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Idaho National Laboratory Lead or Lead-Bismuth Eutectic (LBE) Test Facility

R&D Requirements, Design Criteria, Design Concept, and Concept Guidance

Eric P. Loewen

May 2005

The INL is a U.S. Department of Energy National Laboratory
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Idaho Falls, Idaho 83415

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SUMMARY

The Idaho National Laboratory Lead-Bismuth Eutectic Test Facility will advance the state of nuclear technology relative to heavy-metal coolants (primarily Pb and Pb-Bi), thereby allowing the U.S. to maintain the pre-eminent position in overseas markets and a future domestic market. The end results will be a better qualitative understanding and quantitative measure of the thermal physics and chemistry conditions in the molten metal systems for varied flow conditions (single and multiphase), flow regime transitions, heat input methods, pumping requirements for varied conditions and geometries, and corrosion performance. Furthering INL knowledge in these areas is crucial to sustaining a competitive global position.

This fundamental heavy-metal research supports the National Energy Policy Development Group's stated need for energy systems to support electrical generation.[1] The project will also assist the Department of Energy in achieving goals outlined in the Nuclear Energy Research Advisory Committee Long Term Nuclear Technology Research and Development Plan,[2] the Generation IV Roadmap for Lead Fast Reactor development, and Advanced Fuel Cycle Initiative research and development. This multi-unit Lead-Bismuth Eutectic Test Facility with its flexible and reconfigurable apparatus will maintain and extend the U.S. nuclear knowledge base, while educating young scientists and engineers.

The uniqueness of the Lead-Bismuth Eutectic Test Facility is its integrated Pool Unit and Storage Unit. This combination will support large-scale investigation of structural and fuel cladding material compatibility issues with heavy-metal coolants, oxygen chemistry control, and thermal hydraulic physics properties. Its ability to reconfigure flow conditions and piping configurations to more accurately approximate prototypical reactor designs will provide a key resource for Lead Fast Reactor research and development. The other principal elements of the Lead-Bismuth Eutectic Test Facility (in addition to the Pool Unit and Storage Unit) are the Bench Scale Unit and Supporting Systems, principal of which are the O_2 Sensor/Calibration System, Feed System, Transfer System, Off-Gas System, Purge and Evacuation System, Oxygen Sensor and Control System, Data Acquisition and Control System, and the Safety Systems.

Parallel and/or independent corrosion studies and convective heat transfer experiments for cylindrical and annular geometries will support investigation of heat transfer phenomena into the secondary side. In addition, molten metal pumping concepts and power requirements will be measured for future design use.

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Idaho National Laboratory Lead or Lead-Bismuth Eutectic (LBE) Test Facility

R&D Requirements, Design Criteria, Design Concept, and Concept Guidance

1. REPORT OBJECTIVES AND OVERVIEW

1.1 Introduction

Beginning in FY 2005, and spanning the next three years, the Idaho National Laboratory (INL) is slated to produce research and development (R&D) and design requirements, then conceptualize, design and commence the start-up activities for the facility to support heavy-metal reactor research. The facility is to support DOE-NE needs for the Lead Fast Reactor (LFR) and Advanced Fuel Cycle Initiative (AFCI) application of Pb or Lead-Bismuth Eutectic (LBE) to meet programmatic goals. The facility will build off the previous six years of funded work by DOE (AFCI) at the Los Alamos National Laboratory (LANL).

The INEEL,[a] in collaboration with the Massachusetts Institute of Technology, completed six years of safety and operational evaluation of medium powered Pb-alloy cooled reactors. The project pursued a discipline-based approach that coordinated research in core neutronics design, plant engineering, structural material testing, and coolant activation. A special issue of *Nuclear Technology* presented the actinide burning Pb (or Pb-alloy) cooled fission reactor concept.[3-10] The nine coordinated papers in this dedicated issue provide an inclusive review of the project, and demonstrate INL's technical competence in Pb-alloy cooled reactors.

The project, internally funded by the INL as a Laboratory Directed Research Development project, focused on industry concerns and issues (e.g., fabrication, cost, maintenance, and safety) and DOE expectations (e.g., Generation IV road mapping activities).

The author of this report dedicated the previous five years at the INL to Pb and LBE corrosion experiments, serving in 2003-2004 as Project Manager. Prior to joining the INL, he led private industry experiments in uranium hexafluoride processing, mixed waste processing, and spent radioactive ion exchange resin processing. The confluence of previous and current experience qualifies the author to propose the initial set of R&D requirements and Design Requirements; put forth a conceptual facility design; address potential operational issues; and develop cost estimates in support of the technical bases for an experimental facility at the INL for LFR and AFCI technical development.

The current INL Pb-Facility Planning Project Engineer requested a summary of experience gained in INL experiments and from visits to other Pb facilities around the world.

This report complements the extensive LBE Handbook that is currently being prepared by the International Working Group on LBE Technology, part of the Organization for Economic Co-operation and Development Working Party on Scientific Issues in Partitioning and Transmutation.

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[a] Beginning February 1, 2005, the name of the Idaho National Engineering and Environmental Laboratory (INEEL) was changed to Idaho National Laboratory (INL).

The purpose of this report is to suggest a logical progression for work to ensure that the INL leverages off the extensive prior work in Pb and Pb-alloy research. It suggests the detailed thinking and planning that must be accomplished to allow the INL to deploy a word class Pb research facility that will gain world recognition. In that vein, this report provides an innovative conceptual design for that facility.

The world currently has ~100 Pb or LBE corrosion loops operating in support of future Pb-cooled reactor deployment. But most Pb-cooled reactors are not of a loop design; rather, they are pool design. Specifically a pool design means a large vessel containing the molten Pb along with the reactor core, the heat removal system, and in some cases the fluid motive device (for the current Generation IV Battery Concept reactor this is not applicable since it is natural circulation).

To move this reactor technology forward, building just another experimental loop is not needed. What is needed is an operating flexible experimental facility to test and validate

- Different pumping options (steam, gas lift, electromotive force [EMF], centrifugal, natural circulation)
- Heat exchanger designs
- Large-scale heavy-metal control
- Oxygen control

while providing comprehensive data collection.

This report is bold to propose this option for the future. It also addresses many of the issues that must be considered by INL so that we can successfully deploy this facility.

1.2 Background

The United States led the world in fast reactor development. The EBR-1, built and operated at the INL, was the first liquid-metal (sodium) cooled reactor in the world. It was followed by the sodium-cooled reactor in the U.S. Navy's second nuclear powered submarine, USS Seawolf (SSN 575). The U.S. had also explored using Pb and Pb-Bi as a coolant for fast reactors, but ultimately selected sodium due to shorter doubling time to produce plutonium, and operational and corrosion issues with Pb. Russia continued work with Pb-coolant based reactors and pioneered Pb-Bi cooled reactors culminating in the deployment of their Alpha class submarines, the fastest submarine in the Russian fleet. They improved upon their military technology with the design of a Pb-cooled commercial power-generating reactor, called BREST, which can generate up to 1,200 MWe. The Russians are marketing the Pb-cooled BREST reactor for commercial electricity generation. It was these Russian advances that sparked an interest in the Western world to investigate this type of reactor for future energy production.

The U.S. Department of Energy (DOE) is leading an international initiative to develop the Generation IV Nuclear Reactor for deployment in the United States by 2020. The initiative is in direct response to forecasts that the nation will need at least 50,000 MW of additional electricity-generating capacity in 2020. Considering that the nation's 104 existing reactors, which generate approximately 20% of the electricity demand, are, in majority, of Generation II design, it is evident that we need to design and certify new reactor concepts. The generally accepted criteria state that the Generation IV reactors must be (1) economically competitive, (2) inherently safe, (3) able to minimize waste, and (4) proliferation resistant.

Among the various reactor concepts being considered is the Pb-cooled or Pb-alloy-cooled (primarily Pb-Bi) fast reactor designed in the Generation IV roadmap as LFR (Pb fast reactor). Pb-alloy coolants offer a number of attractive properties: chemical inertness with air and water (unlike sodium), low vapor pressure over the relevant temperature range, high boiling point (in contrast to sodium), high atomic number, and favorable neutronics in high scattering and small absorption microscopic cross sections. The LFR presents two significant technical issues that must be well understood: corrosive nature of LBE on structural materials, and production of Po and its subsequent handling. With about 100 corrosion test loops facilities worldwide, there is great expectation that the materials-compatibility issue will soon be resolved. But additional technical issues must be addressed to make this reactor concept viable for deployment.

This section provides a summary of worldwide research activities and LBE research facilities currently in operation. By providing the reader with this overview, the need for an active and flexible LBE facility will be evident.

1. USA: Idaho National Laboratory (INL)

   With an existing isothermal loop, INL has obtained corrosion data from both Pb and Pb-Bi operations. Details of the experiments are given in (see Reference 10). Recent experiments at INL used a chemistry buffer system ($C/O_2/CO/CO_2/H_2$) to maintain the oxygen between the accepted bounds. In addition to material-corrosion work, nuclear-reactor-systems codes originally developed for water-cooled reactors are being modified to investigate heavy-metal-cooled reactors. At INL, the ATHENA code was modified for the analysis of a Pb-cooled reactor.[12] The ATHENA code is incorporated as a compile-time option in the RELAP5-3D code and retains all of the capabilities of RELAP5-3D but allows the use of working fluids other than water.

2. USA: Massachusetts Institute of Technology

   Massachusetts Institute of Technology (MIT) has supported Pb and Pb-Bi reactor concepts for actinide burning and electrical generation. The Department of Nuclear Engineering at MIT, established in 1958, is the largest university nuclear-engineering program in the United States, with 17 professors, 120 graduate students, and 30 undergraduates. This department was one of the first to start an aggressive research program on Generation IV reactors. With respect to Pb-cooled reactors, the research activities include reactor physics and fuel management, reactor thermal hydraulics, nuclear materials, structural engineering, and coolant chemistry. The research facilities available on campus include a rotating-electrode system in which the liquid metal is contained in a ZrO_2 crucible, which is, in turn, contained in a stainless-steel retort. The test sample is a 7.5-cm-diameter disk, which is attached to a shaft, which rotates at speeds up to 1000 rpm, allowing the characterization of corrosion in a velocity field. For coolant-activation studies, a high-temperature reaction cell is deployed to accommodate a liquid Pb-Bi bath with radioactive polonium. The radioactive polonium is produced by irradiation of 99.99% Bi samples in the MIT research reactor. The cell consists of a single autoclave, which hosts the molten Pb-Bi and polonium. Removal of Po from the coolant is studied as the gas, gas-injection rate, temperature, and coolant chemistry are varied.

3. USA: Los Alamos National Laboratory

   LANL has conducted Pb-alloy R&D in their role as the lead U.S. laboratory in the DOE AAA program.[13] In collaboration with the University of Las Vegas, LANL is considering the entire scope of development and demonstration of transmutation technology. However, LANL itself is more focused on technology using Pb-Bi eutectic (LBE). Specifically, LANL is investigating the following areas of LBE as both spallation target and nuclear coolant:

(1) Kinetic modeling of corrosion with oxygen control in LBE systems

(2) Oxygen sensor development and testing

(3) The operation of a materials test loop

(4) The corrosion test of U.S. standard steels

To date, LANL (see Reference 13) has demonstrated that active oxygen control, via H_2/H_2O mixture control, can reduce corrosion in their LBE system and that their sensor, which is made of yttrium-oxide–stabilized (Y_2O_3) zirconia (ZrO_2) ceramic (YSZ) and which contains a Bi/Bi_2O_3 reference, responds well to changes in oxygen concentration. The materials test loop is 19 feet high, is constructed from stainless steel 316, and is equipped with a 25-horsepower mechanical sump pump. The loop also has a variable heat exchanger and loop configuration to accommodate thermohydraulic testing of target designs. The expected operational flow range is from 0.2m/s for natural-convective flow to 2m/s for forced-convective flow. The thermal range is 350-550ºC, within which a maximum of a 100ºC temperature difference between high and low temperatures can be accommodated.

4. Russia: Institute of Physics and Power Engineering

The Institute of Physics and Power Engineering (IPPE) has carried out a number of comparisons between reactor designs using Na, Pb, and Pb-Bi primary-system coolants. The neutronic analysis has confirmed some advantages for the utilization of Pb and Pb-Bi coolants.[14-17] IPPE has also developed designs for 300 MWe and 1200 MWe Pb-cooled fast reactors: the BREST-300 and BREST-1200 reactors, respectively.[14,15,16] These nuclear-power-plant designs include the use of a pool-type reactor, a new system of refueling that permits a reduction of the overall dimensions of the central hall and buildings, a system of emergency cooling via tubes arranged directly in the Pb, and the use of emergency natural-circulation cooling, in case the circulating pump trips. Corrosion management was developed at the Laboratory for Heavy-metal Coolants Technology (IPPE-HMCT). IPPE-HMCT conducts research in the following areas: (1) studies of the physics and chemistry of processes in circulation circuits, (2) development of methods and means for coolant and circuit state monitoring, (3) development of methods and instrumentation for coolant purification and circuit cleaning, and (4) development of methods and instrumentation for coolant state control.

Salient results of their research are as follows:

- An extensive database of Pb and Pb-Bi thermo-physical and physical-chemical properties.[18,19]
- A methodology for injection of gaseous mixtures of H_2 and H_2O into the coolant flow to purify the Pb and Pb-Bi circuits of slag deposits.[20]
- The development of solid phase oxidizers to control the thermodynamic activity of Pb and Pb-Bi coolants.[20]
- The development of an absorption technique to extract dissolved impurities in liquid-metal coolants (e.g., Ga, Pb, Pb-Bi). The technique is based on retention of dissolved and highly dispersed impurities in a liquid-metal by absorbent surfaces in a filter medium, through which the coolant is pumped.[21]

- The development of a series of sensors to monitor the chemistry, level, and flow of Pb-Bi in vessels and circulating loops.[14, 15]
- The selection and testing of high temperature structural materials, by using them in the presence of Pb and Pb-Bi at temperatures up to 1000°C.[22]

Two facilities are of particular interest at IPPE:

- The ISR–Pb-Bi facility for control-systems tests of oxygen activity in liquid-metal coolant. This facility has a coolant flow rate of 6 m^3/hour, a power of 0.40 MW, and a temperature range of 160 to 650°C.
- The SVT-3M–Pb-Bi facility hydrodynamic investigates single- and two-component flows of liquid-metal coolant in reactor circuits. This facility has a coolant flow rate of 20 m^3/hour, a power of 0.30 MW, and a temperature range of 160 to 400°C.

5. Germany: Forschungszentrum Karlsruhe

Forschungszentrum Karlsruhe (FzK) is investigating an accelerator driven system (ADS), including the potential of transmutation of minor actinides and long-lived fission products. The study serves as a feasibility and preliminary safety-analysis study and considers the core design, neutronics, safety systems, materials, and corrosion. The generic design is a pool-type ADS with three spallation targets located in the mid-region of a liquid Pb or Pb-Bi blanket. Pb or Pb-Bi is also the spallation material and coolant. Further details and references are given in Reference 23. The Karlsruhe Lead Laboraotry (KALLA) is one of the few European Pb facilities conducting experiments on Pb/Pb-Bi coolant flow, corrosion, and spallation materials.

KALLA currently has six Pb/Pb-Bi experiments: three stagnant and three loop-type. The stagnant experiments are intended to study corrosion mechanisms, surface treatment, oxygen sensor development, and oxygen control systems. The experimental loops emphasize measurement techniques, ADS-relevant component testing, and corrosion in flowing Pb-Bi systems. A fourth loop is planned to study the system thermohydraulics, under normal and decay heat removal conditions, for a projected 4MW facility. A summary of the experimental objectives, corresponding to the name of the experiment, is given in Table 1.

