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Design and implementation of a hydraulic test facility

Zachary C. Nielsen
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A Thesis

entitled

Design and Implementation of a Hydraulic Test Facility

by

Zachary C. Nielsen

Submitted to the Graduate Faculty as partial fulfillment of the requirements

for the Master of Science in Mechanical Engineering

Dr. Walter W. Olson, Committee Chair

Dr. Abdollah Afjeh, Committee Member

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The University of Toledo
August 2011
An Abstract of
Design and Implementation of a Hydraulic Test Facility
by
Zachary C. Nielsen
Submitted to the Graduate Faculty as partial fulfillment of the requirements
for the Master of Science in Mechanical Engineering
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August 2011

Hybrid vehicles improve fuel efficiency and reduce harmful emissions. Hybrid
Hydraulic Vehicles (HHV) have the potential to double the efficiency of currently
available hybrids. To improve the efficiency of hydraulic components used in a HHV,
testing needs to be conducted in a laboratory environment.

Testing of hydraulic components determine parameters critical to performance
such as speeds, torque, fluid flow, and operating pressures. Efficiency maps are gen-
erated. Durability of components is evaluated through endurance testing. Oper-
a tional limits are established for both components and systems. Simulated operating
cycles determine the effects on pump/motor (P/M) and other hydraulic devices in
the system. Side effects of operating a hydraulic system such as noise, vibration, and
heat are determined. Manufacturer data can be validated and data unavailable from
manufacturers can be established. In this thesis, the design and construction of a
hydraulic test facility to perform this testing will be detailed. Safety precautions and
testing procedures will also be discussed.

The laboratory is capable of testing hydraulic pumps and motors up to 5,000 PSI.
Data can be collected on inlet and outlet pressure, inlet and outlet flow rates, fluid
temperature, torque, and speed. All test cells can be configured for both pump mode
(powered by electric motor) and motor mode (power absorbed by electric dynamome-
ter).
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My family, especially my parents Don and Connie Nielsen, has supported me in all my endeavors both academic and personal. I would also like to thank Natalie Deel for all her support. I will always be grateful for their guidance and unending confidence.
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C-8 900 RPM, 4500 PSI constant value test.

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<th>Definition</th>
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<tr>
<td>BDC</td>
<td>Bottom Dead Center</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>GPM</td>
<td>Gallons per Minute</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>HHV</td>
<td>Hybrid Hydraulic Vehicle</td>
</tr>
<tr>
<td>HIL</td>
<td>Hardware in the Loop</td>
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<tr>
<td>HLA</td>
<td>Hydraulic Launch Assist</td>
</tr>
<tr>
<td>HP</td>
<td>Horse Power</td>
</tr>
<tr>
<td>HTF</td>
<td>Hydraulic Test Facility</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>ID</td>
<td>Internal Diameter</td>
</tr>
<tr>
<td>NVFEL</td>
<td>National Vehicle and Fuel Emissions Laboratory</td>
</tr>
<tr>
<td>PHH</td>
<td>Parallel Hydraulic Hybrid</td>
</tr>
<tr>
<td>PRV</td>
<td>Pressure Relief Valve</td>
</tr>
<tr>
<td>PSI</td>
<td>Pounds per Square Inch</td>
</tr>
<tr>
<td>P/M</td>
<td>Hydraulic Pump Motor</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions per Minute</td>
</tr>
<tr>
<td>SHH</td>
<td>Series Hydraulic Hybrid</td>
</tr>
<tr>
<td>SwRI</td>
<td>Southwest Research Institute</td>
</tr>
<tr>
<td>TDC</td>
<td>Top Dead Center</td>
</tr>
<tr>
<td>TEBRC</td>
<td>Totally Enclosed, Blower Cooled</td>
</tr>
<tr>
<td>NIC</td>
<td>Network Interface Card</td>
</tr>
<tr>
<td>UPS</td>
<td>United Parcels Service</td>
</tr>
<tr>
<td>UT</td>
<td>University of Toledo</td>
</tr>
<tr>
<td>VFD</td>
<td>Variable Frequency Drive</td>
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<tr>
<td>ZD</td>
<td>Zero Displacement</td>
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List of Symbols

$C_f$ ......... Friction Coefficient
$C_v$ ......... Viscous Coefficient
$D_d$ ....... Derived Capacity of P/M
$\mu$ .......... Fluid Dynamic Viscosity
$\eta_{mech}$ .... Hydraulic-mechanical Efficiency
$\eta_{vol}$ ...... Volumetric Efficiency
$\Delta P$ ...... Pressure Difference across P/M
$Q_a$ ........ Actual Flow
$Q_t$ .......... Theoretical Flow
$T_f$ ........ Mechanical Friction Torque
$T_t$ ........ Theoretical Torque
$T_v$ ........ Viscous Friction Torque
$\omega$ ......... Rotational Speed
Chapter 1

Introduction

1.1 Background

Hybrid vehicles are designed to provide a more efficient power train, by adding a secondary power system to the conventional internal combustion engine (ICE). There are a few hybrid vehicles available to the public currently. While these hybrids represent a step in the right direction, what if there were a better technology available? One that was more reliable, more efficient, and ready to use now?

Hydraulic power is that technology. While the concept of using pressurized fluid to perform work is not new, the designs of modern pump/motors (P/M) are. Bent axis and swash plate P/Ms have reciprocating pistons which move in and out of their cylinder bore to move fluid. Both bent axis and swash plate designs offer variable displacement models allowing for better control of flow, pressure, torque, and speed [7]. Variable displacement bent axis P/Ms offer the highest efficiency, but also tend to be the most expensive P/M models.

The improved overall efficiency of hybrids is the result of making several aspects of the vehicle more efficient. By accompanying the ICE with a second system the ICE can be operated closer to it’s point of highest efficiency. When the vehicle is at rest
or under light load, the ICE can charge the secondary system; later when more power is required, the secondary system can supplement the power provided by the ICE. Vehicles with conventional drive trains require an engine powerful enough to propel the vehicle to highway speeds and handle heavy acceleration; this amount of power is only needed for a small portion of most driving routines. With a secondary power source on board, the ICE can be scaled down, saving on fuel. Another way hybrid vehicles improve overall efficiency is through the recovery of braking energy. The brakes of a conventional vehicle use friction to stop the vehicle. The kinetic energy of the vehicle is converted to heat, which is wasted. Hybrid vehicles, which have regenerative braking, use resistive torque to convert the kinetic energy into potential energy which is used when needed later. A HHV has the potential to recover upward of 70% of braking energy that is lost in a vehicle with a conventional drive train [18]. The higher round trip efficiency of the hydraulic system over an electric system is due to more efficient energy transformations.

1.2 Definition of Problem

The objective of this work is to design, build, and document a hydraulic test facility to support research and development of hydraulic hybrid vehicles. There is a need to test hydraulic components to gather data regarding performance and efficiency. Testing such components requires a laboratory specially designed to accommodate the pressure levels and flow rates of currently available, and future, high pressure hydraulic equipment.

With data collected from physical tests, more accurate P/M models can be generated. These models can be used to advance component design and refine the control system used on a HHV.

Equally as important as using high efficiency components is a control system that
utilizes these components to their fullest potential. Simulated driving conditions could be generated using the electric dynamometer; this would eliminate possible variables experienced when testing in a vehicle, while keeping the cost down by only testing the hydraulic circuit outside a vehicle platform. By testing full hydraulic circuits within the simulation system, the so called hardware in the loop (HIL), more accurate analyses are created. HIL testing can expose potential issues generated by the complete system before development moves forward.

Noise, Vibration, and Harshness (NVH) are side effects that accompany hydraulic components. Steps can be taken to reduce each of these items. For the effects of NVH to be minimized in a HHV platform, accurate acoustic analysis needs to be conducted in a laboratory environment where outside factors do not alter data.

1.3 Outline of Thesis

This thesis details the processes required to implement a test facility capable of meeting the previously discussed criteria.

Chapter Two presents a framework of existing technology which will be presented with a review of current literature.

Chapter Three presents the proposed design of the HTF. Safety equipment, testing capabilities, and ratings will be discussed here.

Chapter Four shows the elements of construction engineering involved in bringing the HTF to completion. This includes site location, installed devices, the control system, and DAQ.

Chapter Five will discuss the operation and testing of a hydraulic Pump/Motor in the HTF.

Chapter Six will present the future work to be conducted in the HTF.
Chapter 2

Literature Review

A number of current technologies were investigated prior to the design and construction of the hydraulic test facility (HTF). Modern designs of hydraulic pumps and motors were examined. Their benefits, disadvantages, and operational requirements were evaluated and considered. Since testing components for use in HHV is the primary focus of the HTF, HHV platforms currently in use were reviewed. Developments in advanced HHV control strategies were investigated. Computer modeling of hydraulic circuits and control systems was examined and its benefits to a laboratory were discussed. Finally, safety standards and safe practices for a HTF were reviewed for successful implementation.

