, within the framework of our postulate, the pressure at which the number of vanadium ion nearest neighbors equals that of the alloy $Au_{1-x}V_x$ very nearly coincides with the pressure at which we observe the disappearance of a ferromagnetic transition and within the range of pressures obtained from X-ray experiments where the sample undergoes a structural phase transition.

3. PROJECT SUMMARY

We have successfully created an ultrahigh pressure research facility that is capable of investigating a wide range of materials using techniques such as electrical resistivity, ac susceptibility, and magnetization measurements under applied pressure. This facility has the capability of achieving a wide range of pressures up to 1 Mbar using piston-cylinder, Bridgman anvil, and diamond anvil cells, which, owing to the differing natures of the three aforementioned techniques, provide overlapping pressure regimes as well as various sample configuration options.

Measurements have been performed over a large range of pressures. In the low-pressure regime, we have investigated the magnetic ordering of several rare earth filled skutterudite compounds. The robust character and minimal pressure dependence of the magnetism present in these compounds is particularly interesting and is possibly caused by the large unit cell volume of these compounds. Additionally, quasihydrostatic measurements of the $CeRh_{1-x}Co_xIn_5$ system have revealed quantum critical behavior and superconductivity over a wide range of parameter space around an antiferromagnetic quantum critical point, a point where magnetic order is suppressed to zero temperature by a tuning parameter, in this case, applied pressure and doping. This research highlights the peculiar interdependence of quantum criticality and superconductivity, two phenomena thought to exist in the high temperature cuprate superconductors and thus of great interest to superconducting materials applications. Furthermore, the heavy fermion material URu_2Si_2 has been investigated as a function of applied pressure and magnetic field. Results indicate that the superconductivity present at ambient pressure is suppressed to zero temperature near 15 kbar, the pressure at which the "hidden order" state is seemingly converted to long-range antiferromagnetic order. The coincidence of the suppression of superconductivity and the appearance of antiferromagnetism suggest that the superconductivity could be the ground state of the "hidden order" phase, which would provide an empirical restraint upon any theories describing this enigmatic phase that has remained "hidden" for 20 years. The compound Au_4V and its related alloy $Au_{1-x}V_x$ were examined by means of electrical resistivity up to 200 kbar and via X-ray diffraction up to 600 kbar using diamond anvil cell techniques. Results from this experiment suggest that the ferromagnetism of Au_4V is intricately linked to its annealed crystal structure, and that a high-pressure structural phase transition is partly responsible for the destruction of ferromagnetism.

The research that has been performed in the ultrahigh pressure facility at UCSD has been greatly beneficial to the fields of magnetism, superconductivity, quantum criticality, and heavy fermion behavior. This research illustrates the vast experimental success that can be garnered from exploring the properties of materials under extreme conditions such as low temperatures, high magnetic fields, and high pressures.

4. PROJECT PARTICIPANTS

Faculty

Name: M. Brian Maple
Percent Contribution: 10%
Contribution to Project: Research group leader and Principal Investigator.

Administrative Assitant

Name: Carolyn Rosado
Percent Contribution: 25%
Contribution to Project: Performs tasks benefiting the project including preparing or assisting in the development of manuscripts, illustrations, publication artwork, technical presentations; arranging travel of PI, graduate students, or collaborating faculty; and maintaining our research database.

Assistant Project Scientist

Name: Pei-Chun Ho
Percent Contribution: 50%
Contribution to Project: Designs and performs laboratory experiments in collaboration with PI.

Graduate Students

Name: Jason R. Jeffries
Percent Contribution: 100%
Contribution to Project: Prepares intermetallic samples and performs high-pressure measurements, responsible for development and implementation of ultrahigh pressure facility.

Name: Nicholas P. Butch
Percent Contribution: 100%

Contribution to Project: Prepares intermetallic samples and performs measurements of magnetic and transport properties of f-electron materials.

Name: Ryan E. Baumbach
Percent Contribution: 100%
Contribution to Project: Prepares thin film and polycrystalline samples of intermetallic f-electron and high temperature superconducting compounds and performs magnetic and electrical transport measurements.

Name: Neil A. Frederick
Percent Contribution: 25%
Contribution to Project: Prepares filled skutterudite compounds and performs specific heat, magnetization, and transport measurements on heavy fermion, non-Fermi liquid, and other f-electron materials.

Name: Todd A. Sayles
Percent Contribution: 25%
Contribution to Project: Prepares intermetallic samples and performs specific heat, magnetization, and transport measurements.

Name: Daniel J. Scanderbeg
Percent Contribution: 10%
Contribution to Project: Prepares thin film samples of high temperature oxide superconductors and performs magnetization and transport measurements.