Significant results to date are the measurement of the characteristics of oxygen sensors in flowing liquid Pb-Bi, the development of a robust oxygen control system for a loop, the application of an ultrasonic flowmeter to Pb-Bi at 400ºC, and the improvement in the corrosion resistivity of steels in Pb-Bi, via surface treatment/modification.

6. Israel: The Ben-Gurion University of the Negev, Center for Magnetohydrodynamic Studies:

The Center for Magnetohydrodynamic Studies has completed extensive R&D on liquid-metal thermal sciences. Led by Branover, Tsirlin, and co-workers,[23-28] the institution is now investigating two-phase flows of heavy liquid metals with volatile water/steam. These recent studies are being conducted in support of novel, high-efficiency energy conversion systems. Four natural circulation, two-phase experimental facilities have been built and tested: water-air, mercury-steam and Pb-Bi-steam. Their major parameters are presented in Table 2.

Table 1. Summary of KALLA Pb/Pb-Bi experiments.

Stagnant Experiments		
Acronym	**Full Name**	**Objectives in Summary**
COSTA1-3	**CO**rrosion test stand for **ST**agnant liquid lead **A**lloy	Objectives are to… study corrosion mechanisms, study protection layers/coatings evaluate GESA treated surfaces evaluate surface alloying effects
KOSIMA1-6	**K**arlsruhe **O**xygen **S**ensor **I**n **M**olten **A**lloys	Objectives are to… develop oxygen sensors assess sensor performance calibrate sensors
KOCOS	**K**inetics of **O**xygen **CO**ntrol **S**ystems	Objectives are to… develop oxygen control system measure diffusion coeff.; O_2 in PbB measure O_2 mass exchange rates
Loop Experiments		
THESYS	**T**echnologies for **H**eavy-metal **SYS**tem	Objectives are to… optimize the oxygen control system develop TH measurements techniques do convective heat transfer experiments develop inconel heaters (fuel rod simulator) set-up TH database for code validation TH-thermohydraulic
THEADES	**THE**rmalhydraulics and **A**ds **DES**ign	Objectives are to… investigate beam window cooling study flow field, windowless design study cooling of fuel elements study PbBi/PbBi heat exchanger study steam generator heat exchanger set-up database for code validation
CORRIDA	**CORR**osion **I**n **D**ynamic lead **A**lloys	Objectives are to… study fundamental corrosion mechanisms study formation/stability of protective layers assess performance of mechanical tests develop structure/beam window materials
K4T, in planning	**K**arlsruhe **4**MW **T**arget experiment	Objectives are to… study the heat transfer in closed spallation module study steady-state & transient convective flows set-up TH database for code validation

Table 2. Major parameters studied in Israeli metal flow loop.

	Facility			
Parameter	Water-Air	ER-4	ETGAR-3	OFRA
Working fluids	Water + air	Hg + steam	Pb-Bi + steam	Pb-Bi + steam
Upcomer diameter (cm)	4.4	7.8	20.3	5.1
Downcomer diameter (cm)	4.4	7.8	20.3	5.1
Effective height (m)	5.45	5.5	7.5	3.0
Working temperature (°C)	Room	155-165	155-180	Up to 480

Extensive experiments have been conducted in ETGAR-3 and OFRA—two large-scale facilities for studies of Pb and Pb-Bi circulation when propelled by steam bubbles or droplets of boiling water. Detailed measurements of two-phase flow characteristics, void-fraction changes, and slip between the phases have been performed and a unique database has been accumulated. This database has enabled the development of new and improved correlations for void fraction, slip ratio, and other characteristics of the two-phase flow.

Investigations of direct-contact heat transfer from hot liquid metal to water droplets or steam bubbles are being conducted in the ETGAR-3 loop where a number of novel energy conversion systems have been conceived. They benefit from two unique features of the liquid-metal coolant: the feasibility of circulation via “lift-pump” effects, and the feasibility of direct energy conversion using magnetohydrodynamic generators.

The Center for Magnetohydrodynamic Studies and Solmecs have also been studying the oxidation of steels by high-temperature Pb alloy, using both spinner test rigs and cooling loops. Control of the oxidation is achieved by regulating the oxygen potential in the coolant through injection of slightly oxidative, gaseous media. Corrosion tests of various steels, including pre-oxidized and pre-aluminized steels, have been carried out under conditions simulating the hydrodynamic operating conditions of a reactor loop.

7. Japan: Tokyo Institute of Technology

Several coordinated and parallel research efforts are being made at the Tokyo Institute of Technology as part of a national effort to assess the feasibility of the heavy-liquid-metal-cooled reactor in Japan. The activities, in summary, are as follows[29-32] :

- Measure the KeV-neutron cross sections of Bi-209 by the activation method (reaction cross-section of Bi-209 [n, gamma] Bi-210g) and prompt gamma-ray detection method (Bi-209 [n, gamma] Bi-210g+m).
- Study engineering solutions to removing polonium contamination on material surfaces. Initial tests to remove polonium from contaminated Pb-Bi deposits on a quartz glass surface, via a baking process at 500°C and low pressure (2 Pa), were successful.

- Test the performance of three types of electromagnetic flow-meters in Pb-Bi:
    - Pt-coated stainless steel 316 electrodes, electrically linked to the flow-meter wall,
    - Rh-plated electrodes, electrically insulated (MI cable-type) to the flow-meter wall, and tubular electrodes made of liquid and solid Pb-Bi.
- Study the corrosion resistance (to Pb-Bi) and associated phenomenology of projected structural materials, such as SS316, SS405, SS430, and Japanese industry standards (SCM420, STBA26, F82H, STBA28, NF616, HCM12 and ODS).
- Study the direct heat contact reactor with a large experimental facility.

Condensed details of each activity are given in References 29 through 32. In addition to the experimental program at the Tokyo Institute of Technology, Sekimoto and co-workers have studied the details of the Pb-alloy-cooled-fast-reactor concepts, including the types of fuels, the core design, and the fuel cycle.

8. Japan: Mitsui Engineering and Ship Building Co., Ltd.

Mitsui Engineering and Ship Building (MES) has worked cooperatively with IPPE in Obninsk, Russia, since 1999 to develop Pb-Bi application technology for neutron-source target systems and coolant for ADS and also for the Japanese Liquid Metal Fast Breeder Reactor. In this Russian-MES cooperation, IPPE performed some initial corrosion testing in its flow loops with Japanese steel samples and provided expertise on loop design. In 2001, MES began operating its own Pb-Bi flow loop to look at the following technologies: (1) corrosion behavior of Japanese steels, (2) Pb-Bi interaction with water and air, (3) coolant conditioning techniques (oxidation/reduction control) and sensor development, and (4) engineering feasibility of both ADS and fast reactor designs. Corrosion tests at 550°C with an oxygen content of 3×10^{-8} wt% revealed that erosion-corrosion weight loss was most severe in SS316, followed by SS405 and SS430. In contrast, the presence of a M_3O_4 oxide film on SS316 immersed in Pb-Bi at 550°C and oxygen content of 4×10^{-6} wt% revealed no apparent corrosion damage.[29]

9. Japan: Japan Nuclear Cycle Development Institute)

Japan Nuclear Cycle Development Institute (JNC) has been conducting a multi-year feasibility study, outlined as Phase 1 (1999-2000) and Phase 2 (2001-2005), to assess the prospects for early commercialization of a Japanese prototype fast breeder reactor (J-FBR). The objectives of the study, as well as the ongoing R&D effort at JNC, are (1) to maximize the economic competitiveness of the J-FBR, (2) to establish a commercialization strategy, and (3) to outline a development scenario. The effort includes J-FBR systems design and development of both advanced-fuel fabrication and reprocessing technologies. Phase 1 consisted of preliminary conceptual-design reviews of many advanced reactors, their associated economic advantages and disadvantages, as well as the feasibility of various development target scenarios. One of the promising candidate concepts from Phase 1 is a Pb-Bi-cooled, medium-scale, modular, pool-type (natural circulation) FBR. In collaboration with the German and Russian efforts in the Pb-alloy areas, but within the scope of the feasibility study, JNC is presently working in Phase 2 on the following areas: (1) understanding corrosion phenomena in Pb-Bi melts, (2) evaluating the corrosion resistance of Japanese industry steels for FBR structures and fuel cladding, (3) assessing corrosion-resistant methodologies, (4) developing an impurity control/removal system for Pb-Bi, and (5) performing additional research on advance alloys for Pb-Bi-cooled systems.

10. Japan: Central Research Institute of the Electric Power Industry

The Central Research Institute of the Electric Power Industry (CRIEPI) is a major R&D institute supported by Japan's electric power industry. It works in close collaboration with the Japanese government and major nuclear and energy-related institutes. The primary mission of CRIEPI is to anticipate the near-term and future uses of energy, especially electricity, in Japan specifically and within the global economy. In this objective, CRIEPI is actively engaged in R&D on Pb-alloy cooled advance fast reactor concept, as well as Pb-alloy cooled accelerator driven systems (ADS) for processing of transuranic waste. CRIEPI is working in collaboration with many of the Japanese institutes (JNC, JAERI) and companies (Toshiba), as well as with foreign institutes (Forschungszentrum Karlsruhe, Germany).

The investigations can be categorized into the following areas:

1. Design feasibility study of the FBR systems with innovative Pb-Bi heat exchanger

2. Direct contact heat transfer between Pb-Bi and water,

3. Fundamental aspects of liquid metal-water vapor explosions,

4. System thermohydraulics (Pb-Bi loop, Q ~100 l/min flow) and separate effects studies (visualization via neutron radiography in bubbly Pb-Bi flow)

In terms of advanced reactor system concepts, CRIEPI has proposed the "manufactured" near-term development of small-scale reactors that are economically attractive by virtue of their flexible utilization (other than electricity).

CRIEPI has proposed a compact steam generator design that sidesteps problems associated with sodium-water heat exchanger design, primarily their potential interactions upon contact.[33] By proposing a steam generator design with sodium to Pb-Bi heat exchange in the lower half of the steam generator vessel and direct injection of water into the Pb-Bi in the upper half, this unique Pb-Bi/water/sodium design would prevent contact between water and sodium. As the pressure inside the steam generator would be higher than the primary loop (Na), one would expect the Pb-Bi to flow into the primary sodium upon any tube failure and subsequently form an inter-metallic compound. Equally, because the generated steam vapor bubbles would rise at 20–30 cm/s, compared to 1–2 mm/sec for the Pb-Bi, physical separation between the feedwater injection point and placement of the Pb-Bi to sodium heat exchanger tubes minimizes the possibility of sodium-water interaction. The elimination of any water detection and pressure relief systems in this new design, in contrast to conventional sodium-cooled FBR designs, reduces the overall system costs.

In order to design the Na/Pb-Bi/H_2O steam generator, Furuya, Kinoshita and co-workers have extensively investigated and reported on the heat transfer characteristics and phenomena associated with direct contact heat transfer and vapor explosions issues of relevance to an innovative steam generator design.[33-41]

CRIEPI has also been conducting compatibility testing of prospective structural materials (high-chrome content steel) in Pb-Bi alloy at 500°C with steam injection. Results to date show the existence of oxide films and indications that it prevents corrosive attack of the steel.[33]

11. Italy: CIRCE

Although this facility is listed last, this represents an operational facility most like the one proposed in this document. The objectives of this facility are thermal hydraulic experiments, large scale experiments in a pool configuration while investigation component development.

The CIRCE (CIRColazione Eutettico) facility is mechanically complete and commissioned, and is located at the Brasimone ENEA facility near Bologna, Italy. The cylindrical vessel is filled with ~90 tons of molten LBE with argon cover gas.

The operating principle of LBE circulation in the CIRCE facility is the same conceived for the transmutation community. It consists of cover gas injection into the riser of the relevant test section. Even a modest void fraction in the riser brings about a high pressure head, owing to the high density of LBE. The cover gas at nearly atmospheric intake pressure is fed by compressors via a submerged sparger into the bottom part of the riser. The rising LBE gas mixture two phase flow slows down at the top of the riser and bends over radially until LBE reverses its velocity and flows downwards. The cover gas cannot follow the path of LBE, because buoyancy prevails over entrainment, and separates at the interface with the cover gas plenum, thereby closing the gas loop. The two phase LBE gas mixture in the riser, being lighter than LBE alone in the downcomer by the amount corresponding to the mean void fraction in the riser, creates the driving force for the coolant circulation.

The main parameters of the CIRCE facility are summarized in Table 3.

Table 3. Summary of main parameters of the CIRCE facility.

Parameter	Value
Mail Vessel	
OD (mm)	1200
Wall thickness (mm)	15
Height (mm)	8500
Material	AISI 316L
LBE inventory (kg)	90,000
Heat tracing (kW)	50
Cooling air (N m^3/s)	3
Temperature range (ºC)	200 to 550
Pressure	
Operating (kPa)	15
Design (kPa)	450
Core power heater simulation (MW)	1.1

Unfortunately there is very little in the literature regarding the detailed operations of this facility. If the concept presented in this report is pursued then more information should be obtained from this facility to learn the best practices.

This brief summary of the leading experimental facilities shows the significant amount of technical work going in this area—and the wealth of data that has been accumulated and is available. The INL needs to incorporate the best practices from these facilities and deploy a unique pool-type experimental facility, along with a smaller isothermal loop to reach extreme temperatures, and a liquid Pb (or LBE) oxygen probe calibration unit. The flexibility of such a facility can develop opportunities for the promising heavy-metal coolant technology.

1.3 Design Concept

The INL Lead-Bismuth Eutectic Test Facility (LBETF) will consist of three experimental units and supporting systems. Their functions are described in subsequent sections.

The three experimental units are:

- Bench Scale Unit comprised of iso-thermal corrosion cells
- Integral O_2 sensor and calibration unit
- Pool Unit and Storage Unit, capable of containing two-to-three tons of molten metal, that can be transferred back and forth to conduct experiments in either unit.

The principal supporting systems are:

- O_2 Control System to sense and control oxygen levels in the molten metal
- Gas Handling Train to handle off-gasses
- Cleaning System, using peroxide and acetic acid, to clean the Pool Unit and Storage Unit and package/store hazardous waste
- Coolant Clean-up System for R&D, using Te as surrogate for ^{210}Po
- Data Acquisition and Control System.

To establish the INL LBETF as the world's leading facility for investigation of heavy-metal coolants, it must provide the capability to perform corrosion testing in a quasi flow isothermal system, be able to operate at temperatures significantly higher than current facilities. This is to screen candidate materials. In addition, the separate experimental units—Pool Unit, Storage Unit, Bench Scale Unit—each require a separate oxygen sensor system and calibration support.

Using the lessons learned from demonstration loops around the world, and the extensive INL experience with large-scale experimental apparatus, the following pool-type conceptual design for the LBETF is presented. A simplified block diagram of the heavy-metal coolant experimental facility is shown in Figure 1.