2.1 Hydraulic Devices and Components

A typical HHV drive train is constructed with at least one P/M, two accumulators, valves, and plumbing. The pumps and motors are used to convert rotational energy into pressurized fluid and to convert pressurized fluid into rotational energy respectively. A high pressure accumulator stores pressurized fluid by way of compressing an inert gas. A low pressure accumulator stores fluid before being pressurized by the pump or motor when braking [18]. Valves can be used to control the amount of
flow to a device, redirect flow to change the operation of the system, or to stop flow completely. The plumbing, which connects all of these components, can be either hard piping or flexible hose; whenever possible, hard piping should be used.

There are two primary P/M designs well suited for use on HHVs because of their compact size and high efficiency [7]. Figure 2-1 shows a swash plate piston P/M. Each piston is connected to the drive shaft by means of a swash plate and shoe or slipper plate. The shoe/slipper plate is used to maintain contact between the piston shoe/slipper and the swash plate. Figure 2-2 shows the internal components of a fixed displacement swash plate P/M. As the P/M rotates fluid is drawn in the inlet port and compressed by the moving piston as it moves from bottom dead center (BDC) (largest volume in cylinder) to top dead center (TDC) (least volume in cylinder). Similarly, when operated in motor mode the fluid enters at high pressure while the piston is at TDC, once the piston has been pushed to BDC the fluid leaves through the outlet port [12].

Figure 2-1: Swash plate piston P/M [20].
Figure 2-2: Exploded view of Swash plate P/M.

Figure 2-3 shows a bent axis piston P/M. The design is similar to that of a swash plate P/M; pistons move from BDC to TDC when acting as a pump and TDC to BDC acting as a motor. Unlike the swash plate design the seat of the pistons ride in a ball and socket joint connected to the main shaft.
Figure 2-3: Bent Axis Piston P/M [7].

Both inline piston P/M designs, swash plate and bent axis, can be manufactured as static displacement or variable displacement. To vary the displacement of a swash plate P/M the swash plate angle is changed. When the swash plate is perpendicular to the main shaft, measured to be an angle of zero degrees, there is no displacement. As this angle increases the displacement increases. The variable displacement bent axis P/M is very similar; the angle is measured between the main shaft and the yoke, instead of the swash plate.

The sound generated by hydraulic P/Ms can be broken down into several elements. Airborne noise, structure borne noise, and fluid borne noise all contribute to the overall noise observed from a hydraulic circuit [25]. Pumps commonly generate 1,000 times more fluid borne and structure borne noise than they do airborne noise, which
can interact with other components of the machine leading to more airborne noise. Skaistis recommends focusing noise reducing efforts on the one or two largest noises as reducing these will have a greater effect than reducing a larger quantity of less intrusive noise sources [25].

Vibration analysis in fluid power systems by Ortwig reveals one cause of noise and vibration as well as potential solutions [21]. P/M noise is largely caused by the discontinuous generation of pressure and flow. The modern P/Ms used in HHV designs have multiple pistons which reciprocate, as opposed to a gear or gerotor design. Each piston and chamber generates a pulse that contributes to the noise profile of the system. Manufacturers work continually to reduce these pulses without compromising the efficiency of the P/M. Changes can be made to the internal ports of a P/M. Such as delaying port timing and adding metering grooves, to increase transition times thus reducing the strength of some harmonics. This only effects a narrow frequency range and can have negative effects on performance and efficiency [25].

Another approach to reducing the transmission of these fluid pulses is to install an accumulator or expansion chamber to "absorb" the pulse in a body of fluid rather than continue to send it down the pipe or hose. Hydraulic hoses can also be a source of unwanted noise as a result of fluid borne noise forcing the hose to move [25].

An alternate way to reduce structure borne noise is to add damping to the system. Anderson investigates a viable solution to vibration mitigation by Ayers [9] using a Magnetorheological (MR) Mount. The challenge in isolating vibration generated by a P/M is the wide range of frequencies it is capable of emitting. Conventional dampers and mounts are designed for a narrow band of frequency; anything outside the designed range may not be mitigated and may even be amplified as a result of resonance. By carefully controlling the apparent viscosity of the MR fluid in a hydraulic mount the damping can be adjusted as needed. Such real-time adjustment
broadens the frequency range the mount is able to work in.

There is a growing trend in the hydraulic field to increase maximum operating pressure. Most current systems and labs are designed to operate up to 3,500 PSI. There are very few 5,000 PSI compliant labs, which is the current operating limit for hydraulic hybrids. There is even discussion of pushing pressures as high as 20,000 PSI [18] as this is the most effective way to increase energy storage. Some researchers in the field of hydraulics have projected that pressures greater than 20,000 PSI could be used in HHV systems; however the stresses experienced by components operating at these pressures are significant. Currently hoses and fittings capable of withstanding these pressures are not large enough to handle the flow rates needed by HHVs. New ways of plumbing hydraulic systems may need to be developed to minimize connections and potential locations for failure or leaks. Safety has also been a point of concern in regards to using fluids under very high pressures on a vehicle [23]. This future growth and operator safety was kept closely in mind when the Hydraulic Test Facility (HTF) was designed and built. All equipment, plumbing, and fittings are rated to 5,000 PSI or higher.

As discussed in Hydraulic Hybrid Vehicles [18], there are four main areas of HHV that need to be improved before their use in a production vehicle is feasible. These areas are increased storage capacity, increased reliability of components, optimization of the control system to improve fuel economy, and noise reduction. By controlling the load profile exerted on test components, control system performance can be observed in the HTF. Acoustic profiles of P/Ms can be recorded for a known load profile. Comparing noise to the system load can reveal problematic conditions which may not be easily observable in a real world situation.
2.2 Hydraulic Hybrid Platforms

A Parallel Hydraulic Hybrid, as shown in Figure 2-4, is similar to a conventional drive train in that the ICE has a mechanical connection to the drive wheels. A P/M and two accumulators, high and low pressure, are connected either to the transmission or differential.

![Parallel Hydraulic Hybrid schematic](image)

Figure 2-4: Parallel Hydraulic Hybrid schematic [7].

Automotive manufacturers have begun to take interest, specifically Ford Motor Company, in hydraulic hybridization. In 2002 Ford unveiled a Tonka F-350 concept vehicle featuring Hydraulic Launch Assist (HLA). HLA combines a hydraulic P/M and accumulator to recover kinetic energy normally lost to heat during braking; this system can reportedly improve fuel economy by 25 to 35 percent [1]. The HLA is a form of PHH drive train.

Most recently, in 2010, Bosch Rexroth debuted a fleet of HHV in over ten major
cities in North America and Europe for testing. Unlike the UPS truck developed by the EPA, this fleet utilized a PHH drive train [4].

A Series Hydraulic Hybrid (SHH), as shown in Figure 2-5, relies on the hydraulic circuit to link the ICE to the drive wheels. This style of system can allow for some flexibility in where components can be mounted and also allows the ICE to be operated independently of the drive wheels. There is greater flexibility with regards to engine-off control strategies in a SHH due to the mechanical detachment of the ICE from the drive wheels [8].

![Series Hydraulic Hybrid schematic](image)

Figure 2-5: Series Hydraulic Hybrid schematic [7].

The United States Environmental Protection Agency (EPA) finished a package delivery vehicle for United Parcels Service (UPS) in 2006 which operated on a SHH drive train [2]. This prototype vehicle was anticipated to show a 60 to 70 percent improvement in fuel economy while showing at least a 40 percent reduction in carbon
Research has also begun to investigate a railroad locomotive as a potential HHV platform. Testing would primarily be conducted on switching engines, which are locomotives used to assemble long trains for transport. When building trains, there is a tremendous amount of energy expelled in bringing each car to a stop after moving a short distance. This creates an ideal scenario for a hybrid design to be implemented.

RailPower Technologies Corporation of Vancouver, British Columbia developed the “Green Goat”, a hybrid railroad locomotive using a large bank of lead-acid batteries [22]. A micro turbine serves as a generator to keep the batteries charged. The Green Goat offers a 15 to 45 percent reduction in annual fuel cost and reduced $NO_x$ emissions by as much as 80 to 90 percent when compared to a standard locomotive performing the same operation [22].

In 2007, GE debuted the Evolution Locomotive, as part of the Ecomagination event. A series of on board batteries capture energy dissipated during dynamic braking, thus improving fuel economy by as much as 10 percent [11].

Zhang presents a model for a hydraulic storage system on a hybrid locomotive which would use an Electro-Mechanical Battery (EMB) consisting of an accumulator, P/M, reservoir and electric motor/generator [29]. The EMB provides a high power density solution to energy storage at a relatively low initial cost. A small-scale version of this EMB could be tested in the HTF using the electric dynamometer to simulate the working load. As a small-scale test, this could serve as a proof of concept and inform researchers on the details of the control system required and behavior of the system.
2.3 Hydraulic Modeling

Modeling of hydraulic systems can save significant time and money spent on laboratory testing. This includes both modeling the hydraulic devices and how they interact with the full system, as well as the control system. An accurate computer model of a hydraulic circuit can be subjected to virtual tests, similar to what would be conducted in a test facility, with several advantages. Equipment does not need to be purchased until modeling determines if a specific model will perform as desired. With computer models there is also no risk of component failure due to overload. Similarly, a control system can be verified and fine tuned prior to installation on a test circuit.