Name: Benjamin J. Taylor
Percent Contribution: 10%
Contribution to Project: Prepares thin film samples of high temperature oxide and intermetallic superconductors and performs magnetization and transport measurements.

Undergraduate Students
Name: Stella K. Kim
Percent Contribution: 100%
Contribution to Project: Prepares filled skutterudite and intermetallic compounds.

Name: Patrick Johnson
Percent Contribution: 100%
Contribution to Project: Prepares intermetallic compounds with an emphasis on the synthesis of 1-1-5 alloys.

5. PUBLICATIONS AND TECHNICAL PRESENTATIONS

a. Publications in Refereed Journals

- P. –C. Ho, W. M. Yuhasz, N. P. Butch, N. A. Frederick, T. A. Sayles, J. R. Jeffries, M. B. Maple, "Ferromagnetism and possible heavy fermion behavior in single crystals of $NdOs_4Sb_{12}$," *Phys. Rev. B* **72**, 094410 (2005).

- J. R. Jeffries, N. A. Frederick, E. D. Bauer, H. Kimura, V. S. Zapf, K. –D. Hof, T. A. Sayles, and M. B. Maple, "Superconductivity and non-Fermi liquid behavior near antiferromagnetic quantum critical points in $CeRh_{1-x}Co_xIn_5$,"*Physical Review B* **72**, 024551 (2005).

- N. P. Butch, W. M. Yuhasz, P. –C. Ho, J. R. Jeffries, N. A. Frederick, T. A. Sayles, M. B. Maple, J. B. Betts, A. H. Lacerda, F. M Woodward, J. W. Lynn, P. Rogl, and G. Giester, "Ordered magnetic state in $PrFe_4Sb_{12}$ single crystals," *Physical Review B* **71**, 214417 (2005).

- M. B. Maple, N. P. Butch, N. A. Frederick, P.-C. Ho, J. R. Jeffries, T. A. Sayles, T. Yanagisawa, W. M. Yuhasz, Songxue Chi, H. J. Kang, J. W. Lynn, Pengcheng Dai, S. K. McCall, M. W. McElfresh, M. J. Fluss, Z. Henkie, and A. Pietraszko, "Field-dependent ordered phases and Kondo phenomena in the filled skutterudite compound $PrOs_4As_{12}$," *Proceedings of the National Academy of Sciences* **103**, 6783 (2006).

- W. M. Yuhasz, N. P. Butch, T. A. Sayles, P.-C. Ho, J. R. Jeffries, T. Yanagisawa, N. A. Frederick, M. B. Maple, Z. Henkie, A. Pietraszko, S. K. McCall, M. W. McElfresh, and M. J. Fluss, "Multiples ordered phases in the filled skutterudite compound $PrOs_4As_{12}$," Physical Review *B* **73**, 144409 (2006)

- D. D. Jackson, J. R. Jeffries, Wei Qiu, Joel D. Griffith, S. McCall, C. Aracne, M. Fluss, M. B. Maples, S. T. Weir, and Y. K. Vohra, "Structure-dependent ferromagnetism in Au_4V studied under high pressure," (in preparation).

- J. R. Jeffries, N. P. Butch, J. Paglione, and M. B. Maple, "Hidden order and superconductivity under pressure in the heavy fermion compound URu_2Si_2," (in preparation).

- N. P. Butch, J. R. Jeffries, and M. B. Maple, "The evolution of glassy magnetic order under pressure in $Sc_{1-x}U_xPd_3$," (in preparation).

b. Abstracts for Submitted Presentations

- J. R. Jeffries, N. A. Frederick, E. D. Bauer, H. Kimura, V. S. Zapf, K. –D. Hof, T. A. Sayles, and M. B. Maple, "Superconductivity and non-Fermi liquid behavior near antiferromagnetic quantum critical points in $CeRh_{1-x}Co_xIn_5$," *Bulletin of the American Physical Society* **50**, 1212 (2005).

- N. P. Butch, W. M. Yuhasz, P. –C. Ho, J. R. Jeffries, N. A. Frederick, T. A. Sayles, M. B. Maple, J. B. Betts, A. H. Lacerda, F. M Woodward, J. W. Lynn, P. Rogl, and G. Giester, "Ordered magnetic state in $PrFe_4Sb_{12}$ single crystals," *Bulletin of the American Physical Society* **50**, 909 (2005).

- D. D. Jackson, C. Aracne, S. T. Weir, J. R. Jeffries, M. B. Maple, and Y. K. Vohra, "Pressure-temperature magnetic phase diagram of Au_4V investigated by electrical resistivity using Designer Diamond Anvils," *Bulletin of the American Physical Society* **50**, 1215 (2005).