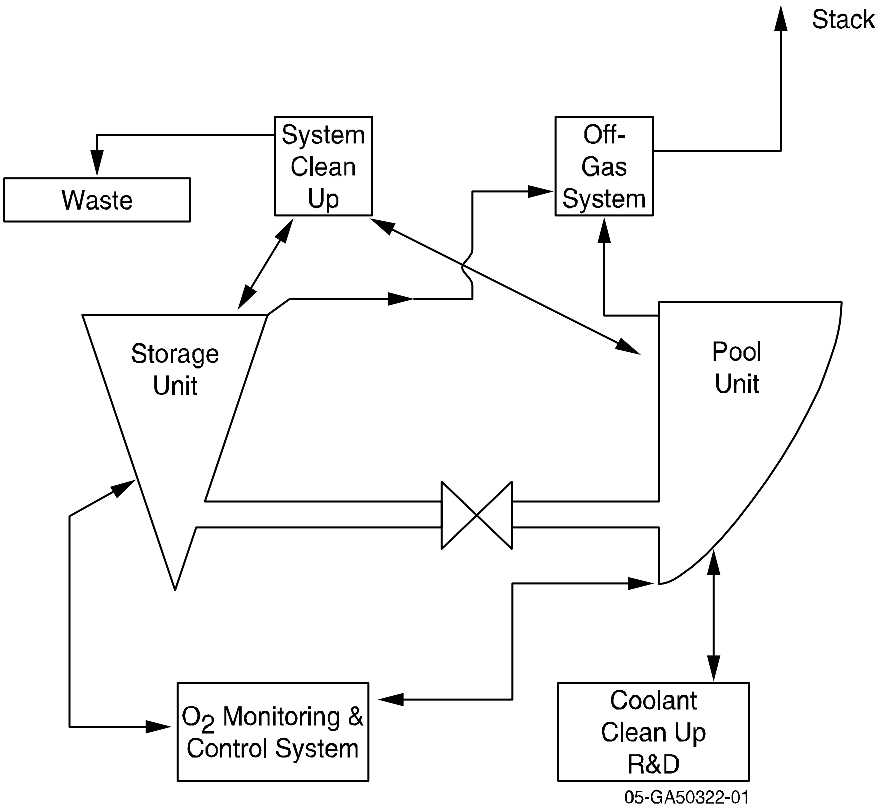

Figure 1. Block Diagram of the INL Lead Bismuth Eutectic Test Facility.

The experimental Pool Unit uses reconfigurable reactor test sections to accommodate testing of different reactor configurations and other technical issues. The reconfigurable system can thus perform a campaign on natural circulation, followed by centrifugal pumping.

This experimental apparatus would support the numerous pool reactor types currently being evaluated by the world technical community. With a clean-up system, the ability to safely switch between different experimental campaigns is made easier. If some of the heat exchanger testing is performed in the Storage Unit, the experimental availability increases considerably. Throughput requirements to support several competing designs for the DOE LFR concept can then be easily evaluated.

Separate but similar designs for the Storage Unit and the Pool Unit will allow system redundancy. The capital costs for the facility reside in finding (or fabricating) an insulated and heated container in which to perform the experiments. (The capital costs need further refining before submitted for review.)

This conceptual design provides sufficient basis for evaluating the other issues presented in the report, and allows decision makers to evaluate this concept. As with any conceptual-level design, uncertainty exists. Risk associated with this uncertainty is factored into decision making by incorporating conservatism in many of the concepts presented. Uncertainty and risk must then be systematically addressed and mitigated thought the final design maturation process. This comprehensive overview of the design, unit descriptions, facility operations, and hazards identification supports early management and mitigation of uncertainty in the selection of future INL facility deployment. Specifically, the ongoing technical support program in both Gen IV and AFCI will mitigate the design uncertainties. Involving the technical community early-on to discuss requirements will improve the design.

2. LEAD BISMUTH EUTECTIC TEST FACILITY

2.1 System Requirements

A system requirements and design criteria document is being prepared for delivery to DOE in FY 2005. This section of the report provides a first draft. It is intended as a living document to support future design efforts and expected new experimental needs as they arise. As uncertainties in any design (hopefully the one presented in this report) are narrowed through on-going research and a more focused effort on defining experimental work, the design will evolve. This section identifies the system and sub-systems that can provide a world respected heavy-metal coolant facility. These system specifications should be in accordance with Management Control Procedure (MCP)-9359.

Note: A list of current INL work management documents that would be applicable to this large research deployment is provided in Attachment 1. Although most R&D efforts are done in accordance with MCP-3571, Independent Hazard Review, it is the author's opinion, due to the complexity of this facility; other best practices of the company work management documents should be used.

2.1.1 Research Requirements

The INL heavy-metal facility must meet research requirements that can be accomplished only by a large pool facility. This section presents an extensive scope for a science-based R&D program, yet describes a facility large enough to also obtain engineering-scale data. This approach allows the following required research capabilities—as viewed by the technical community to be necessary before LFR deployment would be deemed feasible—to be realized:

1. Provide a larger non-isothermal pool of heavy-metal coolant to expand knowledge of the corrosion/erosion mechanism of structural materials immersed in Pb or LBE. This will better document material compatibility, fuel cladding compatibility and large weld areas. The data generated from the large Pool Unit will provide high temperature code cases for new materials.

2. Evaluate structural materials (large components) and weld areas under load at higher temperatures and in LBE environments.

3. Demonstrate safe control of large amounts of molten Pb. This will calm the perceived environmental issues of concern.

4. Demonstrate coolant chemistry control on a large scale, including oxygen control and removal of metallic and oxide contaminants. Removal of ^{210}Po (using Te as a surrogate) can be demonstrated on a pilot scale.

5. Investigate open lattice heat removal by both forced and natural convection while investigating different core internals and support devices. This also includes reactor internal support techniques and a study of clamping strategies.

6. Investigate different pumping options, such as centrifugal, EMF, gas lift and natural circulation.

7. Demonstrate a design with seismic isolation to aid future reactor designers.

8. Develop coupling technologies between heavy-metal coolant and the energy conversion system through heat transfer experiments for proposed heat exchanger designs. This can allow investigation of energy conversion heat exchangers using supercritical CO_2 (Brayton Cycle),

supercritical water (Rankine Cycle), Ca-Br water cracking, and desalinization bottoming. Better understanding of the thermal hydraulics across intermediate heat exchanger tube bundles will support future development of LFR balance-of-plant energy production.

9. Produce basic thermo-physical properties for the coolant at pilot scale.

10. Provide a variety of large plenum flow experiments. These experiments will allow the thermal hydraulic investigation of heat removal from the fuel pins. Using natural circulation or low-speed forced circulation through an open lattice of ductless assemblies will allow the direct measurement of heat transfer correlations, pressure drop correlations, pressure drop form factors for plenum flows and transitions, and flow redistribution patterns as a function of geometry and linear heat rate generation. Long term use of this facility will allow a better understanding of the effects of grid spacers, deposits, and clad aging on core thermal hydraulic performance. The generation of phenomenological date will allow better design of rector core internals.

11. Evaluate in-service inspection technologies using known geometries submerged in a Pb/LBE pool.

12. Measure thermostructural reactivity feedback for neutronic calculations. This is key to the passive safety design strategy for many of the current designs under evaluation.

These requirements define an extensive scope of R&D needs that must be provided before an LFR could be deployed for the Generation IV program. To be useful, any new experimental facility must encompass as many of these research areas as possible. The proposed INL facility (Pool Unit, isothermal loops and O_2 calibration system) is predominantly a science-based R&D effort. However, if built correctly (size counts!) special opportunities for the study of engineering scale-up issues can also be incorporated. In the end, it is un-resolved technology gaps in the scale-up issues that could prevent deployment.

2.1.2 System Requirements and Design Criteria

This section defines the system requirements and criteria for the Pool Unit, isothermal, and oxygen calibration apparatus sub-systems of the INL LBETF. The facility needs to be configured to produce high quality experimental data for LFR and AFCI needs. This means ready reconfigurability to meet a wider variety of user needs. Applicable MCPs are: 3573, 9185, and 9217.

The basic functional requirements should include the following:

1. The incoming Pb and Bi is in solid form, with a minimum purity of 99.9%.

2. The Pool Unit apparatus allows several heating, pumping, and heat removal processes to be studied over the experimental life time.

3. The sealed Pool Unit and Storage Unit operate above atmospheric pressure, within a temperature range of 300 to 600°C.

4. Sufficient in-line analytical capability provides control of the gas environment and pool chemistry.

5. All experimental apparatus with a potential to leak molten Pb or LBE, or chemically hazardous or potentially explosive gas(es) into the general building environment, are located in a secondary containment.

6. A separate general maintenance area for general experimental equipment is located within a secondary containment structure.

7. An overhead crane supports a minimum load of 5 tons.
8. Supporting functions are integral to the facility, e.g., control room, change rooms, toilets, and industrial health systems.

The basic elements of the Facility Performance Requirements should include the following:

1. Careful experimental campaign planning should encourage multi-users of the experimental on-stream function to average 80% use factor. This can be accomplished by performing experiments in the Pool Unit while preparing the Storage Unit for secondary system testing. Upon completion of the Pool Unit experiment, the heavy-metal is transferred to the Storage Unit for secondary heat transfer experiments. This then allows cleaning and reconfiguration of the Pool Unit apparatus for the next scheduled experimental run.
2. The off-gas system removes PbO particulate and small quantities of entrained molten metal from the process gas generated in either the Pool Unit or Storage Unit.
3. Residual heavy-metal and wastes will be packaged to meet requirements for recycle and or transportation.
4. Conceptual design provides one central facility, consisting of the Pool Unit which contains a large amount of molten heavy-metal and provides the Storage Unit to receive molten heavy-metal when drained from Pool Unit.
5. The facility meets all applicable federal and state regulatory requirements. Design and construction is in accordance with nationally recognized codes and standards, such as the Uniform Building Code, the National Electrical Code, National Fire Protection Association, and the ASME Boiler and Pressure Vessel Code. However, being an experimental facility pushing the leading edge of technology, some components will necessarily be outside current codes and standards. Due diligence will be taken to identify and mitigate potential hazards.
6. Human factors engineering is integrated throughout all phases of the facility design to minimize the chance of operator error. Operations and maintenance activities and procedures will accommodate OSHA, ANSI/HFS-100, and NUREG/CR-4227 human factor requirements.
7. Facility components design with incorporate measures to simplify future decontamination. Service piping, conduits, and ductwork are kept to a minimum and are arranged to facilitate decontamination. Ventilation filters are positioned at locations that minimize contamination of ductwork. Walls, ceiling, and floors are finished with washable surfaces. Cracks, crevices, and joints are caulked or sealed smooth to prevent accumulation of contaminated materials in inaccessible areas. A cleaning solution of peroxide, acetic acid and isopropyl alcohol is recommended for clean up.
8. The plant design includes features that facilitate decontamination for future decommissioning of the metals for recycling and reclamation in the public market.
9. Primary confinement provided by vessels and piping will be required for the molten Pb or LBE.
10. Secondary confinement requirements maintain facility structures under a negative HEPA filtered system. Individual areas such as the electrical equipment room, data acquisition components are enclosed separately from the experimental areas.

11. The process off-gas system filtration system removes more than 99.9% of the entrained solids. An active alumina chemical trap and a one stage HEPA filtration system should be provided for the off-gas system discharge.

The basic elements of the Data Acquisition and Control System Requirements should include the following (MCP-550):

1. Flexible data acquisition system captures temperature, pressure, flow, and strain gauge information at variable sampling rates, as required by the experimental plan (MCP-3039).
2. Process surveillance system remotely moves liquid metal between the Storage Unit and Pool Unit components. The system has a master shut-off override for off-normal events.
3. The electronic data transfer system is networked.
4. Local I&C connections for temperature, pressure, flow, and stain gauges are connected to the data acquisition computer via ether net technology. This technology has been effectively demonstrated at the KALLA facility and considerably reduces the amount of signal cables run to the control room. Further making this a hub and spoke I&C system will facilitate putting the data onto the intranet. This allows the possibility for collaborators from around the world have access to raw experimental data in real time.
5. Easy compilation and reporting of experimental data to investigators.
6. Accurate collection, display, storage and reporting of necessary safety parameters in real time.
7. Information display in an orderly manner on video display terminals with color graphic features.
8. Display consoles with a crucial process alarm selection and detecting display screens. The display screens provide an audible and visual alarm, calling attention to the display screen upon which the crucial parameter has been programmed to appear.
9. Interface with the INL ICMS chemical tracking system, with ability to track all waste products stored within the facility.

The basic elements of the sample management requirements should include the following (Program Requirements Document [PRD] -324 and MCP-2708):

1. Compliance with INL requirement regarding sample collection and laboratory note book keeping (MCP-2875).
2. Facility space for sample storage, segregation, and repackaging (PRD-5041).
3. Archival storage for retention of representative samples.
4. Sample shipping capabilities to other INL laboratories (external analyses).
5. Bar code key samples for archive storage.
6. Sample preparation area to prevent cross-contamination.

The basic elements of Safety Requirements should include the following (Program Description Document [PDD]-16, PRD-186, PRD-5060, and PRD-5121):

1. Communications, breathing air, and protective clothing for at least two individuals (located adjacent to molten LBE handling area).

2. Personnel protective equipment for Pb, PbO, and any other hazardous materials in accordance with 29 CFR 1910 and INL requirements.

The basic Building requirements should include the following (PDD-12, MCP-540, MCP-3572, and MCP-3772):

1. All new concrete conforms to fc = 4000 psi, design unit weight 150 pcf with reinforcement of ASTM A615 Grade 60, f=60ksi.

2. Carbon steel is used for support structures and meets the following requirements: Structural steel: ASTM A36, F=36ksi; High-strength bolts: ASTM A325, F= 92ksi; Tube steel: ASTM A500, Grade B, F=46 ksi.

3. Structures that could be subject to intermittent contact with LBE and Pb are stainless steel per ASTM A276, Type 316L. Permanent structures in direct contact with Pb or LBE (i.e., the Pool Unit, Storage Unit apparatus, transfer piping,) will be evaluated for proper material based on ongoing corrosion experiments in the technical community. The use of coatings for liner (either metallic or ceramic) will also be evaluated.

4. All areas of the building have sprinkler systems in accordance with the NFAP Standard 13 and INL requirements (PRD-5042).

5. Non Pb/LBE piping and component material selection is based on compatibility with the commodity, temperature and pressure.

6. Piping with Pb/LBE is analyzed to determine the effects of temperature, pressure and dynamic loads, and the dead weight if the metal froze in the pipe. The off-normal occurrence of Pb/LBE freezing is analyzed regarding strain the pipe.

7. Pipe insulation, heat tracing, or heated enclosures are used to prevent the Pb/LBE from freezing.

8. All pressure system and pressure piping are pressure-tested using the following methods: hydrostatic testing immediately after construction (before the introduction of Pb/LBE), vacuum leak testing for all gas sample lines, and pneumatic testing when hydrostatic testing becomes impractical or would adversely affect the piping material (PRD-320).

9. Standby power is supplied to systems and equipment necessary to safely and properly shut down the experiment, and keep safely systems, alarms and communication equipment operational.

10. The HVAC system provides cooling and heating air to the experimental facility. The HVAC system design prevents the spread of PbO contamination by providing a quick shut down mode in the event of a Pb/LBE spill.

The lists above provide requirements/criteria in five broad areas:

1. Functionality
2. Facility Performance
3. Data Acquisition and Control
4. Sample Management
5. Safety and Building Requirements.

These five areas focus on the design components that will be presented in Section 2.2. Obviously, if the final design is different than the one suggested in this document, changes in the system requirements and design criteria will be required. However, many of the elements presented will remain the same regardless of the type of Pb/LBE experimental facility constructed.

2.1.3 Facility and Utility Requirements

The total facility capability needs to focus around one large experimental unit, and have the floor space to support other molten pots of heavy-metal to keep the entire facility operational.