Work on developing an advanced control system for HHV can be found in Shan [10] and Cheng [24]. The controller presented by Shan makes use of neural networks and dynamic programming to "learn" the driver's typical behavior and the driving conditions, and then improves the vehicle's efficiency based upon that [10]. The theory is that most vehicles driven by the same individual develop a repeatable pattern. While people don't drive a formally defined driving cycle they do have the same commute to and from work. Delivery and refuse trucks drive the same route on a regular basis and with observation; trends and patterns can be developed.

Cheng presents an optimized strategy to manage the division of power from the internal combustion engine between the energy storage system and the drive train [24]. The hydraulic system found on a HHV is not a simple unidirectional drive train like those found on a conventional vehicle only using an ICE. Power modes switch often between the ICE charging the hydraulic system, the hydraulic system propelling the vehicle, vehicle deceleration charging the hydraulic system, or any combination of these. The vehicle control system must make the best possible use of each of the energy sources to maintain the highest possible overall vehicle efficiency.

Abdelgayed presents a system design and control strategy for an ancillary hy-
draulic system on a HHV [6]. This system uses standard P/M components to create a secondary hydraulic circuit suitable for powering hand held hydraulic equipment. It would be possible to operate hydraulic equipment from the same hydraulic circuit that propels the vehicle; however, fluid contamination is of great concern. By using a coupled pair of hydraulic P/Ms, fluid used with ancillary equipment can be isolated, eliminating the risk of contaminating the primary hydraulic system fluid. One application for such a system would be utility vehicles where hydraulic power is often needed regularly.

The HTF can be utilized to test more than just components. Complete hydraulic systems, whether it is a HHV drive system or Ancillary circuit, can be tested before installation on a vehicle. Precise speed and load profiles can be applied in order to develop vehicle control strategies.

2.4 Procedures

Fok, et.al. suggest that testing and prototyping hydraulic components is broken down into two parts, virtual and physical [15]. Any component or system design should first be modeled on a computer, usually in the Simulink package of Matlab. Computer simulations of a test scenario can help reduce the amount of time required on a test stand and offer a safe way to check for potential errors in the system design. Computer modeling also helps determine the power requirements of the system and allows for a control system to be developed prior to testing in the HTF.

Once the computer model is complete, prototype testing can begin. The first step is to find standard components from manufacturers that meet the needs of the system. If more than one product meets the need they should be compared based on price, availability, and reliability. Standard “off the shelf” components should be used when available [23]; this helps in keeping costs down while improving reliability. With the
proper components selected and purchased, the test unit is ready to be mounted to
the tombstone; hoses then can be made to plumb the system. Before testing begins
the system needs to be checked for leaks; not only do leaks create a potential danger
and a mess in the lab they also can affect the performance of the test unit and the
readings on pressure and flow meters.

Tests conducted in the HTF on P/M’s will follow the guidelines laid out in the
SAE J745 and SAE J746 documents [27] [26]. The procedure for testing a hydraulic
power pump covers determining the derived capacity, delivery characteristics, power
input, power loss, overall efficiency, pressure compensator response and recovery, and
flow compensator response and recovery [27]. Similarly, the procedure for testing
hydraulic motors covers determining the SAE volumetric rating, SAE running torque
characteristics, SAE stall torque characteristics, power output, power loss, torque ef-
ficiency, and overall efficiency [26]. Both test procedures are designed to be performed
with fluid temperatures at either 49°C (120°F) or 82°C (180°F).

Post processing of data collected during prototype testing can be used to deter-
mine if a test was beneficial and if further testing is required to achieve the desired
result. Even a test that doesn’t perform as anticipated can provide useful informa-
tion. Determining why a test failed to meet expectations often provides great insight
to the behavior of the system and the parameters that affect it the most.
Chapter 3

Laboratory Design

A specific series of events took place in just the right order to transform this research facility from a complex concept to a fully functioning lab. It is important to know the specifications the lab must have in order to properly size test cells and supporting subsystems. Once test requirements and capabilities are decided, subsystems can be designed. Both an electrical and hydraulic subsystem need to be developed, as well as a DAQ/Control system to integrate the two. Many resources were used in the design of the HTF and will be discussed in the following sections.

3.1 Specifications

The specifications for the HTF at the University of Toledo were a combination of what was used at US Environmental Protection Agency National Vehicle Fuels and Emissions Laboratory (USEPA NVFEL) and later revised as suggested by Southwest Research Institute (SwRI). Early specifications, developed fall of 2007, were based upon testing experiences at the USEPA NVFEL in Ann Arbor, Michigan. The hydraulic P/M testing capabilities at USEPA NVFEL consisted of three separated cells, each of which had the capability to test P/Ms over a range of approximately 50 to 200 \( \text{cc rev} \) displacements, which corresponds roughly to 100 to 500 HP in power con-
sumption. However, the majority of the testing was performed at much lower power. Despite the number of test stands that existed in the USEPA NVFEL, minimizing testing time in the laboratory was critical as there always seemed to be more requests for laboratory use than facilities to support these requests.

Two of the cells at USEPA NVFEL contained a single test stand which used a slave-master relationship, requiring a hydraulic pump and motor. The pump would produce a high pressure oil flow to the hydraulic motor. An electric motor serving as a dynamometer was used to control the testing as well as provide additional power as needed. In this setup, the pump, the motor, or both could be tested depending on the capabilities of the instrumentation. The 300 HP test stand in use at the University of Toledo, built prior to the rest of the lab, uses a similar slave-master configuration.

The third cell at USEPA NVFEL contained three test stands designed for testing units in a “zero discharge” (ZD) mode. A number of losses in a hydraulic pump or motor can be characterized by operating the test unit at given speeds and given pressures with the yoke angle of the unit set at $0 \frac{\text{cc}}{\text{rev}}$, theoretically resulting in no flow through the test unit. In the ZD lab, a common source of pressurized oil was provided to each of the test stands. Each stand also had an electric motor which served as a dynamometer, and as a rotary power source or regenerative power producer. Each test unit was mounted in line with the shaft of the dynamometer through a torque meter. This torque meter offered the capability to record both rotational speed and torque output/input of the test unit.

### 3.1.1 Initial Specifications

Since the overwhelming majority of testing at the USEPA NVFEL facility was well below 500 HP, the decision was made to limit the testing capability at the University of Toledo lab to units below 300 HP, although the existing slave-master unit at the University of Toledo could test well beyond this limitation, if needed. Due to the
workload experienced at USEPA NVFEL, it was decided that at least four test cells would be required. The simplicity of the ZD laboratory was incorporated into the first specification by providing a common laboratory backbone of hydraulic oil at 100 GPM pressurized to 5000 PSI. Therefore, all test units, except the existing slave-master unit, would be operated from the common backbone. Additionally a small parts room was provided for the tools and fittings that would be necessary to operate the laboratory.

The construction concept was that a “turn-key” laboratory would be built where the University of Toledo would take control of the laboratory only after it proved to be operational, with all hydraulic, electrical, data acquisition, and control devices installed.

3.1.2 Modifications of Specifications

Southwest Research Institute (SwRI) has extensive laboratory facilities for hydraulic testing that span a number of buildings in San Antonio, TX. Based on their experiences, they recommended a number of basic concept changes. First, they recommended staggering the capacities of the test cells. Whereas the original specification used four equally rated cells, SwRI recommended that the test cells should range from 5 to 75 HP with the common system pump at 75 HP, which could also be used as a test cell if needed. The existing master-slave unit, rated for 300 HP would serve any higher power needs. The final sizes were determined to be 7.5 HP, 10 HP, 25 HP, and 50 HP, in addition to the 75 HP system pump.

An additional test mode suggestion was for noise sampling. For this scenario, SwRI recommended that the walls of the cells be covered with a noise insulating material. While sound recording equipment could be installed at a later date, installation of insulation would be easiest, and provide the best cell coverage, if incorporated into lab construction.
SwRI also recommended against a fully “turn-key” constructed design, as was originally envisioned. Specifically, this recommendation was due to the difficulties in writing specifications for the sensors and data acquisition and getting contractors to provide units compatible with the tests that would be performed and the test quality that would be needed. For these reasons it was suggested UT purchase and installs these units separately.

3.2 Laboratory Layout

3.2.1 Initial Layout

The initial laboratory floor plan consisted of four test cells, a supply cell, and storage room all accessible from a main corridor. Each cell would have its own computer terminal from which tests would be controlled. The system reservoir would be located in the overhead space of the hydraulic supply cell. Figure 3-1 shows a simple layout of the initial design concept.
The common backbone for the laboratory would consist of three hydraulic lines plumbed to each cell of the laboratory. The first line would be a high pressure line designed for operation up to 5000 PSI which would be used as the input to motors. The second line would be a gravity-feed suction line that would be used primarily to supply pumps. The third line would be a common discharge line returning fluid back to the system reservoir. The non-pressurized system reservoir was to be placed in the overhead space of the system pump cell, sized at 150 gallons. By locating the reservoir overhead in the supply cell, floor space is optimized and positive head on the system can be ensured.