- M. B. Maple, N. A. Frederick, P.-C. Ho, W. M. Yuhasz, T. A. Sayles, N. P. Butch, and J. R. Jeffries, "Strongly correlated electron behavior in filled skutterudite lanthanide osmium antimonides," *Proceedings of the 3rd Hiroshima Workshop*, Hiroshima, Japan, November 17-19, 2005.

- M. B. Maple, N. A. Frederick, W. M. Yuhasz, P.-C. Ho, T. Yanagisawa, T. A. Sayles, N. P. Butch, J. R. Jeffries, Z. Henkie, A. Pietraszko, S. McCall, M. W. McElfresh, and M. W. Fluss, "Strongly correlated phenomena in Pr-based filled skutterudite compounds," *Proceedings of the Joint Workshop on Evolution of New Quantum Phenomena Realized in the Filled Skutterudite Structure and New Phases of Matter under Multiple Extreme Conditions*, Tokyo, Japan, November 21-24, 2005.

- J. R. Jeffries, N. P. Butch, J. Paglione, and M. B. Maple, "Ordered states of URu_2Si_2 under hydrostatic pressure," *Bulletin of the American Physical Society* **51**, 701 (2006).

c. Invited Talks of P.I., M. B. Maple

- Fermi Liquid Instabilities and Superconductivity in the Vicinity of Quantum Critical Points in f-electron Materials, National Nuclear Security Administration Stewardship Science Academic Alliances Symposium, March 29-31, 2004.

- Non-Fermi liquid behavior near magnetic quantum critical points in U-based systems, Workshop on Quantum Critical Behavior in Correlated Electron Systems, KITP, University of California, Santa Barbara, January 18-21, 2005.

- Strongly correlated electron phenomena in Pr-based filled skutterudite compounds, 2nd US-Japan Workshop on Synchrotron Radiation and Nanoscience, San Diego, California, April 4-6, 2005.

- Strongly correlated electron phenomena in Pr-based filled skutterudite compounds, Workshop on Novel Electronic Materials, Lexington, Kentucky, April 24-27, 2005.

- Conference Summary, Workshop on Novel Electronic Materials, Lexington, Kentucky, April 24-27, 2005.

- Strongly correlated electron phenomena in f-electron systems, Workshop on Probing Matter at High Magnetic Fields with X-Rays and Neutrons, Tallahassee, Florida, May 10-12, 2005.

- Pr-doped YBCO: a model system for studies of high temperature superconductivity and vortex physics, UC/Los Alamos Workshop, University of California, Santa Barbara, May 13-14, 2005.

- Strongly correlated electron phenomena in novel f-electron materials, meeting of CIAR Quantum Materials Program, Vancouver, Canada, May 18-21, 2005.

- Strongly correlated electron phenomena in novel f-electron systems: opportunities for neutron scattering, Next Generation Neutron Source: Opportunities in Bio- and Materials Sciences Workshop, San Diego, California June 8-9, 2005.

- Non-Fermi liquid behavior near magnetic quantum critical points in uranium based compounds, International Conference on Strongly Correlated Electron Systems (SCES05), Vienna, Austria, July 26-30, 2005.

- Investigation of superconductivity, magnetism, and quantum critical phenomena in f-electron materials at low temperatures, high pressures, and high magnetic fields, National Nuclear Security Administration Stewardship Science Academic Alliances Symposium, Las Vegas, Nevada, August 23-25, 2005.

- Strongly correlated electron phenomena in Pr-based filled skutterudite compounds, International Institute for Complex Adaptive Matter Workshop on Correlated Thermoelectric Materials, Hvar, Croatia, September 25-October 5, 2005

d. Poster Sessions

- J. R. Jeffries, N. A. Frederick, E. D. Bauer, H. Kimura, V. S. Zapf, K. –D. Hof, T. A. Sayles, M. B. Maple, "Superconductivity, Antiferromagnetism, and Quantum Critical Behavior in $CeRh_{1-x}Co_xIn_5$," Poster Session: National Nuclear Security Administration Stewardship Science Academic Alliances Symposium, March 29-31, 2004.

- P.-C. Ho, N. A. Frederick, W. M. Yuhasz, N. P. Butch, M. B. Maple, E. D. Bauer, A. H. Lacerda, V. S. Zapf, "Unconventional Superconductivity and Quadrupolar

Ordering in Heavy-fermion Compound $PrOs_4Sb_{12}$," Poster Session: National Nuclear Security Administration Stewardship Science Academic Alliances Symposium, March 29-31, 2004.

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