General utilities such as electrical power, raw water, sanitary sewer, potable/fire water, instrument/plan air, inert gas, steam, cooling water, and natural gas are available at a variety of facilities at the INL. The unique utilities to be provided for the facility will determine its location on the INL site to ensure tie in with the available utilities. Then estimated utilities in this section provided the architectural engineer the order of magnitudes of services needed when determining facility siting.

Table 4 provides the utility needs estimate for this facility:

Table 4. Estimated utility needs.

Utility	Minimum	Maximum
Electrical		
Pool Unit Experiment heating	0.2 MW	2 MW
Isothermal Loop	0.005 MW	0.01 MW
O_2 Calibration Loops	0.005 MW	0.01 MW
Ventilation	0.1 MW	0.2 MW
Water		
Cooling	10	100 GPM
Potable	1	10 GPM
Fire	Meet code	
Ventilation		
HEPA	5,000 CFM	10,000 CFM
HVAC	Maintain temperatures	
Gasses		
Compressed air	2 SCFM	20 SCFM @ 100psig
Argon	2 SCFM	10 SCFM @100psig
Nitrogen	2 SCFM	10 SCFM @100psig
Hydrogen	0.1 SCFM	1.0 SFFM @ 100psig
Steam (for cleaning)	1.0 lbs/hr	10 lbs/hr

2.2 Unit Descriptions (Equipment and Process)

The following eleven subsections provide a description of the components that make up the INL LBETF. The details of the facility are described with reference to the accompanying drawings. It will be understood that the particular embodiment presented in these following figures show the principle features of the concept. Limited funding for this document prevented detailed, scaled engineering drawings of the unique components provided. Those skilled in the art will know there are other modifications that can be made to achieve the same basic experimental results. The originality, though, remains with this document.

2.2.1 Bench Scale Unit

Building off the previous INL Pb-corrosion experience the existing bench scale unit will be incorporated into this new facility. The small forced-convection corrosion cell, shown in Figure 2, can perform scoping experiments and tests before incorporation into the large Pool Unit. This provides the users of the INL LBETF a means to expose parts and test chemistries in a responsive facility that has 7,000 hours of previous safe operations.

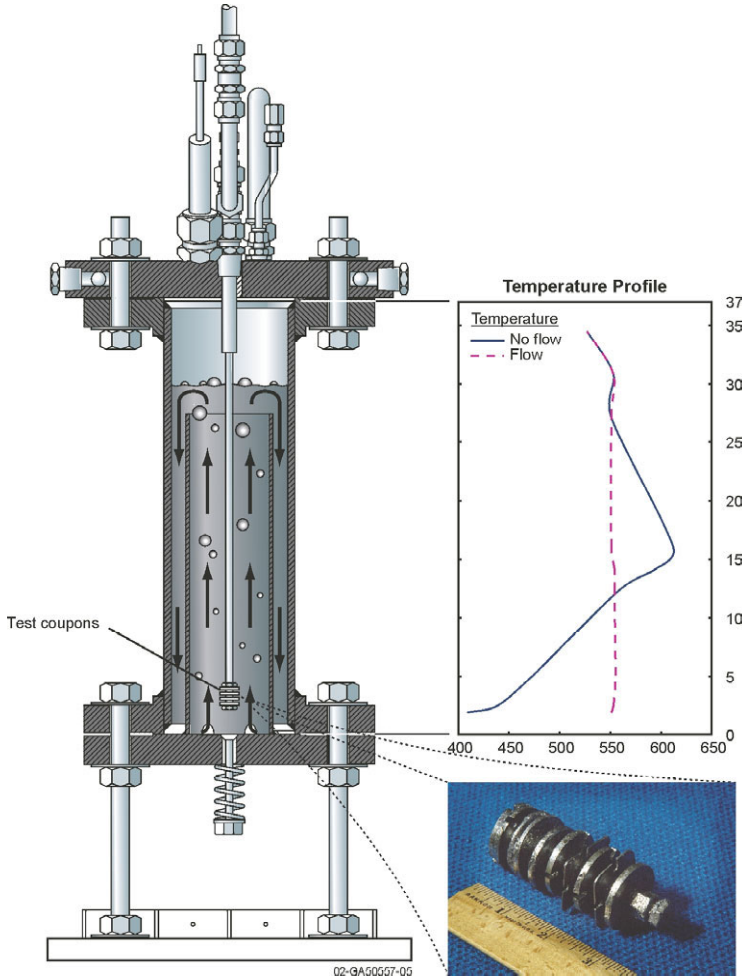

Figure 2. INL Bench Scale Unit.

The Bench Scale Unit consists of an externally heated vessel with a shroud and gas flow system. Flow is induced by the injection of gas at the bottom of the test section. The rising gas bubbles cause flow to proceed upward in the region inside the shroud and down in the region outside the shroud. The gas composition and flow rates, heat input, and shroud and vessel dimensions are adjusted to control LBE coolant flow rate, temperature, and oxygen potential within the vessel. Test coupons are placed on the lance, also used for gas injection, at the center of the vessel, as shown in the lower right of Figure 2. The test coupons are separated from each other and from the lance by alumina spacers. The lance, and hence the specimens, could be removed at selected intervals for examination. Tensile specimens were attached to the outside of the inner shroud (LBE down flow area) for the duration of the experiment and could not be removed during the experiment.

A resistance furnace heats the experimental apparatus to isothermal conditions. The plot imbedded in Figure 2 shows the LBE is isothermal during gas injection. Notice the temperature gradient without gas injection. The corrosion cells have been fabricated from zirconium alloy pipe (1wt.% Hf, balance Zr), 316 stainless steel, 410 stainless steel, and carbon steel. Carbon steel corrosion cells provide the best experimental performance as they introduce the least amount of contaminates into the LBE.

System chemistry was monitored through gas phase and post experiment liquid metal chemical analysis. A mass spectrometer and O_2 meter measured the gas composition entering and exiting the corrosion cell. The mass spectrometer can accurately measure the O_2 level down to ~10 ppm. The oxygen meter, a Thermox II system, is a self-contained portable analyzer using an electrochemical cell made of ZrO_2 heated to 760°C, and has a lower detection limit of 0.1 ppm O_2. By continuously analyzing the gas phase during the experiment and assuming that equilibrium between the gas and liquid phase was achieved, the O_2 potential in each corrosion cell could be determined.

The system oxygen potential was controlled through the use of the carbon buffer system ($C/O_2/CO/CO_2$) and provided acceptable control of the O_2 partial pressure within the range of 10^{-27} to 10^{-40} atm. The INL-developed buffer system (with a provisional patent) uses solid and gaseous C to control the O_2 level in the LBE based on thermodynamics. This system works well when the cell material is iron-based.

2.2.2 Oxygen Sensor and Calibration Systems

Control of oxygen in molten metals has been recognized as a critical function. This requires precision measurement and control of many variables, e.g., temperature, oxygen concentration, oxide layer. To accomplish oxygen control in the Pool Unit, Storage Unit and Bench Scale System, calibrated oxygen sensors are required. The LBETF system should be similar to the one now in use at LANL or the KALLA facility (both have been observed in operation by the author). As the level of LBETF design advances, the best practices from the LANL and KALLA facilities should be incorporated into the INL calibration system.

2.2.3 Pool Unit

The versatile Pool Unit, one-half of a right cylinder vessel, is shown in Figure 3. The flat surface allows the introduction of electrical heating feed-throughs for the ‘reactor core’ region, whereas the curved section allows simulation of different pumping configurations.

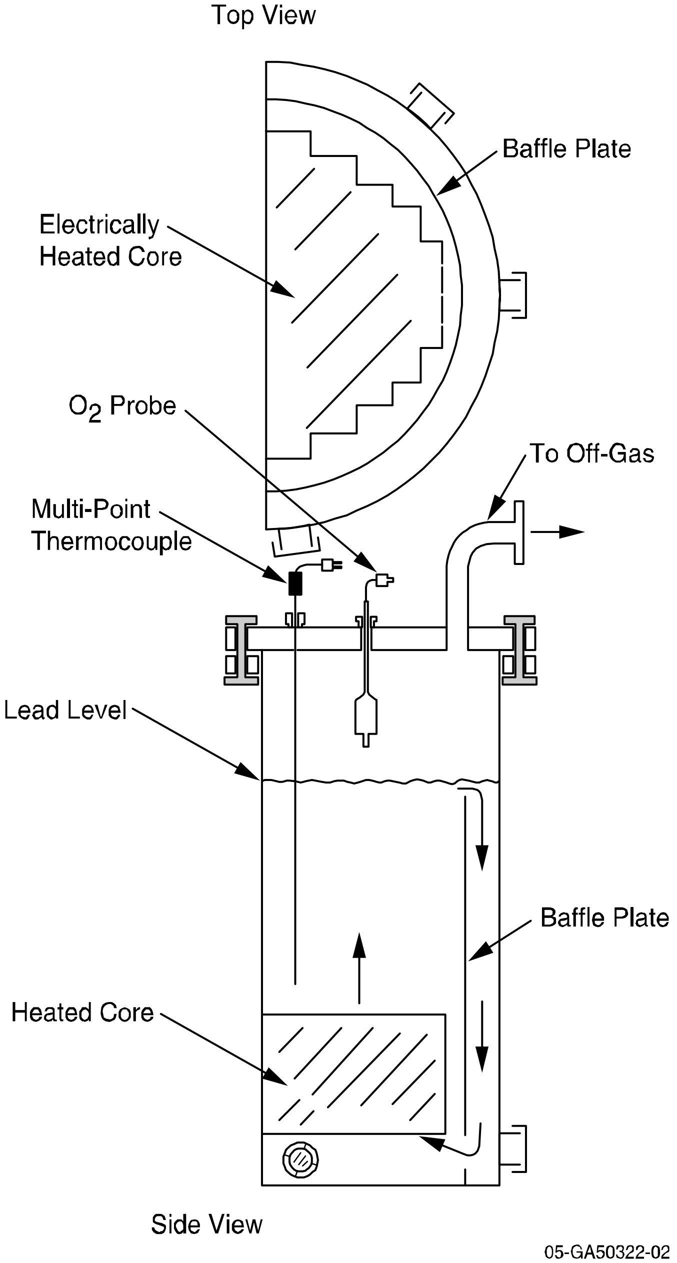

Figure 3. The INL Pool Unit Concept.

Current Russian BREST reactor designs contain hundreds of tons of Pb. The Pool Unit should operate with at least three tons. The larger the tonnage the larger the dimensions of the unit will be. The large tonnage of Pb/LBE used in this facility will put the technical community closer to actual deployment of a LFR. However, this single variable—tonnage—will have the most impact on design, operations, permitting, and finally project cost. Therefore, careful consideration is required before design is finalized.

The volume of the Pool Unit is one-third greater than that required for the molten metal during operations. This creates an upper plenum for injection of reductive and/or oxidative gas to control chemistry; or gas disengagement if the gas-lift option is used. This upper plenum also assures that molten metal splatter will not block fittings and ports installed in the upper face (top) of the unit.

Access fittings through the vertical face (flat wall) of the Pool Unit allow sensor and wiring feed-through to internal heat sinks that will simulate a fuel pin. The vertical face can be configured to provide an experimental heat source in a sinusoidal fashion aging to simulate the power profile expected in a reactor core.

Risers, dividers, voids, and flow partitions can be installed inside the Pool Unit to investigate many reactor thermal hydraulic issues.

The top face of the Pool Unit incorporates a gas-tight cooled flanged fitting to allow the Pool Unit to be slightly pressurized to transfer (pressure pump) molten LBE from the Pool Unit through the transfer line to the Storage Unit during experimental shut downs. This eliminates the need for a mechanical transfer pump.

The external portions of the unit incorporate heaters to hold the LBE or Pb just above the liquids point. Solidification in the Pool Unit is not desired, however the Storage Unit (see Section 2.2.5) is designed to allow the freezing and melting of LBE or Pb.

A heated transfer line, for moving molten metal between the Pool Unit and the Storage Unit, penetrates the unit at the low point.

The entire Pool Unit will be contained in a large “catch-pan” with heat removal capabilities (as a precautionary measure) in case of any leaks.

Molten metal transfer (described in more detail in Section 2.2.5) can be accomplished in a variety of ways. The transfer between the Pool Unit and Storage Unit is accomplished by over-pressurization of the supplying vessel (e.g., over-pressure the Pool Unit to transfer the molten metal to the Storage Unit.)

A centrifugal pump can be lowered into the Pool Unit, or though wall mounted ports. The molten heavy-metal can be withdrawn from the Pool Unit and then pumped (e.g., an EMF pump) back into the heated section of the core. Figure 4 provides a concept overview of four transfer methods that can be used with the Pool Unit.

This reconfigurable loop will allow establishment of flow and temperature gradient conditions that more accurately approximate prototypical reactor design flows. Thermal gradients, controlled by the heating system, can be easily adjusted from the variable heating system to induce natural circulation conditions, or even off normal heating conditions or investigate a hot channel phenomenon. The key here is the flexibility in how the Pool Unit is configured for the campaign of experiments that are under investigation.

The Pool Unit has significant distinctive design features:

1. Gas-tight fittings, allowing gas injection (control coolant chemistry) and temperature and O_2 measurements throughout the apparatus;

2. A multi-point thermocouple with independent terminations inserted through the top or sides to measure the axial or radial temperature gradients,

3. Orifices in the heated section to vary flow rate.

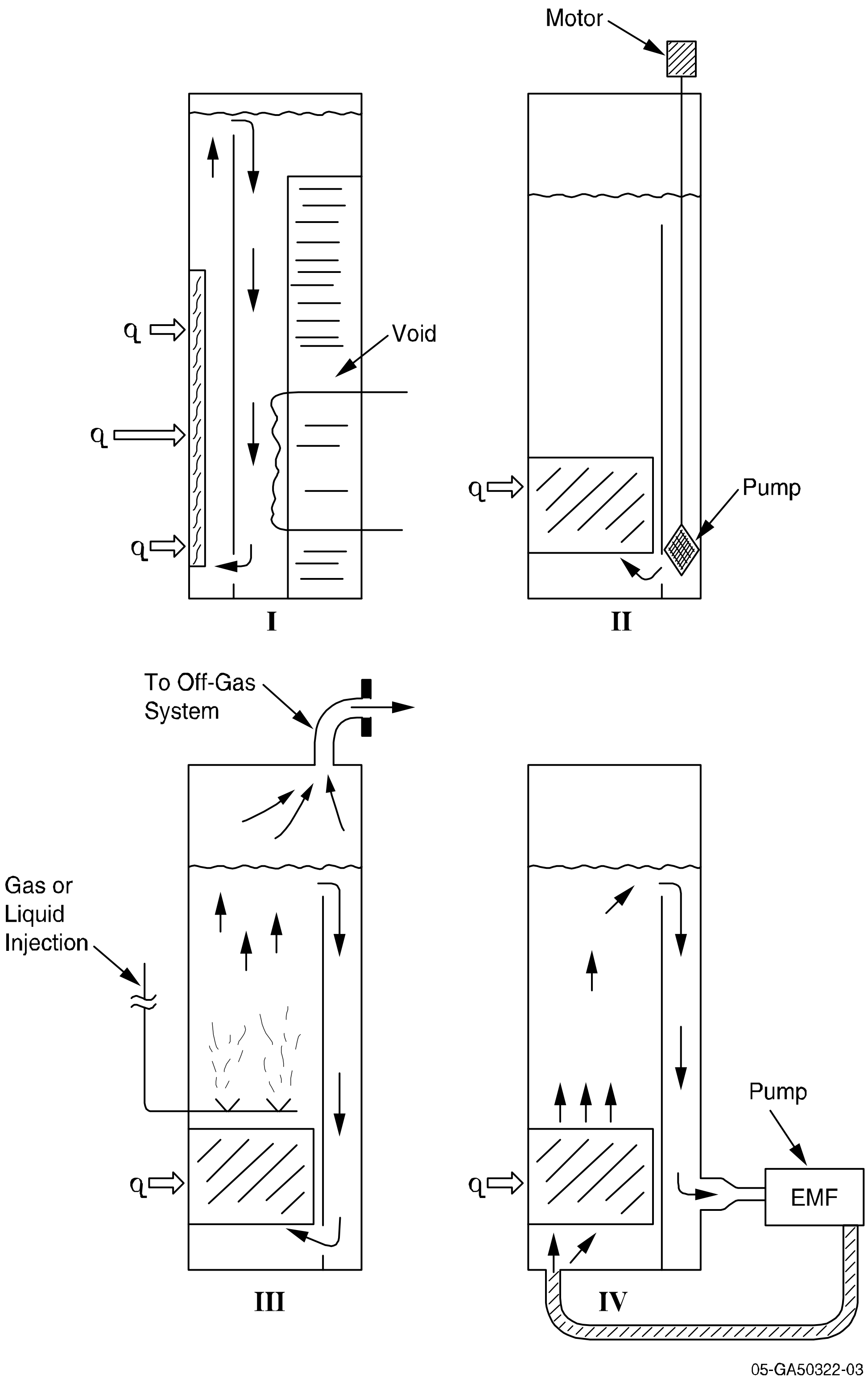

Figure 4. Four transfer methods that can be used in the reconfigurable pool unit design concept.