This initial concept was then presented to the Chief of Facilities and Construction to insure that the laboratory could be built with the funding scope and time limits given. Based on the advice given, the sizes of the laboratory bays and overall dimensions were established, as shown in Figure 3-2.
These changes resulted in the third design shown in Figure 3-3 which was given to the Facility and Construction Branch at the University of Toledo to begin contracting and final planning.
3.2.2 Modified Layout

During the planning stages of the lab the physical location at the University of Toledo changed. To better occupy the new location the layout of the lab was altered. A sixth cell was added at this time to house the existing 300 HP test stand. Figure 3-4 and Figure 3-5 show two possible variations of the rearranged lab.

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Figure 3-3: SwRI modified design.
Figure 3-4: First Modified Layout.
Figure 3-5: Second Modified Layout.

The final layout decided upon for the lab combines elements from both Figure 3-4 and Figure 3-5. The two lowest power test stands share a cell and the tables are installed in the orientation shown in 3-4.
3.3 Facility Design

The lab environment and details of each cell were determined once the layout was finalized. Items such as the arrangement of each cell and what was installed in a cell, interior walls, doors, windows, and the electrical system were decided at that point.

3.3.1 Bay Design

Each test will have a table centered on the back wall which will have a dynamometer, torque transducer, and scavenge unit. Located on the rear wall, next to the table
will be a set of hydraulic three manifolds connected to the main supply circuit. These three manifolds will tie into the high pressure supply, low pressure suction, and return line.

### 3.3.2 Walls

Cinder block construction will be used for all lab walls. The interior cell walls will have all internal cavities filled with sand to improve durability in the event of an impact.

Insulation will be installed on the walls inside each cell to allow for possible future sound sampling. Several options were considered for sound insulation in the cells including fiberglass blankets, polypropylene panels, and spray-on insulation. Several criteria were considered in the decision between each of these alternatives. While the spray-on insulation would provide excellent coverage and sound absorption it is possible for the coating to absorb oil and water, creating a potential danger. Polypropylene panels would also provide adequate sound absorption and are moisture resistant, but the challenge becomes mounting them securely. They must be mounted using an adhesive which means any contours or obstructions on the wall or ceiling would require special treatment. Fiberglass blankets provide a comparable level of sound absorption, are moisture and fire resistant, and can be cut easily with basic hand tools to accommodate any obstructions present on the wall or ceiling of each cell.
3.3.3 Fenestration

Every cell has a dedicated door and viewing window. This allows users to enter and exit cells individually without disrupting activity in an adjacent cell. The door to any cell can be locked to prevent users accidentally entering while a test is in progress. They are also industrial steel doors which provide a high level of impact resistance, much like the sand filled walls.

A viewing window is located in the front wall of each cell for users to monitor tests while they are running without the need to enter the cell. All viewing windows are made of $\frac{1}{2}$ inch Lexan to ensure the windows provide just as much protection as the walls and doors.
3.3.4 Electrical

Every cell is wired with 440V service to operate the electric motor/dynamometer and 110V outlets to be used for tools or auxiliary work lighting. Emergency Stops are a very important safety feature. An emergency stop is located on the side of each test stand as well as immediately outside each cell next to the operator’s station; this will cut power to the test equipment but not the computer terminal. There is also a master emergency stop located outside the lab which cuts power to all five cells, including computer terminals, and the main corridor. Computer terminals in the main corridor required two 110V outlets; two extra were added at each location if needed by students for personal computers or other electronics. Ethernet ports were also installed at each work station in order to connect each computer to the school’s network.

3.4 Equipment Design

The lab required pieces of equipment that were not part of the construction. A dynamometer was needed for each cell. Tables specially designed to accommodate hydraulic equipment and dynamometers were built. Hydraulic manifolds had to be designed and installed in each cell. A Variable Frequency Drive was required to operate each dynamometer. Controlling the oil temperature would also be handled by a computer controlled system. Several safety items were also specified to provide the safest possible lab conditions.

3.4.1 Table Design

Tables for each cell needed to be specially made to accommodate the weight of hydraulic components and the dynamometer. Each table is constructed of a tubular square steel frame with a $\frac{3}{4}$ inch steel work surface. The work surface is 36 inches
high to allow for easy access to equipment while still providing adequate room below the table for the scavenge unit. Around all four sides of each table, a two inch drip tray allows any spilled hydraulic oil to return to the scavenge unit, where it can be pumped back up the reservoir instead of collecting on the floor.

3.4.2 Electrical Motor/Generator

Before generator/motors could be selected to be used as dynamometers, they needed to be sized against the hydraulic P/M’s they would be mated to. Hydraulic components will vary from test to test, so an assumed device had to be used to approximate the power and speed of each hydraulic P/M for a given power rating. Figure 3-8 shows the speed vs. torque profile for a 7.5, 10, 25, 50, and 75 HP electric motor and dashed lines representing the torque transducer limit as well as the maximum RPM.

![Figure 3-8: Electric motor Speed vs. Torque profiles.](image-url)
It is clearly visible that no single electric motor can accommodate the entire speed and torque range, without being grossly over sized. Charts were developed for 10cc, 12cc, 16cc, 28cc, and 32cc hydraulic P/M's to aid in determining the proper electric motor for each cell [17]. The torque transducer rating varies from cell to cell in accordance with the HP rating the cell will be capable of sustaining.

As a result of the differences in speed vs. torque characteristics for electric and hydraulic components, a compromise needed to be made: either the electric motor must be significantly over sized to handle the upper end of the hydraulic test unit, or the higher speed/higher torque P/M conditions simply cannot be tested.

The base speed of an electric motor was also an important factor to consider. The base speed is determined by the number of poles the motor contains; as the number of poles increases the base speed decreases. For example, doubling the number of poles will decrease the base speed by a factor of two. This also doubled the rated torque. This can be observed in Figure 3-9 where 450, 900, 1800, and 3600 Base RPM units are compared.
After examining all of these criteria it was decided that 1800 RPM base speed motors be used throughout the lab. It was also decided that totally enclosed, blower cooled (TEBC) motors should be used since a majority of testing will be performed at low speeds with limited air flow where overheating could be an issue.

3.4.3 VFD Controller

In order to control the dynamometer in each cell a Variable Frequency Drive (VFD) was required. This allows for continuous control of the electric motor/generator by the data acquisition system operated from the computer terminal outside each cell. Each test cell will have a four quadrant regenerative variable frequency drive (VFD) manufactured by ABB, model ACS800. A VFD had already been purchased for use with the 300 HP test stand when it was initially built, meaning only five new units
from ABB would need to be purchased and installed.

Figure 3-10: ABB Variable Frequency Drive.

3.4.4 Manifold

Hard mounted steel lines were used to supply hydraulic fluid to the manifolds in each cell. Each manifold has a manual shut off valve which can be locked out when not in use. Hydraulic supply lines were sized using the 50 GPM maximum flow rate and the 5,000 PSI maximum operating pressure. To allow for an adequate factor
of safety, lines should be designed with a minimum burst pressure of 20,000 PSI. Common pressure lines between cells should be able to accommodate no more than 30 $\frac{ft}{s}$ fluid velocity meaning $1 \frac{1}{4}$ inch pipe would be acceptable. The same $1 \frac{1}{4}$ inch size will also work for the common return line with a fluid velocity of 10 - 15 $\frac{ft}{s}$. A larger diameter is required for the common suction line to accommodate 2 - 4 $\frac{ft}{s}$ at about 25 GPM; for this application 2 inch pipe will suffice [17].

Figure 3-11: Hydraulic manifolds in test cell. (Top to bottom: High Pressure Supply, Return Line, Pump Suction).
Located along the back wall of each cell are hydraulic manifolds which can be used to run a test from the main hydraulic supply that feeds the entire HTF; the layout of these manifolds can be seen in Figure 3-11.

### 3.4.5 Oil Temperature Control

Maintaining a constant fluid temperature offers several benefits to a test procedure. If a test is run more than one time every variable should be repeatable, including the temperature of the hydraulic fluid. As the temperature of oil increases the viscosity decreases, which can affect the results of a test by changing the internal resistance a P/M experiences. Over the course of a test the oil is prone to heating up; with an oil heater installed the oil can be preheated to reduce the affect of temperature change during the test.

A Watlow Immersion Heater will be installed in the reservoir to bring the oil up to operating temperature before testing. With a 4 inch, 10kW flange heater the 160 gallon reservoir can be heated in approximately 2 hours. A Watlow DIN-A-MITE B controller enables control of the immersion heater directly from the control system.