2.2.4 Feed Systems

The feed subsystems consist of the Solid Addition (metal feed) Subsystem, Carbon Addition Subsystem, and Gas Addition Subsystem. All materials and components of the feed systems must accommodate exposure to molten Pb or LBE up to a temperature of 600°C.

Solid Addition Subsystem: Solid Pb or Bi can be added via a gas type lock hopper system (with internal purges) to the Storage Unit (described in the next section). This allows replacement of the molten metal that is lost during sampling and cleaning operations. The interlocked lock hopper facilitates safe addition of solid metal to liquid metal during operation, while mitigating operator exposure and egress of oxygen.

Carbon Addition Subsystem: This feed subsystem supplies solid carbon to either the Pool Unit or Storage Unit to reduce surface layer (floating) oxide. Sealed rods, tipped with carbon disks are lowered onto the surface of the molten Pb/LBE where the carbon reduces the oxide layer to Pb while producing carbon monoxide. The oxide scale can be effectively reduced by the carbon method at temperatures between 350 and 600°C.

Gas Addition Subsystem: The ability to add oxidative or reductive gas into the Pool Unit or storage apparatus will be key for several experimental conditions. This feed subsystem supports injection below and above the surface of the molten metal. The location for injection will be dictated by the experimental objectives.

2.2.5 Storage Unit

The Storage Unit is a cone (or tapered bottom) shaped container with internal heat exchanger and external induction coils. A heated transfer line, for moving molten metal between the Storage Unit and the Pool Unit, penetrates the unit at the low point. The concept is presented in Figure 5.

The top flange bolts onto top of the Storage Unit. It contains penetrations and access ports for sensors, probes, lances and other apparatus required for various experiments. Different heating methods are used for the Storage Unit and the Pool Unit. Whereas the Pool Unit uses resistance heating both internal and external, the Storage Unit will use induction heating.

The Storage Unit is encased in a large susceptor, made of either carbon or Fe. (A susceptor can also be placed inside the Storage Unit). By using induction heating, it allows the Pb/LBE to freeze during experimental shutdown. To heat/re-heat the metal mass, the unit uses induction heating. Induction heating—a “best practice” in the foundry industry—is reliable, cost effective, and safe. If heat exchange studies are to be conducted, this heating method provides the ability to rapidly increase heat input so that the heat exchange response can be measured. Figure 5 shows an induction heat exchanger submerged into the Storage Unit to perform such testing.

The ability to transfer molten Pb/LBE between the Pool Unit and the Storage Unit provides the flexibility for near-continuous experimental operations, e.g., while the Pool team reconfigures the system to perform EMF pump testing, the Storage team is testing super critical CO_2 heat exchange technologies.

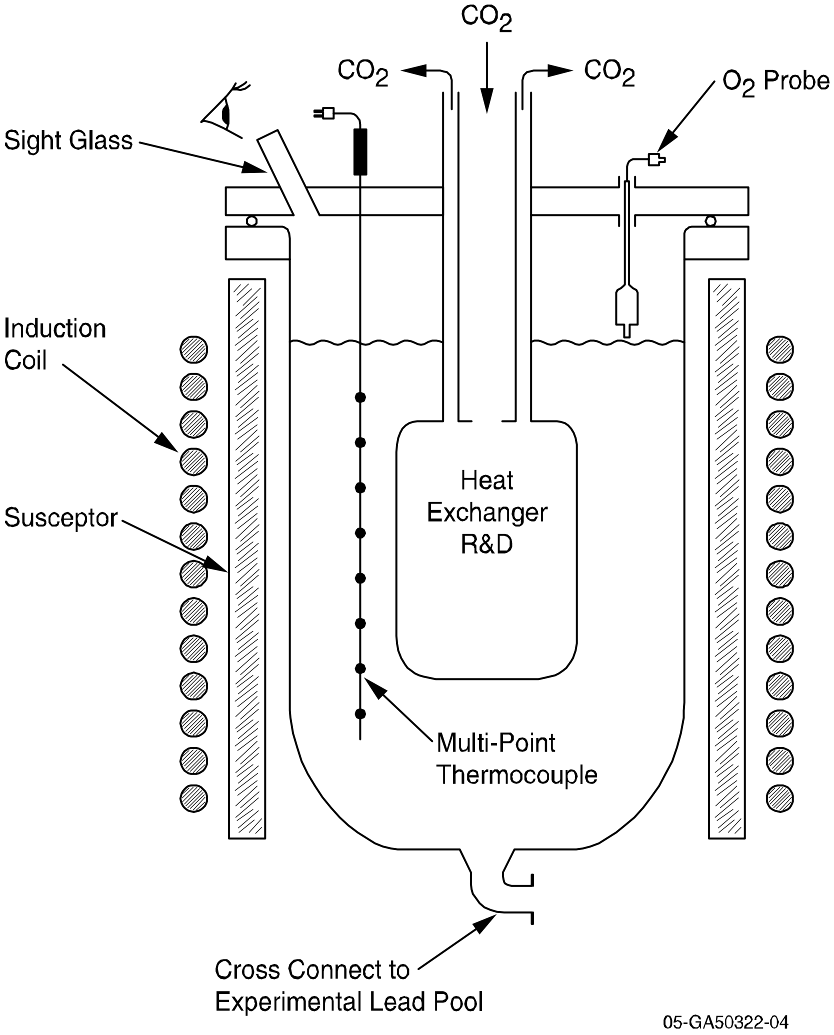

Figure 5. The INL LBETF Storage Unit.

2.2.6 Pumping Systems

Various pumping modes can be used in the Pool Unit during its experimental life time. The different pumping modes:

- Mechanical pumping
- Natural circulation
- Gas-lift techniques
- Electromagnetic pumping

will allow various thermal-hydraulic issues to be studied using the same experimental apparatus.

Heat transfer measurements can be made for cylindrical and annular heated length geometry. Mixed and forced convection heat transfer studies and buoyancy-aided and buoyancy-opposed configurations will be conducted using different pumping methods. This flexibility allows experimenters to quantify the accuracy of various water- and sodium-based convective heat transfers and transport correlations for a LBE system, and provide experimental data not currently available in the literature.

Comparisons to various current models for convective heat transfer, multiphase transport, and electromagnetic pumping can also be made. Correlations for multiphase transport, such as the El-Boher and Lesin model, can then be evaluated using pumping methods shown in Figure 4.

<u>Mechanical pumps</u> that can handle molten metals are available off-the-shelf from various manufacturers. Three representative manufacturers:

- LaBour Pumps www.kthsales.com/website/vendors/LaBour/Taber
- Zenith® Submersible Pumps www.zenithpumps.com/products/sub
- Gusher Pumps www.gusher.com/prod09.

These types of vertical mechanical pumps are used in the industry for pumping of pits or for tank transfer. For this facility, all metal pump construction (ductile iron, 304SS, or 316SS) will allow operation in the Pool Facility. This type of pump is submerged into the LBE/Pb fluid. The Pool Unit is free of contamination and air is replaced with a nitrogen blanket. In order to protect the LBE from oxygen, a double shaft seal on the Pool Unit top could be used. Holding the pump at a certain temperature can be difficult with LBE if the pump is in a loop using electrical heater controls. By submersing the pump into the LBE/Pb, eliminates the need for pump temperature controls. Some vendors allow the pump to be fixed to the bottom of the vessel or by supports attached to the lid which allows the pump to be removed when the lid is taken off of the Pool Unit.

Two basic parameters for vertical pumps are the flow capacity (GPM – pressure) and whether the pump shaft will require a seal to prevent fumes from escaping from the Pool Unit. A bottom bearing is used to support the shaft within the pump. Intermediate bearings are used to support the shaft at mid-points when the pump length exceeds four feet. The exact length is a combination of pump size, shaft diameter, and RPM that can be determined as the experimental design is refined. The bearing lubrication source will be the LBE/Pb itself to prevent the leaking of external water or grease into the Pb-Pool. Although these manufacturers provide two stage pumps for lower flow applications that require higher pressure, a single-stage/single-volute design is expected to work.

Some vendors provide a cantilever design when lower and intermediate bearings are not desirable. This would become an issue if the Pool Unit becomes much longer than four feet. It is apparent that various models may be researched to determine functionality, operating parameters, and applicability to different applications and test functions.

Some uses for these types of pumps are urethane products, sulfur, and solder. Urethane-like pre-polymers and catalysts are typically fluids that are better handled with a submersible pump. These fluids contain isocyanates that harden when exposed to air/moisture. The pump is submersed in the fluid. These fluids have high viscosity; however, cavitation is prevented by submerging the pump.

Pumping molten sulfur with a submerged pump allows control of the sulfur temperature to a very specific heat range. Too high a temperature degrades the product while too low a temperature would return the sulfur to its solid state. Heating the pump and maintaining a tight temperature range with a fluid or electric heat jacket is a difficult task. However, by submersing the pump into a vessel, the pump is held at the same temperature as the process fluid.

Molten solder is another application which is similar to molten sulfur and most applicable to this R&D facility. Although the melting temperature is low 182°C, there is industrial experience using submersible pumps in molten metal. This project can build from that experience.

Natural Circulation. The use of natural circulation as a means of passive cooling of nuclear reactors has received considerable attention. The Pool Unit can be configured to perform this type of R&D by inserting electrical heaters on the flat portion of pool. A few general reviews on natural circulation can be found in Japikse,[42] Zvirin,[43] Mertol and Greif,[44] Mertol and Greif,[45] and Greif.[46] Some of the many experimental studies can be found reported in Alstad et al.,[47] Agarwal, Alam, and Gopalakrishna,[48] Huang and Zelaya,[49] Loomis and Soda,[50] Ardron and Krishnan,[51] and Bau and Torrance.[52] This work reveals that direct comparison with predictions for molten metal systems is few.

The applicability of natural circulation to liquid metal reactors is hampered by concerns of physical properties, geometry, and laminar versus turbulent flow. Most free convection work has been done with fluids having Prandtl numbers (ratio of a fluid's transport properties with respect to momentum and heat) near unity (air, water) whereas liquid metals have very low Prandtl numbers. At 700°C the Prandtl number for Pb is 0.016, LBE is 0.18, and sodium is 0.0038. This is due to liquid metals' much larger molecular conduction component. The free convection heat transfer differences between liquid metals and fluids of higher Prandtl number are noted by Bejan.[53] For liquid metals, the thermal boundary layer extends much further than the velocity boundary layer into the free flow. Scaling analysis shows that the Nusselt number, and hence the free convection heat transfer coefficient, will have a different functional dependence upon the Prandtl number for liquid metals than for liquids such as air and water. Liquid metals amongst themselves exhibit great differences in physical properties. The density of LBE is 10 times—the kinematic viscosity is half—that of sodium. These variations in Prandtl number and physical properties invite questions as to whether correlations developed for water, air, or even sodium may be used with accuracy for LBE systems.

Gas Lift Multiphase Transport. The Ben-Gurion University, in conjunction with Solmecs Ltd. in Israel, has investigated the feasibility of using injected steam for molten metal transport (Branover, Lesin, and Tsirlin.[29,54] LBE-steam systems were examined in addition to mercury-steam and air-water. Empirical correlations were developed for estimating void fraction and slip ratio. Limited experiments were also conducted injecting water into an LBE mixture. The extensive mixing of the two-phase mixture due to the boiling process increased the circulation efficiency (decrease in the slip ratio) of the flow loop can be investigated in the facility presented.

Electromagnetic pumps in molten metal handling have the ability to simultaneously transport mass and heat as a result of forced convection. The pump will be external to the Pool Unit (as shown in Figure 4) using connections provided on the Pool vessel during fabrication. The pump force can be described by Fleming's Left or Right hand rule which states that when a current carrying conductor is placed in a magnetic field a force is exerted on the conductor at right angles to the direction of current. The conductor here is liquid metal. A representative source for EM and pump would be Metaullics www.metaullics.com/emp_acquisition.

The use of electromagnetic pumps for applications outside the metal production industry, other than in the former USSR, has been limited. KALLA currently has an operational LBE loop using an electromagnetic pump originally designed for sodium.[55] Due to low pump efficiency it adds enough heat to the system that piping heaters can be turned off at steady state conditions. Sodium has lower density and low resistively, resulting in a very low efficiency when sodium pumps are used in LBE.

A first principle design study looking at D.C. and A.C. pumps for both sodium and LBE coolants found[56]:

1. A.C. traveling pumps have acceptable pump efficiencies for low density liquids (sodium)
2. Much larger pumping requirements are needed for LBE coolants with high resistivity
3. The power requirements for heavy-metals can be met via a compact D.C. pump design with an hydraulic efficiency of 98% and a mean value of pressure rise of 7 psi/cm.

Depending upon the parameter being optimized (e.g., head, efficiency, and size), hydraulic efficiencies up to 98% could be achieved. However, further knowledge needs to be obtained for startup (if an electromagnetic pump is energized with no flow, overheating damage may occur) and operation of LBE-electromagnetic pump. Also, the pump slip, wall current, and heating of the pump channel need to be better quantified. Research efforts could easily start from Watt's work designing and deploying an EMF pump external to the pool. An operational EMF pump will allow the exploration of thermal physical properties in all flow regimes.

2.2.7 Off-Gas System

The off-gas system is a shared system for the Storage Unit, Pool Unit, Bench Scale Unit, and the Oxygen Sensor and Calibration System. It prevents the release of Pb and its oxides to the environment, while also providing a means to sample and analyze the gas content to better understand process conditions during experiments.

As shown in Figure 6, the off-gas is first quenched to reduce temperature, then directed through a sintered metallic filter (cleaned by pulse blow-back technology) to remove any particulate and collect it for disposal. After leaving the sintered metallic filter, the gas stream is directed through activated alumina to remove any reactive gasses and odors from the gas stream. The gas stream is then directed through a bank of HEPA filters before venting to the environment. This filter and collection process is standard in the foundry industry with the exception of the HEPA filter bank.

Some processes will generate H_2, but the concentration is expected to be low (<2 vol %). Therefore, a flare is not included in the off-gas system.

During normal operation the quantity of solid particulate, primarily PbO particulate, collected on the primary filters is expected to be small. However, there may be experimental campaigns (direct contact/gas lift experiments [see Figure 4]) where considerable Pb and PbO will be carried into the off-gas system. The configuration of the off-gas system allows investigators to quantify the carry over amounts. Further, ports can be directed to the gas sampling system to quantity the gas compositions. This is an important measurement for determination of the oxygen levels.

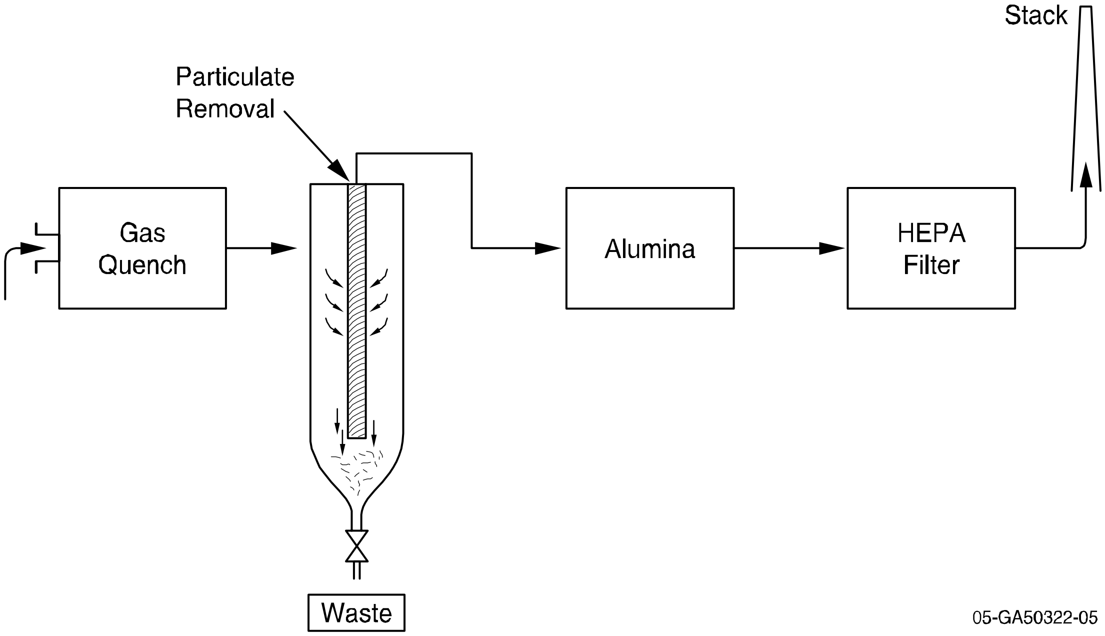

Figure 6. Storage Unit, Pool Unit and Bench Scale Unit Off-Gas System Block Diagram

2.2.8 Purge and Evacuation System

The Purge and Evacuation System removes oxygen from piping manifolds and tanks before the introduction of molten Pb/LBE. This will significantly reduce production of oxide scale normally produced during filling operations using molten metals. The purge system utilizes off-the-shelf vacuum pumps. The off-gas from the vacuum pumps will be directed into the Off Gas System just before the HEPA filters.

Small inline HEPA filters (with clear case) are in-line ahead of the vacuum pump to prevent particulate from entering the pump. Using a clear-cased HEPA filter will provide operators with the ability to observe when the filter requires change out. This eliminates the need for a differential pressure gauge across the filter.

2.2.9 Oxygen Sensor and Control Systems

The significance of oxygen in the corrosion control process of structural materials by liquid metals makes an oxygen-monitoring and control system mandatory. Oxygen sensors for liquid sodium coolant have been investigated by numerous research groups from the early 1960s to the 1980s (e.g., Westinghouse, Interatom, Central Institute for Nuclear Research (ZfK), General Electric, Harwell). For the liquid Pb-17Li system, research was also conducted under the European Fusion Technology Program. Both MIT and INL fabricated and calibrated O_2 probes. The most comprehensive work has been completed at the Los Alamos National Laboratory. This LANL work stimulated the LBETF oxygen control system design. It utilizes an oxygen probe appropriate to the molten Pb-alloy environment. By evaluating the electrochemical oxygen potential, the probe (equipped with a solid electrolyte and appropriate reference electrodes) can measure the oxygen potential in the molten Pb/LBE. This facility will further test compatibility of these probes with liquid Pb-alloy and ionic conductivity.

The LANL probes exhibit the correct temperature dependence and follow the well-known Nernst law.

There are concerns regarding choice of an oxygen-ion-conducting solid electrolyte that will hold up under industrial use. The initial probes should use yttria-stabilized zirconia. A platinum/air reference electrode should be used for calibration.

For oxygen control in the Storage Unit and the Bench Scale Unit, a mixture of H_2/H_2O or H_2/O_2 will be injected, via the oxygen probe(s), into the molten Pb/LBE to control the oxygen potential in the selected operational bands.

Since the control of oxygen is of major importance to the successful operation of the large Pool Unit, an additional oxygen control system will be employed. INL developed an oxygen control system using C and CH_4.[57,58] It uses thermodynamic control and is less complex, more forgiving, and easier to control then the previously described method. The full details cannot be provided in this document but should come available by the time this facility will be deployed (the author can provided details independent of this report on receipt of a non-disclosure statement.).

2.2.10 Data Acquisition and Control System

The Data Acquisition and Control System (DACS) integrates all process monitoring and control functions for the large Pool Unit. The DACS includes the instruments required to measure process variables such as flow, pressure, and temperature and off-gas composition. Control valves and other control elements, and ventilation are also be controlled by the DACS. Voltage/current measurement connections are integral to the sensors, instruments and other elements.

DACS components and devices are interconnected through a data communication networks using standard software. The DACS design incorporates human factors engineering for operator interfaces. Field instruments (around the apparatus) such as control valves, transmitters, thermocouples, and pressure devices are interfaced with the DACS via input/output (I/O) cabinets distributed throughout the facility. The I/O cabinets are connected to the control consoles via a redundant data highway (e.g., ether net). The control consoles are located in the main control room and provide operator interfaces (e.g., CRT displays, alarm and report printers, operator keyboards, remote control and safety system initiators).

The smaller Bench Scale System and Oxygen Sensor/Calibration System are independent from the DACS.

2.2.11 Safety Systems

The safety requirements for the company are broad and are covered in many company Management Documents such as: PRD-185, MCP-3562, MCP-1176, PRD-5117, and MCP-3449. This section of the document breaks these company documents into two broad areas for project consideration: Administrative and Engineered Controls.

2.2.11.1 Administrative Controls. Hazards analyses, authorization bases, and directive development establish administrative controls for operations and personnel safety.

Administrative controls for operations and maintenance assure that pre-start checks are conducted to validate operability of safety systems; that monitoring systems and control systems are within specifications; that operating parameters are validated frequently to assure safe limits are maintained; and that calibration and maintenance requirements are met.

Administrative controls for personnel safety include requirements for personal protective equipment, lock out tag out, inspections for Pb or PbO contamination, and stand-off distances from hot surfaces. Work uniforms, donned and doffed in the Change Rooms, are required for admittance to the facility. The uniforms are not allowed outside the facility except for approved cleaning.

2.2.11.2 Engineered Controls. The primary hazards in the LBETF are the large amount of very hot molten metal, high-power energy sources, and overhead crane operations.

Hot Pb/LBE presents a burn and toxic hazard:

- Prevention of burns will occur through containment of molten metals in sturdy, conservatively-designed containment structures. External surfaces of heated components—Pool Unit, Storage Unit, Bench Scale System—will be heat traced and insulated, and stand-off distances will be prescribed.
- To prevent both burns and inhalation of toxic fumes, the external insulation will slow any pin-point leakage and/flow of molten metal, allowing avoidance of hot metal and providing and evacuation time cushion.
- To contain spilled or leaking molten metal, a containment enclosure (wading pool enclosure) is incorporated into the Pool Unit, Storage Unit, and Bench Scale System designs.

The building design provides negative-pressure ventilation, with a large local flow-around patterns where airborne PbO might be encountered. Continuous online monitoring system for airborne Pb is incorporated to protect personnel and provide a baseline measurement in case of release.

All electrical heating systems are double insulated and grounded. Remote operation for high-capacity controllers is incorporated into monitoring and safety systems.

Control of overhead cranes is accomplished using remote or stand-off controllers, so the operator is not in the immediate vicinity of potential drop zones (PRD-6500).

Alarm set-points are established to monitor limits and trigger alarms to alert operators to out-of-specification conditions.

The separate Personnel Area provides an additional engineered barrier to physical hazards.

2.3 Preliminary Facility Design

2.3.1 Description

The LBETF is configured around the three principal experimental elements—Pool/Storage Units, Oxygen Calibration Unit, and Isothermal Bench Scale Unit. Suggested support areas are the Control Room Area, Sample Preparation Area, Maintenance Area, and Personnel Support Area (change rooms, showers, restrooms, break room). The following company policies and procedures should be consulted before final selection of the Facility: MCP-6206, PRD-5030, LST-96, PRD-25, and PRD-155.

2.3.2 Facility Layout

This section provides a proposed facility layout concept. A facility structure that provides a separate enclosure for the Pool/Storage Units, Oxygen Calibration System, and Isothermal Bench Scale System, and the support areas would be ideal. This provides segregation of research activities, allows the researchers to operate virtually independently of each other, and provides better containment between activities.

The activities from the two smaller experimental units feed the Pool Unit. Access through the enclosures should be non-restrictive to equipment, material and personnel movement. Accessible communications—loudspeaker system, phones, computer terminal/screen, quick-actuated emergency signal—would enhance the facility.

The separate Sample Preparation Area supports analytical work with facilities such as a balance, optical digital microscope, and a Pb detection kit. Detailed analytical work (such as electron micrsocopy and chemical analysis) would be completed at existing INL facilities performing such measurements.

A separate Packaging/Storage Area provides space and equipment to package waste, primarily from the experimental unit cleaning process and the Off-Gas System and package samples for further analytical work at other INL facilities. The waste could be stored in this area until a specified amount is on hand to justify shipment off the facility. Packaging procedures will prevent facility cross contamination.

2.3.3 INL Location

This period of contract change and consolidation at INL and ANL-W provides opportunities to select the site for the LBETF. There are several large buildings that could be used to support the vision of this facility. This section provides details on one INL facility whose current program landlord is offering this project space in the Mixed Waste Storage Facility (PBF-613). Their goal is to make the facility a multi-user facility.

The Mixed Waste Storage Facility was built in 1962 in support of the SPERT reactor program. It was constructed of concrete, was steel framed, and has a masonry exterior with a foot print of 10,364 sq ft. The building has three levels, two of which are below grade.

What makes this building attractive for this deployment is the floor structural designed heavy loads (300-500 lbs/sq ft). The building has two roll-up doors, a 12-ton operational bridge crane, and several rooms for operational staff and other support activities. The following three figures provide an external view and floor plan.

This facility is being used to develop and test protection/detection technologies. Of interest to LBETF operations is the high-energy accelerator used in the specialized detection system. The accelerator is a transportable, pulsed electron accelerator (INL VARITRON) used to produce energetic (8–12 MeV) x-ray (bremsstrahlung) radiation.

The high-energy portion (>6MeV) of the bremsstrahlung photon spectrum from an electron accelerator will produce copious quantities of high-energy photons (i.e., $>10^9$ photons/s) capable of penetrating through most shielding configurations. The author used bremsstrahlung photon to investigate molten Pb-water interactions for reactor safety studies. With a different detection system (than the one just explained) he was able to see density differences to be able to quantify the violent metal/water interaction. That detection system or using the one described above (and using depleted uranium targets) could be used to observe flow instabilities inside the Pool or Storage Unit.

Figure 7. Mixed Waste Storage Facility

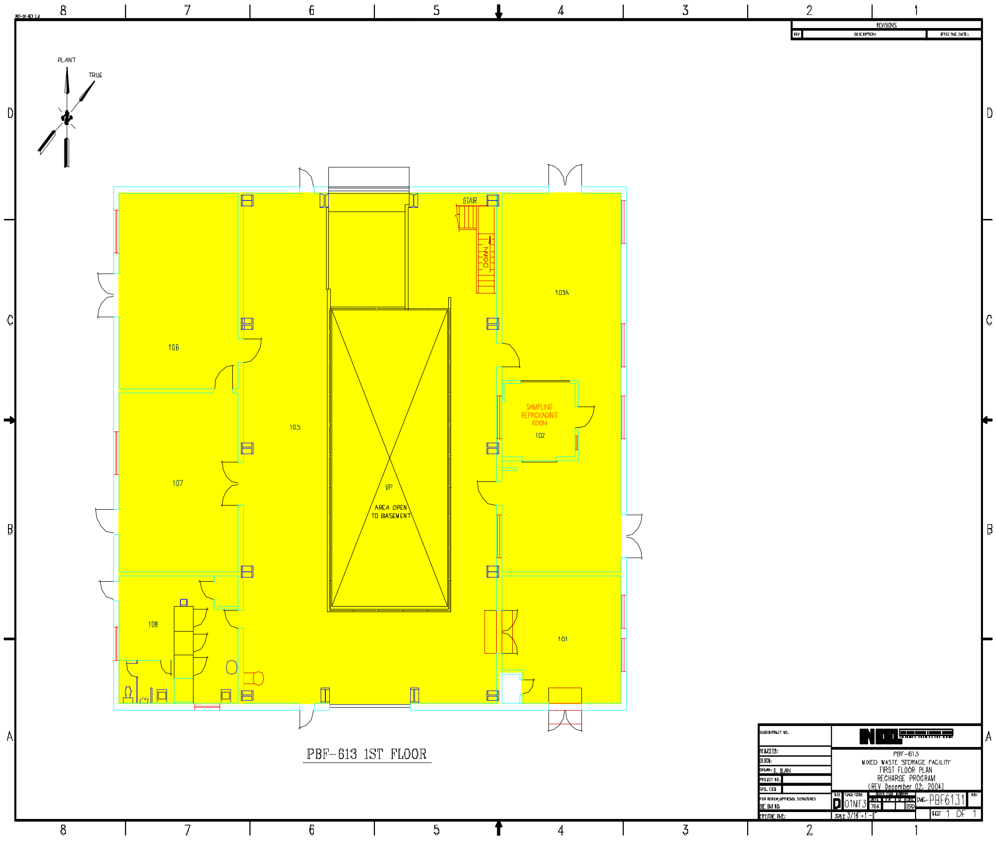

Figure 8. PBF-613, first floor.