### 3.4.6 Safety Equipment

Safety is a critical element in any laboratory or testing environment. In the case of a hydraulic test facility even stricter safety policies must be established. Most hydraulic equipment is very heavy and can cause severe injury if it were to fall on someone. Fluid under extremely high pressures can result in leaks which often are not visible and can cause injection injuries as well as put hazardous oil mist into the air. Each test cell has an exposed rotating assembly where the torque transducer is connected that can reach speeds of up to 4000 RPM. There is also 440V electricity in every cell to power the VFD controlling each dynamometer. Each of these potential dangers had to be addressed individually to ensure the safest possible environment
could be provided.

### 3.4.6.1 Mist Detection

Every cell will be equipped with a mist detection sensor which is wired to a central control panel located in the main corridor. This system will pick up on a very small amount of hydraulic oil suspended in the air and alert all users of the lab that there may be an unsafe situation; this system is illustrated in Figure 3-12 and Figure 3-13.

![Figure 3-12: Mist Sensor in each cell.](image)
3.4.6.2 Floor Treatment

The floors in the HTF can make the work environment safer or more dangerous depending on the how they are surfaced. Spilled hydraulic oil can be very slippery if on anything other than a non-skid finish. Three options were considered for the floor treatments; textured tiles, Stonhard MRT, and a polyurethane floor coating. Tiles would provide a durable surface well suited for the lab, but installation over the existing floors would be challenging as the floors are not perfectly level. While the Stonhard MRT surface would provide a slightly better finish on the floor at over double the cost, a polyurethane coating was chosen for the floors. Rubber floor mats were also fitted to each cell as shown in Figure 3-14, next to each test stand where the operator is most likely to work on the system. This provides a non-slip surface that
is slightly elevated off the cell floor so the risk of stepping in spilled oil is reduced.

Figure 3-14: Rubber floor mat and polyurethane floor treatment.

3.5 Auxiliary Items

A network of supporting systems also needs to be present for the test facility to operate. Data Acquisition hardware and software are required to operate a test form outside the cell. Materials and equipment to make hydraulic hoses should be available for setting up tests. Consumable items and personal safety equipment should be kept in the lab at all times.

3.5.1 Data Acquisition

Due to the unique nature of the Data Acquisition (DAQ) system to be installed in the HTF it was decided that it would be designed and installed by the research team using the lab. The DAQ system, also referred to as the control system, plays a very
important role in the hydraulic test facility. This system allows the hydraulic system to communicate with the electrical system via the computer terminal. Without the DAQ system there would be no way to control tests, or collect information from the test for analysis. Every cell has the same sensors and controls with the exception of the 75 HP cell as that has additional sensors since it serves as the common source of hydraulic power.

Originally specified to handle communications between the test unit and computer terminal was a Field Point unit from National Instruments, however it was determined this product line wouldn’t offer the flexibility required to analyze and control the HTF configuration. The CompactRIO series was better suited to meet the labs needs. Different sensors have different electrical requirements and therefore must be connected to the CompactRIO with a specific interface. Each test stand has its own computer terminal and CompactRIO (model: cRIO-9073) with the following cards installed: NI9211, NI9422, NI9201/NI9263. The NI9211 is a four channel Thermocouple Input Module. NI9422 is an eight channel 24V Sinking/Sourcing Digital Input Module. NI9201 is an eight channel, twelve bit Analog Input Modules. There is also a FieldPoint Power Supply (FP-PS-4) installed at each terminal to provide 24V DC power to any sensors requiring it. Each card has wire and terminal ratings to accommodate the power/signal of the sensors connected to it. Since the range of wiring requirements for each card has a margin of overlap, 18 AWG meets the needs of all the cards and sensors. By using a common gauge size, purchasing wire is simplified and there is no risk of connecting a sensor with an inadequate wire.

The Modbus protocol is used to ensure all DAQ equipment communicates throughout the HTF. This serial communications protocol is openly published and has become the de facto standard in industry [28].

Figure 3-15 shows the arrangement of DAQ components outside of the 75 HP cell.
From top to bottom on the DIN rail in Figure 3-15 is a 24V power supply, two distribution blocks to provide 24V power to sensors requiring it, a second 24V power supply dedicated to powering the CompactRIO, and finally the CompactRIO with the four cards discussed earlier.
3.5.2 Sensors

Sensors are required to collect data from a test. Without the correct sensors monitoring system conditions there would be no way of determining how a unit performed during a test. Fluid flow, pressure, rotational speed, and torque can all be observed and recorded using the sensors described in this section.

3.5.2.1 Flow Meters

Turbine flow meters, also referred to as axial turbine flow meters, were chosen for use in the HTF. These use a turbine suspended in the fluid flow. As fluid passes it forces the turbine to rotate; once the rotation becomes steady it can be correlated to a steady flow rate. Typically the turbine speed is measured magnetically, removing the need for a mechanical connection to the turbine. Figure 3-16 shows a turbine flow meter. The 75 HP cell also houses controls for the overhead reservoir; these include a temperature controller for the hydraulic oil and a level switch to monitor oil level in the reservoir. The oil level must be monitored to protect the system from cavitation, as that can induce premature wear on components. An oil heater brings the hydraulic oil up to operating temperature before tests begin to ensure the data collected aren’t affected by variations in oil temperature. As the fluid’s temperature decreases, the viscosity of the hydraulic fluid increases, requiring more viscous friction torque to be overcome there by reducing mechanical efficiency. Conversely, as the fluids temperature increases and viscosity decreases, leakage occurs more readily, causing the volumetric efficiency to decrease [19].
3.5.2.2 Pressure Transducer

Measuring fluid pressure in the system is critical in determining losses in a P/M and verifying pressures experienced by components are within their limitation. Sensotec Type Z Pressure transducers were selected for use in the lab. These sensors feature a dual diaphragm construction with the strain gauges hermetically sealed to avoid contamination with the hydraulic fluid. They have a maximum operating pressure of 7,500 PSI and read with an accuracy of ± 0.05%.
3.5.2.3 Torque Transducers

Torque transducers serve two purposes: to read the torque level generated by or absorbed by the motor/dynamometer, and to read the rotational speed of the system. Different horsepower ratings in each cell require torque transducers that are capable of registering the torque while not being over sized and compromising on accuracy. The 7.5, 10, and 25 HP stands would be well sized with a 100 N-m model, where the 50 HP stand would need a 200 N-m model, and the 75 HP stand would need a 500 N-m model. These sizes allow for the unit not to be damaged by overpowering and still offer the best accuracy.
3.5.3 Control Valves

Solenoid operated cartridge valves installed on each high pressure manifold allow for the flow of high pressure fluid to be shut off from outside the test cell. The valves selected are produced by Eaton and are operated by a 24 VDC signal and default to a close position when unpowered. Two different sizes were specified to accommodate the flow requirements in each cell. An SV13-20-CO-24DWH valve, which has a $1\frac{1}{4}$ inch ID, is used in the 50, 75, and 300 HP cell; while an SV13-16-CO-24DWH valve, with a 1 inch ID, is used in the 7.5, 10, and 25 HP cell.

3.5.4 Control and Data Wiring

The wiring harness for the DAQ system, while not complicated in principle, takes on a level of complexity due to the number of wires that had to be run in the same conduit. In total more than fifty wires were pulled to each test stand. This includes
two and four strand pairs required for the torque transducer, thermocouple wires for inlet and outlet temperature of test units, and a minimum of one extra run in each color of 18 AWG wire for future additions to the DAQ system. Care was taken to route data acquisition wires away from power wires to minimize any interference in the signal. Full schematics for each cell can be found in Appendix B.

Two possibilities were considered for placement of the DAQ components. Components could be mounted either in the cell, on the test stand, with only an Ethernet cable run to the computer terminal or, mounted outside the cell with a bundle of sensor wires run from the computer terminal to the test stand. While mounting the components inside each lab would have allowed for less wire to be pulled, the risk of the system suffering damage due to contamination with hydraulic fluid was too great. Locating the DAQ components near the computer terminal left several options to route wire between the test stand and computer terminal. The bundle of wires could be run across the floor with a protective cover over it, run along the wall around the outside of the room, or run overhead secured to the ceiling. While laying wires across the floor would permit the shortest length of wire, this option also would create a possible trip hazard in the cell which would be unacceptable. Wires directly on the floor also run the risk of being subjected to hydraulic fluid and cleaning solvents that might compromise the wires’ insulation. Routing wires around the perimeter of the room eliminated any trip hazard and would keep the wires out of direct contact with hydraulic fluid. The layout of each cell made running the DAQ wiring overhead the best solution. Chemical and crush resistant 2.5 inch ID flexible conduit was cut to length and mounted with wall anchors every few feet.

3.5.5 Hose Making Equipment

Making hoses requires an abrasive cut off saw for cutting bulk hose to the correct length, a hydraulic hose crimper to secure end fittings, and a cleaning tool to remove
dust and debris from inside the hose. Figure 3-19 shows an abrasive saw with a fixed clamp cutting hydraulic hose to be assembled for a test stand.

Figure 3-19: Hydraulic hose being cut on abrasive cut-off saw.