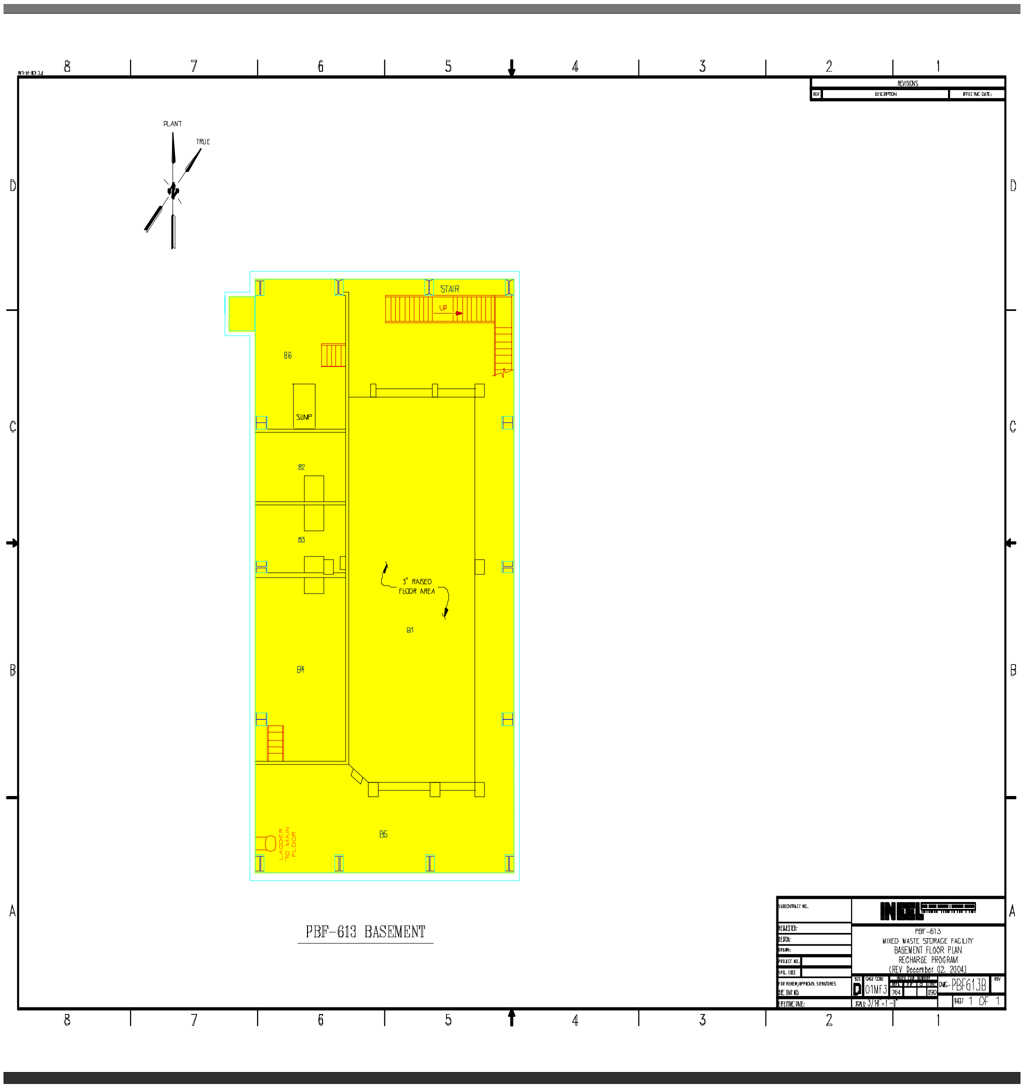

Figure 9. PBF-613, basement.

The National Security leads have assured the author this project is welcome to deploy in PBF-613. The confluence of these building physical capabilities (e.g., overhead crane, rated floor, and several rooms) and the ability to use the accelerators for investigation of physical flow phenomena would truly make this faculty world recognized. This type of collaborative research, sharing resources, is what the new vision of the INL is moving towards.

Another option could be a site in or around the IRC in Idaho Falls. A new facility could be included in the design of the planned Center of Excellence (described in the Request for Proposal). A site in town would provide easier access for informational tours and visiting dignitaries.

There are many unique options for the deployment of this facility at the INL. The planers for this project need to ensure the deployment of the facility leverages as many interests possible for the future of INL.

3. FACILITY OPERATIONS

This section outlines the design basis operating procedures for the large Pool Unit and sets the tone for operations. They are based on the author's experience in developing detailed Standard Operating Procedures (SOPs) that have been used for operation of the INL's two isothermal corrosion units. (The author has previously prepared first-of-a-kind SOPs for a radioactive resin processing unit, a UF_6 processing unit, and a two-ton molten metal unit to process Hanford tank waste.) Although more details are required for actual deployment, these general outlines provide the reader with process flow so that he/she can appreciate the simplicity of operation for the design presented in this document.

As facility configuration and experimental and supporting equipment are finalized, these general outlines can be expanded. Further expansion will result from facility construction and equipment procurement, then installation and testing. Start-up procedures will then be finalized through hazards analyses and in accordance with approved authorization bases.

Managers, supervisors, operators and maintainers will be trained in the SOPs and qualified for their position (MCP-22, PRD-600, STD-101, and PRD-185).

The following operational outline is conceptual at this time, but it provides the logic for starting operation and sets the framework for SOP development.

3.1 Start Up and Shut Down

1. The Pb and Bi is received in drums. The drums are unloaded and inspected for purity and gross contaminates. (Authors experience has found wood debris in Pb that can be easily separated through washing).

2. The drum is weighed and moved to the deck on top of the Storage Unit using the overhead crane. (PRD-6500) The contents of the drum are emptied into the Storage Unit. The drum is reweighed to determine the exact mass loaded into the Storage Unit. This is continued until the Storage Unit is filled to the prescribed amount.

3. The Storage Unit flanged lid top is bolted on and a pressure check is performed (PRD-5040).

4. A lance from the Purge and Evacuation System is inserted into the Storage Unit at the top of the flange. Once measured (with the Oxygen Sensor and Control System) oxygen levels are below 10 ppm, a steady gas purge is established. The Storage Unit is vented to the Off Gas System.

5. The induction coil around the Storage Unit is energized and the metal is heated slowly to 50°C below the liquids point. This temperature is held until the entire system is isothermal. Heat rate is then increased rapidly to cross the liquids point to prevent bridging inside the Storage Unit. A lance is lowered into the bath for gas stirring. Carbon can be added to remove any oxide layer floating on the surface.

6. Solid metal is added via the lock hopper if necessary to reach the desired amount.

7. The Pool Unit and transfer line are then purged using the purge and evacuation system. (This assumes the desired core and plenum configuration have been preloaded into the Pool Unit, the flanged cover in place, and a pressure check was satisfactorily performed). The Pool Unit surfaces and transfer line are heated to within 100°C of the molten metal in the Storage Unit. This prepares the Pool Unit to accept the molten metal from the Storage Unit.

8. To accomplish the metal transfer, the Purge and Evacuation System reduces pressure in the Pool Unit side, while inert gas flow is initiated into the Storage Unit to increase pressure. Care is taken to prevent sloshing/splashing when the bottom connection valves are opened (remotely via the Control Room) to allow molten metal to flow from the Storage Unit into the Pool Unit.

9. To shut down the system, the steps are reversed to transfer the molten metal back into the Storage Unit. Depending on the experimental schedule, the liquid state of the metal can be maintained with the Storage Unit induction coil, or the metal can be allowed to solidify.

Note: Permanent shut down is not covered by this sequence and can be discussed as desired.

3.2 General Operations

Most normal, hands-on experiments will be conducted in the Pool Unit. These experimental operations should be conducted with an approved Experimental Run Plan (MCP-3571). The run plan will provide the proper management approval while setting the bounds and duration of the experiment. The following monitoring activities should be typical for these operations:

1. Heating system(s) temperature and current flow of the heaters will be monitored to ensure proper operations. This monitoring is accomplished via the Data Acquisition and Control System (MCP-3039 and -3056).

2. The oxygen potential inside the Pool Unit will be continuously monitored by the Oxygen Sensor and Control System. Gas injection will be managed to keep the oxygen potential (as measured by the oxygen probes) within the experimental requirements.

3. The Pool Unit, both the headspace and molten metal, will be continuously monitored. Pressure and temperature, analytical control instrumentation and associated experimental feed or pumping systems, metal inventory, molten metal height, oxide accumulation, and heating system parameters will be recorded by the Data Acquisition and Control System.

4. The Off Gas System steady state temperature and pressure, delta-P across filters, purge rates of inert gases, and inventory of the levels of metal/powder accumulation will be continuously monitored. Through pre-determined technical specifications, alarms will alert operators if shut down is required.

5. The experimental process, fixture, and component under investigation will have operating parameters as determined in experimental run plan. If the experimental parameters are exceeded the experiment is stopped.

6. During steady state operations the major responsibilities for the Control Room are to assure that the valve lineups are correct, operating parameters are within specification, accurate logs are maintained, containment systems are monitored, and auxiliary activities are properly integrated with experimental operations.

3.3 Integrated Operations

Simultaneous experiments can be conducted in the Storage Unit and the Pool Unit.

The Pool Unit is constructed with the ability to modify both the way the system is heated and how the molten metal is transferred/flows within the Pool Unit. This flexibility allows many concepts to be investigated.

The Storage Unit, using induction heating, allows the ability to directly (if submerged susceptors are added to the bath it will be heated internally rather than externally) heat the molten metal. The induction furnace, with its ability to heat rapidly, allows testing of submerged devices (e.g., heat exchangers, steam generators, simulated fuel pins). Feed-though from the Storage Unit lid (top) will allow injection of fluids (gas or liquid) into the heat exchanger. The dual use and unique symmetric heating of the Storage Unit will allow unit testing of many components.

This unique re-configurable loop facilitates better engineering understanding of different plant designs. It provides flexibility and utility that existing loop facilities, dedicated to basic material science studies, are unable to perform.

3.4 Experimental Changes: Cleaning and Decontamination

Basic operational procedures for cleaning and decontamination between experiments will be prepared as part of future work.

4. COST ESTIMATE

Before a cost estimate can be completed for this project the following company management documents should be consulted: PRD-182, MCP-2871, MCP-3796, and MCP-3672. However, this section provides future planners some guidance from company documents and the author's experience.

4.1 General Methodology

Cost estimating for a one-of-a-kind research facility such as the INL LBETF is unstructured. Firm guidance cannot be provided at this stage. It is essential that the basic design concept be defined, then controlled estimates for accomplishment can be made. When the equipment/system concepts, technical requirements, and process requirements are established, the INL Business Planning Support Department should be brought in to assist with planning and budget development.

Planning and cost estimating for the INL LBETF should use the functional concept design flow as the basis. Table 5 provides a gross functional work breakdown structure (that can be expanded as new issues are identified) and a checklist to guide the developer so that issues are captured and addressed.

Once the design is finalized the direct field costs for the equipment can be estimated. The sizing requirements will dictate the project costs. With the basic structure known, the commodities such as steel and piping can be costed using material take-off sheets.

Other elements that planners must include in the projects costs are such non capital items such as:

- Start up costs (operational procedure development, training, spare parts, safety walk downs)
- INL Safety support functions (Hazards and Operability Study, Independent Hazard Review, Management Walk Down)
- Key vendor delivery delays.

4.2 Special Exclusions

The following various elements of cost should not be included in the project estimate to DOE and should be absorbed by the INL as cost of doing business. This are:

- Soil testing for Pb to establish an environmental background for the facility
- Building testing for Pb residual to establish a baseline and remediation if needed
- Internal costs such as internal audits, self evaluations, or other company imposed requirements once the project has been funded.

Table 5. Project Functional Work Breakdown Structure

	Define Requirements	Identify Hazards	Identify Controls	Implement Controls	Determine Readiness	Start-up & Operations	Feedback & Improvement	Life Cycle Support	Decontamination & Decommissioning
SYSTEM REQUIREMENTS									
Technical Characteristics									
Hazards Identification & Mitigation									
Regulatory Requirements									
Systems Design									
Production									
Maintenance									
Operation									
UNIT DESCRIPTIONS									
Bench Scale System									
O_2 Sensor and Calibration System									
Pool Unit									
Feed Systems									
Storage Unit									
Pumping Systems									
Off-Gas System									
Purge and Evacuation System									
Oxygen Sensor and Control Systems									
Data Acquisition and Control System									
Safety Systems									
FACILITY									
Structure									
Experimental Systems Support									
Containment Systems									
Safety Systems									
Personnel Support									
UTILITIES									
Electrical									
Water									
Communications									
HVAC									

4.3 Cost Risk Analysis

With any large DOE deployment project there will also be a certain risk regarding the cost of the project. Since this project has the expectations of building a large multi-user facility that will take a few fiscal years to complete, it produces project cost risk.

After completing the preliminary cost estimate, a probabilistic risk analysis should be performed on the facility to determine the contingency that should be included in the total estimated cost. By developing a risk model the completed cost estimate can be tracked. In the model each of the elements of cost is assessed for uncertainty, which is then supplied as input to the risk model. By definition, the uncertainties include an assessment of the estimate basis definition and an assessment of future design changes that may occur within the defined scope of the research.

A refined model would input the uncertainties into the mathematical model, using such techniques as Latin Hypercube risk analysis methodologies to randomly select estimate uncertainties and run several iterations to generate a probability of distribution. The analysis can also be geared to do a sensitivity analysis, keying on parameters the design is less certain about. This type of insight communicated to DOE will allow the project to move forward with very little in cost surprise and project overruns. This requires more planning than a typical project management scheme where costs are tracked to a fixed budget.

5. HAZARDS IDENTIFICATION AND SAFETY ASSESSMENT

5.1 Introduction

The immediately obvious hazards in the INL LBETF are human toxicity associated with Pb and thermal energy. But they must not distract attention from the many other hazards that will exist in the proposed facility such as electrical, over-head crane operations, machinery operations, chemical exposure, and explosion (H_2 use for oxygen control) hazards. All potential hazards that may be encountered during normal and off-normal operations and conditions must be evaluated and mitigated. INL and the DOE require that before start-up of any facility, management must:

1. Identify existing and potential workplace hazards and evaluate the risk of associated worker injury or illness

2. Implement a hazard prevention/abatement/mitigation process to ensure that all identified hazards are managed through final abatement or control.

For experimental operations this is accomplished through the Independent Hazard Review process described in MCP-3571.

Larger experimental programs that have multi-principal investigators, pilot scale experimental apparatus, extended operations, and several subject matter experts for operation (e.g., I&C technicians, pipe fitters, operators, and safety support) require a more detailed analysis to identify and mitigate potential hazards.

A recent example to consider for guidance is the INL's Diesel Reformer project. The manager used the Independent Hazard Review process to govern experimental operations, then implemented other INL work practices to design, evaluate safety, build, and test, before advancing to the operational stage. Appropriate INL best work practices can be found in MCP-3562, Hazard Identification, Analysis and Control of Operational Activities; MCP-540, Documenting the Safety Category of Structures, Systems and Components; and STD-107, Configuration Management Program.

Many of the hazards identification and safety assessment activities are functionally interactive. It is essential that the personnel performing these activities establish good communications early in the process.

To ensure proper monitoring of these necessary activities, the following overview is provided for the LBETF Manager and/or Lead Principle Investigator.

5.2 LBETF Process Hazards Analysis Overview

The generally accepted large-scale process for hazards identification and safety analysis is the Process Hazards Analysis (PHA). This overview of the PHA process is organized along the lines of the DOE Integrated Safety Management System core functions.

5.2.1 Define Scope of Work

This function requires identification of all experimental operations proposed in the R&D requirements list and the scope of facilities work (e.g., experimental set-up, operations, maintenance, hoisting and rigging, Pb waste packaging).

5.2.2 Identify and Analyze Hazards

The PHA Development activities associated with this core function include:

1. Identify hazards
2. Screen hazards
3. Identify hazardous events
4. Screen hazardous events
5. Identify consequences.

Hazards identification is performed comprehensively and systematically so that all known facility and operational level hazards (hazardous materials and energy sources) are ascertained and documented. One method the author used for previous INL Pb-experiments was a Hazards and Operability Study (HAZOP). The HAZOP identifies initiators of hazardous events by recognizing internal and external energy sources (electrical, thermal, mechanical, or chemical). This systematic process with each experimental component or experimental process yields a comprehensive hazards list.

The PHA identifies and evaluates both facility and process hazards. Also evaluated is the interaction of the identified hazards and potential external and natural phenomena events.

1. <u>Identify Facility Level Hazards</u>. At the Facility Level, the hazards identified are those external to the facility and those that result from energy sources within the facility. The types of facility hazards and hazardous material inventories considered are:
    a. Natural phenomena (e.g., earthquake, high winds)
    b. External events (e.g., vehicle impact, grass fire, neighboring facility explosion)
    c. Energy sources (electrical, air, vacuum, HVAC, gas, thermal)
    d. Chemical inventory (type, form, quantity, location)
    e. Flammability/explosive (type, quantity, form, location).
2. <u>Identify Operational Level Hazards</u>. At the operations level, the hazards identified include those that are introduced as a result of performing the operations or activities/tasks associated with the operations. These hazards are typically identified through document reviews (e.g., procedures, standards), walkdowns of the facility and the processes, and through discussions with representatives from operations during the PHA Project Team Meetings. The types of operational hazards and hazardous material inventories considered are:
    a. Facility environments (mechanical, electrical, chemical, thermal)
    b. Process equipment failure (action when not expected, inaction when action is expected)
    c. Personnel error (action when not expected, inaction when action is expected)
    d. Chemical inventory (type, quantity, form, location).

3. Screen Hazards. This activity identifies those hazards that require further analysis in the PHA process. Examples of such hazards are working in confined spaces (e.g., when installing baffles in the Pool Unit), dusty environments (cleaning the Off Gas System), noisy environments, and/or extreme temperature conditions (operating at highest design temperature).

4. Identify Hazardous Events. Based on the hazards identified in the previous step and the activities to be performed, hazardous events are identified. Hazardous events identify the method or mechanisms by which hazardous material or energy sources can be released to an unwanted location and result in a serious personal injury or fatality and/or damage to equipment and facility (e.g., excessive H_2 in off-gas system ignites, over-head crane rail fails, the Storage Unit is breached when filled with molten metal).

5. Identify Potential Consequences. For each hazardous event, the potential maximum unmitigated consequences are identified.

The consequences for the hazardous events are generally qualitative with little analysis. Consequence Categories:

- Personnel Serious Injury/Fatality
- Significant Facility/Equipment Damage
- Environmental Impact
- Major Industrial Hazard.

5.2.3 Identify Controls

The PHA Development activities associated with this function include

1. Identify Operational Safety Controls
2. Evaluate effectiveness of Operational Safety Controls.

Identifying controls focuses on determining the preventive and mitigative features that prevent the hazardous event from occurring or reduce the consequences of the hazardous event.

1. Identify Operational Safety Controls. Based on the hazards analyses, operational safety controls are developed and implemented to prevent the hazardous events from occurring, or to mitigate the consequences resulting from the hazardous events.

There are two types of controls: engineered features and administrative controls.

- Engineered controls rely on structures, systems, or components; they may be passive or active
- Administrative controls rely on human action.

Engineered controls are generally more reliable than administrative controls.

When identifying controls, the following control relationships are to be considered. These control relationships provide the foundation for the determination of adequacy for a set of controls.

- Preventive controls over mitigative controls
- Engineered features over administrative controls
- Passive engineered features over active engineered features.

2. Evaluate Effectiveness of Operational Safety Controls. Controls selected in the hazards analysis are evaluated to determine their overall effectiveness by evaluating their potential failures and associated causes.

All facility- or operational-specific operational safety controls are evaluated for effectiveness. The evaluation considers functionality, reliability, and/or availability associated with each potential failure, which defines the effectiveness of the control (or conditional probability of failure).

The effectiveness of the operational safety controls is evaluated to ensure that the control provides sufficient reduction in risk.

5.2.4 Implement Controls

The activities associated with this core safety entail developing the information required to accomplish the following:

1. Demonstrate Operational Safety Controls. Demonstrating operational safety controls is essential before operations can start.
2. Develop Procedures, Guides, and Other Tools for Implement Controls.

5.2.5 Confirm Readiness

The activities associated with this core safety function include (PRD-185, Conduct of Operations and MCP-1126, Performing Management Self-Assessments for Readiness):

1. Required Inputs for Confirm Readiness
    a. Peer review and concurrence
    b. Management approval of the PHA document.
2. Participants for Confirm Readiness. Significant participants of the project team include
    a. PHA Leader
    b. System Engineers and Subject Matter experts
    c. Facility Management
    d. Experimental Management.

5.2.6 Perform Work

When start-up has been authorized, work is performed in accordance with approved standards and procedures (MCP-3571, Independent Hazard Review; PRD-185; Conduct of Operations; PDD-1027; Conduct of Engineering).

5.2.7 Provide Feedback and Continuous Improvement

When deficiencies or improvements are identified through evaluation of operations, assessments and reviews, changes are proposed. These proposed changes are evaluated for their impact on the safety of the operations (GDE-77, Engineering Self-Assessment Program and MCP-2398, Developing and Maintaining Emergency Management Hazards Assessments).

Feedback and improvement is an iterative process.

5.3 Documents for PHA

The following INL directives address some aspects of the PHA process. These documents and their requirements need to be known by the LBETF management and the persons participating in the PHA. Note that they may change as the M&O contractor changes and the INEEL merges with ANL-W.

This list is not all encompassing. Related DOE directives and Code of Federal Regulation sections have not been included. The directives are grouped generally for the same topic.

MCP-6206, Maintenance and Use of the Facility Hazards List

MCP-3562, Hazard Identification, Analysis and Control of Operational Activities

GDE-6212, Hazard Mitigation Guide for Integrated Work Control Process

PRD-164, Safety Analysis for Other than Nuclear Facilities - Suspended

MCP-3571, Independent Hazard Review

PRD-25, Activity Level Hazard Identification, Analysis, and Control

PRD-5042, Facility Hazard Identification

MCP-579, Performing Fire Hazards Analysis

MCP-2398, Developing and Maintaining Emergency Management Hazards Assessments

MCP-2411, Developing and Maintaining Emergency Management Hazards Surveys

MCP-6403, Assured Equipment Grounding Conductor Program

PRD-5099, Electrical Safety

MCP-6501, Hoisting and Rigging Operations

MCP-6502, Hoisting and Rigging Maintenance

MCP-6503, Inspection and Testing of Hoisting and Rigging Equipment

MCP-6504, Hoisting and Rigging Lift Determination and Lift Plan Preparation

MCP-1206, Monitoring Chemical Limits in Research and Development Laboratories

PRD-5039, Chemical Storage

GDE-236, Management of Time Sensitive Chemicals

GDE-237, Compatible Chemical Storage

MCP-2708, Maintaining Facility Chemical Storage Limits

MCP-2720, Controlling and Monitoring Exposures to Lead

PRD-5040, Handling and Use of Compressed Gases

PRD-5103, Walking and Working Surfaces

PRD-5107, Aerial Lifts and Elevating Work Platforms

PRD-5110, Welding, Cutting and Other Hot Work

MCP-2737, High-Temperature Systems Change DAR #40813

MCP-2734, Explosives Safety

MCP-69, Waste Generator Services – Hazardous Waste Management

MCP-2669, Hazardous Material Shipping

MCP-3775, Acquisition, Control, and use of Hazardous Material Packaging

MCP-9208, Hazardous Waste Data Verification and Annual and Biennial Reporting

5.4 Decommissioning

Prior to authorization for start-up, DOE requires identification of systems and materials that will require special attention when a facility is decommissioned. The parts of the system that will require hazardous materials disposal will be primarily severely degraded metals, porous surfaces, PbO contaminated materials, expended personal protective equipment, and contaminated Off Gas System components.

Previous operating experience at the INEEL included recycling experimental Pb/LBE with an off-site metal recycler. Most of the structural steel (even that in contact with Pb) can be recycled as scrap metal. Integrating a clean up system (as shown in Figure 1) into the design for experimental reconfigurations can also be used to remove Pb from internal surfaces during decommissioning.

The Decommissioning Plan should include sufficient reserve for project termination (planned or unplanned).

6. MANAGEMENT RISKS

6.1 Technical Risks

Technical risks are associated with the scale-up of the design from the current bench top iso-thermal cells with supporting systems to a large R&D facility. Although the LANL DELTA II loop facility is large, the INL LBETF will handle another order of magnitude of Pb/LBE, along with more complex experiments. The risks can be mitigated by capturing and incorporating the extensive base of LBE technology and engineering experience developed around the world.

The flexible configurability of the Pool/Storage Unit presents additional risks. Well-defined and verifiable scaling laws have been developed and are extensively used in the sodium reactor arena, and can be interpreted for application to provide LBETF configurations for various reactor designs.

Bench-scale operations at the INEEL May Street Lab provided valuable experience in safety issues associated with Pb operations. Besides the Pb experimenters, the significant INL organizations (Safety, Industrial Hygiene, Fire Protection, and Regulatory Compliance) also gained valuable experience in the handling the issues associated with Pb. This experience should place most of the risk into the technical area, rather than in regulatory space.

Development of the Pool Unit begins with customer specifications, leading to design variables which could be preliminarily verified in the operating DELTA loop. This will allow design iteration, permitting technical advancements for technical—and safety—optimization.

6.2 Funding/Support Risk

An incremental approach is suggested for the Pool Unit. Select the configuration with the least technical risk. When the unit concept is proven through successful experiment, then ask the customer for additional funding to enhance the capabilities. This approach has been successful at other large federal experimental facilities such as Stanford Linear Accelerator Center, which used incremental funding to increase the operating power in their discovery of the quark.

6.3 Availability Risk

The success of the DELTA II loop has been limited by it’s experimental availability. All experimental design has uncertainties which impact the ability to conduct experiments. The uncertainties consist of:

- Operability (ease of operation)
- Start-up and shut down time
- Control the oxygen potential (DELTA I loop air egress resulted in PbO formation and permanent shutdown)
- Cost of operation.

The LBETF optimizes experimental availability with the key design feature that the Storage Unit can be—and is expected to be—used for research. Technical support program(s) for secondary side components can be conducted in the Storage Unit concurrently with thermal hydraulic studies in the Pool Unit.

Overall system availability for the LBETF is targeted at 80%. Uncertainties in individual component availability, human resources, and funding constitute risk components to this level of operability. This risk is mitigated by careful management.

6.4 Safety and Environmental Risk

Three principal factors contribute to safety and environmental risks:

1. Engineering and design flaws
2. Equipment failures
3. Human error.

These risks can be contained through aggressive leadership and management. The INL's work programs are rooted in preventing these risks from leading to injures or release of Pb into the environment. See Appendix 1 for the applicable work documents that should be used for this project.

To prevent design flaws, comprehensive operability reviews (such as a HAZOP Program) and a rigorous Process Hazards Analysis will be performed early in the design phase. Prior to start-up, detailed cold- and hot-checks of all systems—singularly, then integrated—must be completed.

Since process changes, experimental feed rate variances, and equipment and procedures changes can potential introduce new hazards into experimental operation, the HAZOP program is an ongoing activity. This program accommodates and supports the dynamics of experimental operation.

Safety can best be maximized through engineered controls that trigger self-correction without operator control actions, and conservative operating margins that prevent off-normal excursions from causing failure.

Successful management of equipment failures is assured through over-design, control system redundancy, and planned defense in depth against material failure. For example, expect Pb leaks; therefore, the Pool Unit, Storage Unit, and Bench Scale Unit are within a "catch basin" for the molten Pb.

Pre-op check lists, planned maintenance, material inspections and rigorous record keeping with constant review enhance operability and safety.

Potential for human error is reduced through human factors engineering. The INL Human Factors Department has extensive expertise in this discipline, and this group should be consulted early in the design and safety review process. The principal value of human factors engineering is designing in people friendly operating stations and control systems.

Effective management reduces human error by delegating responsibility only to individuals who are trained and qualified, and use only validated and approved operating standards and maintenance procedures. Formal conduct of operations further enhances operational safety.

Periodic safety reviews and audits monitor equipments, operations and personnel qualifications. They provide feedback and identify corrective actions and improvements.

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8. INL REQUIREMENTS APPLICABLE TO THE INL LBETF

INL work management documents applicable to design, development and start-up of the Lead-Bismuth Eutectic Test Facility are identified in this section. They are also called out in related sections of the report.

Although the documents will change with the new M&O contractor and merger with ANL-W, planners will be able to map into—and integrate with—current work practices.

This list is not absolute. As additional requirements are identified during the design and development process, additional management and requirements guidance can be found in other MCP documents. This attachment provides an excellent starting point for project personal.

PRD-182, Requirements of the Project Control System

MCP-22, Work Authorization

MCP-2871, Estimating Project Costs

MCP-3796, Planning and Scheduling

PRD-600, Maintenance Management Requirements

STD-101, Integrated Work Control Process

MCP-6201, Preventive/Predictive Maintenance Program

MCP-6206, Maintenance and Use of the Facility Hazards List

PRD-6500, Hoisting and Rigging Program

PRD-267, Accumulation and Temporary Storage of RCRA and TSCA Regulated Waste

PRD-271, Small Quantity Generators and Conditionally Exempt Small Quantity Generators

PRD-5030, Environmental Requirements for Facilities, Processes, Materials and Equipment

MCP-3672, Regulatory Inspections

LST-96, Environmental Aspects of INEEL Work Activities

PRD-185, Conduct of Operations

MCP-3562, Hazard Identification, Analysis and Control of Operational Activities

STD-107, Configuration Management Program

PDD-12, Engineering Design

MCP-540, Documenting the Safety Category of Structures, Systems and Components

MCP-3039, Analysis Software Control

MCP-3056, Test Control

MCP-3572, System Design Descriptions

MCP-3573, Vendor Data

MCP-3772, Use of Commercial Grade Items in Safety Structures, Systems, and Components

MCP-9185, Technical and Functional Requirements

MCP-9217, Design Verification

MCP-9359, Specifications

MCP-550, Software Management

MCP-1206, Monitoring Chemical Limits in Research and Development Laboratories

MCP-2875, Maintaining Laboratory Notebooks

MCP-1176, Safety Analysis Process

MCP-3571, Independent Hazard Review

PDD-16, Occupational Safety and Health Program Overview

PRD-25, Activity Level Hazard Identification, Analysis, and Control

PRD-186, Occupational Safety Program

PRD-5060, Occupational Safety and Health Functions, Roles, Responsibilities, and Interfaces

PRD-5117, Accident Prevention Signs, Tags, Barriers and Color Codes

MCP-3449, Safety and Health Inspections

PRD-320, Pressure System Safety

PRD-324, Material Handling and Storage

PRD-5040, Handling and Use of Compressed Gases

PRD-5042, Facility Hazard Identification

PRD-5121, Personal Protective Equipment

MCP-2708, Maintaining Facility Chemical Storage Limits

PRD-155, Emergency Management System

MCP-2398, Developing and Maintaining Emergency Management Hazards Assessments

MCP-2411, Developing and Maintaining Emergency Management Hazards Surveys

PDD-1003, Waste Generator Services Program

PRD-5041, Packaging and Transportation

MCP-2720, Controlling and Monitoring Exposures to Lead

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