A sixty ton hydraulic press designed for crimping hose ends was purchased for the lab and permanently mounted to a roll around cabinet, as seen in Figure 3-20. Dies were made to fit the common fitting sizes and can be adjusted within a specifically designed range using a micrometer mounted on the guide of the press. The press uses a two piece die set that slides over the collar of the fitting and when force is applied crushes the outer sleeve of the fitting securing it to the hose. When crimped correctly this connection is safe to over 5,000 PSI. To ensure hoses are assembled correctly students are required to go through a training session and are not permitted to make hoses unsupervised.
3.5.6 Supplies

Consumable items needed to be accounted for when the design of the lab equipment was considered. Each time a test unit is installed new hoses need to be made, requiring coils of hose to be kept in stock along with crimp and non-crimp fittings and adapters.

Protective and safety supplies need to be present in the lab at all times. Safety glasses should be available to any occupants. Hearing protection may be required when entering a test cell. Gloves may be desired when handling parts with oil of grease on them. Rags and absorbent matting should also be available to clean up any spills.

Tools also need to available when setting up and disassembling tests. Wrenches,
both metric and standard, ranging from $\frac{1}{4}$ inch (6mm) to 2 inch (52mm) may be used on fittings and mounting hardware depending on test unit size. Sockets and ratcheting wrenches from $\frac{1}{4}$ inch (6mm) to 1 inch (26mm) can also prove useful. When working with hardware in confined spaces Allen Wrenches are used. These should also be kept on hand in metric and standard. An assortment of general purpose tools can also be beneficial to have, including screwdrivers, hammer (metal and rubber), pry bars, and various pliers.

### 3.6 Summary

The design of the HTF consisted of many stages. The initial specifications were determined based off testing experiences at the USEPA NVFEL. Modifications were made to these specifications based on suggestions from Southwest Research Institute.

Designs were considered for the layout based on the desired specifications. After several revisions and a change of location a final layout was decided upon. Details of the lab construction were then finalized, including design of each test cell, lab walls, doors and windows, and electrical.

Primary lab equipment was specified. Tables were designed for the test cells. Motor/Generators were selected based on power required and performance curves. VFD’s were specified to meet the needs of the dynamometers. Hydraulic manifolds for each cell were designed. A system was specified to manage oil temperature control. Safety equipment was determined for all aspects of the lab.

Secondary lab equipment was also specified. This consisted of the data acquisition system, sensors, control valves, and wiring associated with each. Hose making materials were determined. Finally supplies required to set up and operate tests were specified.
Chapter 4

Construction

4.1 Introduction

Specifications of the HTF were defined, along with a layout that was well suited to the laboratories potential site. A construction plan was the next step forward once these details were known. Conditions of the site location are discussed in detail. The process of contracting and budgeting the construction are covered. Installation of the hydraulic system and its associated construction needs are explained along with post contractor work performed in the lab.

4.2 Initial Site Conditions

Originally the HTF was to be constructed in an undeveloped portion of the North Engineering building. This was an ideal space for many reasons, overhead space was available and clear of obstructions, open floor space allowed for a variety of layouts, there was clear access to the loading docks of the building, and the existing structure surrounding the lab was in good condition. However the mandated relocation of the Engineering Technologies Department from Scott Park to North Engineering interfered with a number of proposed laboratories including the HTF.
The HTF layout was redesigned as a result of its new location. The footprint of the new location was much wider and not as deep therefore the initial design was no longer feasible. A new layout featuring all the test cells on one side of a long main corridor was considered. While this presented some challenges it also made routing of the common hydraulic backbone much simpler as it only needed to run along one wall.

The space provided had been in use as a compressor station for manufacturing operations. The compressors and the receivers were mounted on massive concrete blocks. In addition, there was sub floor piping to other parts of the building. The overhead area was a mezzanine with a catwalk. Directly under the catwalk was additional plumbing. While most of the plumbing would be removed some was still in use thus the overhead space was limited.

To prepare the site for construction, the foundation blocks were removed and the sub floor trenches were filled in. The result was an uneven concrete floor. Unfortunately the construction budget was insufficient to correct this.

The construction project for the laboratory was assigned to the contractor constructing the new facilities for the Engineering Technologies Department. After assignment, it was determined that they would not be able to construct the laboratory as a turnkey project as they did not have access to a number of the required skills. After reviewing the construction contracts proposed for the subcontractors, it was determined that the University of Toledo would have to write separate specifications for the hydraulics of the laboratory for a bidding process. In addition, in order to insure that research measurements could be taken, the University of Toledo would have to be responsible for the design and purchase of the data acquisition equipment. After the bidding process was completed, only one hydraulics firm was found that was responsive to the specification.

Originally, it was expected that the construction would be complete by the first
week of January, 2009. However, numerous delays were experienced both in the project contracting and the budgeting process that ultimately resulted in construction completion in June 2009. The project was scheduled to begin October 1, 2008. Legal approval of the initial of the contract with Southwest Research Institute and the US Army resulted in a two month delay in the signing of the funding contract. Then, in December, 2008, the construction cost estimate made by the Facilities Planning Section was received. This estimate was clearly incorrect. After a month delay for re-estimating the project, the new estimate although more than twice the previous estimate still did not match the magnitude of the funding estimated for the project. However, it was decided to move forward with contracting of the construction firm with an expected completion at the end of February, 2009.

At the end of January, 2009, the principle investigator for the research was informed that the general contractor could not perform the hydraulic work and that a separate specification would have written for the hydraulic subcontractor. This further delayed the project by to a new finish date of March 26, 2009. After the hydraulic contract was awarded, the new estimated completion date was changed to May 1, 2009. Equipment delays further delayed completion of the construction until July 2009 with a total cost overrun of 34% of original funding budget and seven times the initial construction estimate provided. This cost was made up by reducing the budget for data acquisition equipment.

4.3 Construction

Since the HTF was an addition to an existing structure at the University of Toledo certain structural elements from the existing facility could be used. Three of the exterior walls were pre-existing and therefore only had to be inspected for safety and integrity before the remainder of the lab was constructed. Five interior walls
were constructed from sand filled concrete block. This was to prevent any material escaping the cell in the unlikely event of a catastrophic failure.

The long wall for data acquisition and control hall was also constructed of sand filled block. This was perforated by extra wide steel doors to each cell and viewing windows. The walls of each cell were surfaced with noise suppression blankets.

Viewing windows into each test cell are constructed of double pane $\frac{1}{2}$ inch thick Lexan. These windows serve as a safety barrier between the test setup and operator, while still providing a clear view of the test cell. Below each viewing pane were desks to support the control computers and data acquisition equipment.

To allow for uniformity and control during testing as well as user comfort the HTF has its own thermostat that controls heat, from a common steam heat system, and a standalone air conditioner unit dedicated to the lab. Over the doorway to each cell is a vent allowing air to pass from the cells to the main corridor to help maintain a uniform temperature, when testing is taking place. Exhaust fans are positioned in each vent to aid in air circulation if needed.

### 4.3.1 Electrical

Each cell, with exception of the 300 HP, contains a variable frequency drive for the electric motor that is used as both a dynamometer and a drive motor. An electrical panel was mounted outside the lab with a dedicated breaker for each test cell to accommodate the load each test may draw. Each cell was also equipped with lighting and 110V outlets to be used with power tools, auxiliary lighting, and any other electrical equipment. In addition, the electrical contractor installed the electric motors in each cell.

Eight outlets were installed at each computer terminal in the main corridor. These outlets also provide power to the data acquisition equipment for each cell. In total each work station uses three 110 V outlets, remaining outlets are available as needed.
Every cell has its own light switch located in the main corridor. There are two switches located just inside the double doors of the lab, one for the lights in the main corridor, the other for the ventilation system that draws air out of every test cell.

Emergency stops were installed on each test stand, outside the door of each cell and outside the main door to the lab. The emergency stops allow users of the laboratory to cut off electrical power should an unexpected event occur. The emergency stop located outside the cell cuts power to the entire lab, leaving on only lights. Emergency stops are shown in Figure 4-1 and Figure 4-2.
Figure 4-1: Emergency stop located outside each cell.
4.3.2 Oil Mist

Small leaks in hydraulic plumbing can result in a mist of oil that is extremely dangerous to lab users. Often leaks of this nature are nearly impossible to see. Installation of an oil mist detection system is important to the well being of anyone working in the lab, and for preventing potential explosions.

A sensor is mounted in each cell and a central controller is located in the main
corridor. Each cell is displayed as a channel on the controller; if mist is detected in a cell that channel will trigger an alarm.

4.4 Hydraulic Installation

The installation of the hydraulic system was completed once most of the facility construction was finished. Passages were built into the walls between each cell to allow for the common supply lines to be run.

4.4.1 Placement of the reservoir

The final location for the system reservoir was on a second story mezzanine outside the lab. This location still allowed the system to maintain a constant head due to gravity without interfering with the pipes that were pre-existing in the overhead space of the 75HP test cell. Since the mezzanine is only accessible by University of Toledo maintenance personnel there are no concerns of unauthorized access. A benefit of this location is that it provides 145 inches of hydraulic oil head.

The main hydraulic supply for the lab can be accessed from any cell through hydraulic manifolds located on its back wall. The hydraulic system schematic for the 75 HP cell and 7.5, 10, 25, and 50 HP cells are shown in Figure 4-3 and Figure 4-4 respectively.
Figure 4-3: 75 HP hydraulic schematic.
A more detailed schematic including all components installed in the 75 HP cell is shown in figure 4-5. Similar schematics are available for each cell in Appendix A.
Figure 4-5: Schematic of including components in the 75 HP cell.
A table is shown in Figure 4-6 with a dynamometer, torque transducer, and hydraulic mounting fixture installed. The fixtures used to mount hydraulic P/M’s to a test stand have a similar design throughout the lab; however they are not entirely interchangeable between cells. Each fixture is composed of two parts. The base, shown in Figure 4-7, is a welded and gusseted bracket made of aluminum with four bolt holes to attach it to the table, another four holes to secure a P/M mounting plate, and two alignment holes to receive dowel pins. The motor mounting plate is a machined piece of aluminum to which the P/M can be fastened independently then later mated with the base, also referred to as the tombstone. By using a fixture of this style the tombstone can be reused and only the mounting plate needs to be manufactured for each different P/M configuration. This modular design allows for quicker exchanges of components on a test setup.
Flexible drive couplers were required to join each test unit to the torque transducer and the torque transducer to the dynamometer. Magnaloy Flexible Drive Couplings were chosen for their availability and wide range of compatibility with test units. Figure 4-8 shows a Magnaloy coupler joining a dynamometer to a torque transducer. A separated Magnaloy coupler is shown in Figure 4-9 revealing the polymer bushing between each magnesium coupler. There is very little tolerance for misalignment in Magnaloy couplers. Only five thousandths of an inch in any direction is allowable run out. By keeping the alignment and concentricity as close as possible, the couplers will show a greater service life and will transfer the least vibration.
Figure 4-8: Mated coupler connecting dynamometer to a torque transducer.
Unlike the hard mounted lines supplying the cells, flexible hydraulic hose is used to plumb test units to the common system. This allows for more flexibility between test units. Hydraulic hoses must be the correct length and size for every test application meaning that whenever a new test was setup hoses would have to be made by a local supplier if they could not be assembled in the lab.

Making hoses requires an abrasive cut off saw for cutting bulk hose to the correct length, a hydraulic hose crimper to secure end fittings, and a cleaning tool to remove dust and debris from inside the hose.

A sixty ton hydraulic press designed for crimping hose ends was purchased for the lab and permanently mounted to a roll around cabinet. Dies were made to fit the common fitting sizes and can be adjusted within a specifically designed range using a micrometer mounted on the guide of the press. The press uses a two piece die set
that slides over the collar of the fitting and when force is applied crushes the outer sleeve of the fitting securing it to the hose. When crimped correctly this connection is safe to over 5,000 PSI. To ensure hoses are assembled correctly students are required to go through a training session and are not permitted to make hoses unsupervised.

4.4.2 Testing

A common center line height was set at eight inches for every test stand to help keep mounting fixtures consistent across cells. Eight inches was chosen because the largest dynamometer measures that without the use of shims or riser blocks. Risers were machined for each of the smaller cells as shown in Figure 4-10.

![Image of riser plates installed under a dynamometer.]

Figure 4-10: Riser plates installed under a dynamometer.

The additional height added by the risers meant longer fasteners would be needed
to secure the dynamometer, however longer bolts won’t clear the case. All thread rod was cut to the required length and threaded through the table. A jam nut was installed on the underside of the table locking the rod in place, and then a lock washer and nut were installed on top securing the dynamometer.

Figure 4-11: Jam nut securing all thread.
Proper test procedures were developed for running both pump and motor tests in the HTF Appendix B contains numbered diagrams as referenced in the following test sequences.

The process of testing a Hydraulic Pump is as follows:

- With the test pump mounted, hydraulic connections made, and control system connected; the valve connecting the test pump flow to the pressure filter and test manifold can be opened.
- The valve porting the reservoir for the pump suction port can be opened.
- Open the valve allowing the test manifold to return fluid to the return header and finally the reservoir.
At this point the motor should be jogged or “bumped” briefly to check rotation of the test pump. Once verified speed can be ramped up on the pump.

Pressure can now be applied by way of the DAQ system through the proportional pressure control valve. Flow can also be monitored at this time from the output of the test pump.

A process similar to pump testing is defined for testing of a Hydraulic Motor:

1. With the test motor mounted, hydraulic connections made, and control system connected; the valve allowing flow from the test motor flow to the pressure filter should be opened.
2. The valve to the suction line must be closed and the valves allowing flow from both the return line and high pressure line must be open.
3. At this time a command signal from the DAQ can be sent to the proportional pressure controller. Torque generated and outlet pressure and flow can be monitored now as well.

In order to run a Hydraulic Motor test the 75 HP cell must also be run to provide pressure to the system.

4.5 Post Contractor Work

The data acquisition system was installed by the research team after the facility construction was complete and the hydraulic system was installed. There were several reasons for the research team to design and install the data acquisition system. Defining specifications for a contractor to install an adequate data acquisition system would have been very complicated. Designing and installing the system provides a better working knowledge, for students and advisors, of how the system functions and components interact.
4.5.1 Installation of the computers and DAQ

Every test cell required a computer, series of data acquisition hardware, and wiring to operate. Desktop computers were ordered for every cell. To communicate with the VFD and the CompactRio multiple network connections were required. Additional, CAT5E (Ethernet) compatible, Network Interface Cards (NIC) were purchased and installed in each computer. Three CAT5E connections were used at each terminal; one connects the computer to the school network, another communicates directly with the CompactRio, and one communicates directly with the VFD.

A portion of the data acquisition system in each cell was installed by Sentinel Fluid Controls, as that was an integral part of the plumbing installation. Pressure transducers were installed on the high pressure line at each test stand. Flow meters were installed, just after the filter, on the hydraulic return line. Components used to monitor and control oil temperature were installed and tied into the 75 HP cell. A thermocouple reads oil temperature from the reservoir, a heating element can be turned on to bring the oil up to operating temperature before testing, and a chiller system, utilizing cool water, can remove heat in the oil generated by testing.

The data acquisition system receives signals generated by sensors such as the pressure transducer, flow meter, and torque transducer. Control signals can also be sent out to the proportional controller and oil chiller. These input and output signals are managed through a LabView program written specifically for use in this lab. Each signal needs to be processed in a specific manner, resulting in a very complex program to operate and monitor tests.

Outside each test cell, mounted on DIN rails, were the CompactRio unit with four cards installed. Each card is designed for a specific type of data signal; digital or analog within a specific frequency range. Also mounted on the same DIN rail are two 24V DC power supplies, one is dedicated to powering the CompactRio, the other provides power to sensors which require power.
4.5.2 Installation of the low voltage wiring

Transferring data from the sensors in each test cell to the CompactRio, and computer, required a series of low voltage wires to be run from inside the cell to the computer terminal. To protect these wires from the potentially harsh environment in the cell they were run inside a 2\(\frac{1}{2}\) inch oil and crush resistant, flexible conduit. Minimizing noise and interference from electrical power lines was important for collected data to be as accurate as possible. Conduit was run overhead in each cell to keep it away from power lines run to the VFD and dynamometer. Avoiding power lines completely was not possible; anywhere this occurred the conduit was positioned perpendicular to the power wires to minimize interference.

The majority of wires pulled were run directly from the CompactRio outside each cell to a junction box mounted on the side of each test stand. Additional wires were routed from the junction box up to the surface of the test stand for use with the torque transducers, high pressure cartridge valves, thermocouples, and any sensors added in the future. Sensors installed by Sentinel Fluid Controls were already wired to the junction box and only required a signal to be run to the CompactRio.

4.6 Summary

Construction of the HTF involved several stages of work before completion. A site relocation presented challenges, resulting in design changes. The final location also had some limitations which had to be overcome in design and construction. Work was divided over three different contractors for facility construction, electrical installation, and hydraulic installation. The budgeting process cost over runs were discussed. Details on construction of the facility, including windows, electrical, and oil mist detection were covered. Construction of the hydraulic system, including additional specifications for the 75HP cell, reservoir placement, and basic testing
procedure were detailed. Finally post contractor work such as data acquisition and wiring installation was reviewed.
Chapter 5

Testing

5.1 Introduction

Completion of the lab required system testing. Obtaining a working knowledge of the performance characteristics of the P/M is essential in the operation of future tests run in the HTF. Real world testing scenarios are the best way to determine this information.

Tests described and performed in this chapter serve two purposes; to characterize the performance of the 75 HP supply pump, and to verify the lab performs as expected. An accurate representation of the P/M performance can be determined from data collected on speed, pressure, and flow. Speed, pressure, and flow can then be plotted against each other in 3D plots showing the values required to achieve certain conditions.

In most test cases, the hydraulic P/M will either be a specific model or known displacement and style. Hoses then are routed for the specific test unit with the following in consideration; maximum system pressure, maximum flow, and length of hose [7]. Environmental conditions are usually considered, but with the HTF being a climate controlled environment this can be overlooked. For longer sections of hose
a larger diameter is recommended, to reduce system resistance.

All hydraulic hoses in the HTF are constructed with 4 or 6 wire high pressure hose to ensure low pressure and high pressure supplies are not mistaken. Crimp fittings for hoses are all Code 61 and Code 62 four bolt flange couplings. Control system components including valves, filters, pressure sensors, and flow meters mounted to each cells table are rated for 5,000 PSI or greater. By using components with these ratings, data collection and fluid filtration can be achieved in both pump and motor mode tests.

The P/M tested was an Oilgear model PVK 140 P/M, which was installed as the supply pump for the HTF. This is a variable displacement axial piston pump with a maximum displacement of $140 \frac{cc}{rev} (8.54 \frac{in^3}{rev})$, maximum intermediate pressure of 5000 PSI (345 bar), and a maximum speed of 1800 rpm.

5.2 Test Plans

The system supply at inlet port of the P/M plumbed to the suction manifold in the test cell. The outlet was ported to the high pressure supply line and the case drain plumbed to the scavenge unit under the table. The electric motor was be used to power the hydraulic pump. The ball valve on the manifold for the high pressure and hydraulic suction lines were opened in the 75 HP cell. A flow restriction was created in the 10 HP cell, hose was connected from the high pressure manifold to the return manifold with the ball valve.

Two types of tests were performed; tests at constant values and tests where one control variable was varied. The initial set of tests were performed at constant operating conditions. The variables changed from one test to another were speed and pressure; four different values were used for each variable, resulting in sixteen total tests. Speed was tested at 450, 900, 1350, and 1800 RPM, these values represent
25, 50, 75, and 100% of the pumps speed range respectively. Pressure set points were tested at open flow (100-500), 2400, 3600, and 4500 PSI. A list of all sixteen tests was compiled then randomized using a random value assigned to each test and sorted accordingly. Table 5.1 shows each test in the randomized order they were run. Maximum pressure was controlled by a solenoid operated pressure relief valve (PRV).

There were concerns of whether the pump would be able to sustain 4500 PSI at the lower speed values. In practice, the pump would never be operated at speeds lower than 900 RPM because of high mechanical loses and reduced mechanical efficiency. However, for the sake of consistent testing these values were included. Each test was allowed to reach steady state then held there for approximately three minutes.
A secondary set of tests was determined necessary after the test data from the first series was analyzed. These tests, referred to as “ramp” tests, swept either PRV value or speed through a range of values rather than remaining at a constant value. By ramping these parameters the effects of dynamic values could be observed. Each of these tests was conducted with different values of flow restriction which represented a system load. The constriction was created by partially closing a ball valve. Valve closure angle was measured using a goniometer with one leg aligned with the plumbing,
and the second leg aligned with the center of the valve handle. Using this method, flow restriction at 20°, 15°, and 10° were tested \(^1\). Similar to the constant value tests, each test was assigned a random value which was used to determine the order of the tests. The only parameter that was not randomized was the valve restriction. Accurately setting the valve to the same angle in a random order was not practical, for this reason tests at each value of valve restriction were run at the same time as seen in table 5.2.

\(^1\)Angle measurements refer to 0° as full closure and 90° open flow.
### Table 5.2: Randomized order of Ramp tests.

<table>
<thead>
<tr>
<th>Test Mode</th>
<th>Speed (RPM)</th>
<th>PRV Value</th>
<th>Ball Valve Restriction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>5.0</td>
<td>Open</td>
</tr>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>0</td>
<td>Open</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>1800</td>
<td>-</td>
<td>Open</td>
</tr>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>10.0</td>
<td>Open</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>1400</td>
<td>-</td>
<td>Open</td>
</tr>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>2.5</td>
<td>Open</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>600</td>
<td>-</td>
<td>Open</td>
</tr>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>7.5</td>
<td>Open</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>1000</td>
<td>-</td>
<td>Open</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>600</td>
<td>-</td>
<td>20°</td>
</tr>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>10.0</td>
<td>20°</td>
</tr>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>5.0</td>
<td>20°</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>1800</td>
<td>-</td>
<td>20°</td>
</tr>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>2.5</td>
<td>20°</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>1400</td>
<td>-</td>
<td>20°</td>
</tr>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>7.5</td>
<td>20°</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>1000</td>
<td>-</td>
<td>20°</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>1800</td>
<td>-</td>
<td>15°</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>600</td>
<td>-</td>
<td>15°</td>
</tr>
<tr>
<td>PRV Ramp</td>
<td>1400</td>
<td>-</td>
<td>15°</td>
</tr>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>2.5</td>
<td>15°</td>
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<tr>
<td>PRV Ramp</td>
<td>1000</td>
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<tr>
<td>Speed Ramp</td>
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<td>Speed Ramp</td>
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<td>10.0</td>
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<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>5.0</td>
<td>15°</td>
</tr>
<tr>
<td>Speed Ramp</td>
<td>-</td>
<td>0</td>
<td>15°</td>
</tr>
</tbody>
</table>

5.3 Test Procedure

First, the ball valve in the 10 HP cell would be set to the position required for a particular run. The control program was then started in LabView. After program communication with the VFD and sensors established, data collection was started. The final step to starting a test was increasing the dynamometer speed to the desired
value and setting the pressure relief valve to the desired set point.

Constant value tests were run for three minutes at test conditions. Data collection and communication with the VFD and sensors were then stopped. Finally the control software could be shutdown.

When conducting ramp testing the control system runs an internally programmed routine over a 285 second period then returns to the initial set speed when running the pressure ramp profile, or shut down (0 RPM) when running the speed ramp profile. The speed ramp profile started at 600 RPM where it increased to 1800 RPM over a two minute period, speed was held at 1800 RPM for 30 seconds, then ramped back down to 600 RPM over a 2 minute period. Similarly, the proportional pressure control ramp test sequence was started with the PRV set at minimum value, ramped up to the maximum pressure over a two minute period, held for 30 seconds, then ramped down over a two minute period.

5.4 Data Collection

Torque, flow rate, pressure, and temperature data were collected. The sensors used and their specifications are presented in the following sections.

5.4.1 Torque

Values of the torque present on the dynamometer were recorded by both the VFD and the Torque transducer. An Interface torque transducer, model T5-500-A6A, rated for up to 500 N·m was used in line between the P/M and dynamometer. This unit was used to log both rotational speed and torque of the system. Additionally, speed and torque values were collected directly from the ABB ACS800 VFD used to set the dynamometer speed.

The data collected from the VFD and torque transducer showed different values.
The VFD is responsible for setting the system speed and therefore read speed and torque as part of the control process. The torque transducer on the other hand has no influence on speed control and is simply sampling the value after it has been set, creating a slight delay in value readings.

5.4.2 Flow

The flow meter used was made by Flow Technologies, an FT-20 model. This was rated for a maximum flow rate of 100 GPM [13]. Accurate data collection requires laminar flow in the pipe before and after the flow meter. Flow Technologies recommends a length of ten times flow diameter before the sensor and five times flow diameter after the sensor. Attached to the flow meter is an amplifier to convert the output signal of the sensor into a signal the DAQ system can read. A Flow Technologies PA03 amplifier is used here. This offers a frequency range of 0 to 10 kHz, and can operate in a temperature range from -40°F to 185°F (-40°C to 85°C) [14].

5.4.3 Pressure

The pressure sensor in the 75 HP cell is a Honeywell TJE series pressure transducer, model 060-4256-02TJG. This sensor offers pressure readings from 1 PSI up to 7,500 PSI, with an accuracy of ±0.1% [16]. Pressure is read on the outlet plumbing just after the pressure relief valve.

A considerable amount of noise was observed in the high pressure signal. This may be a result of other noise introduced by neighboring wires run in the same conduit.

The standard deviation was calculated for the high pressure signal of each test and the values appear to increase as the pressure increases. Tests at the same pressure set point also showed very similar standard deviation values. This does not support the theory of noise introduced by neighboring wires as the standard deviation should decrease with increased pressure, as the signal strength would be stronger and therefore
the interference accounts for a smaller percentage of the signal. The standard deviation calculated appears to support noise from the pressure transducer itself. It also appears the noise occurs before the signal is amplified since the standard deviation increases with pressure and therefore with signal strength.

After completing the set of constant value tests the pressure transducer wiring was checked for ground loops and any possible interference that could be responsible for the noise experienced.

5.5 Data Analysis

5.5.1 Constant Value Tests

Post processing of test data consisted of smoothing the pressure data with moving averages (for the constant value tests), calculating values such as power and displacement, and generating plots. After the data from the constant value test was analysed a Butterworth filter was added to the high pressure signal to reduce the noise. The filtered data was used for all the plots shown on ramp data. Torque and speed values collected from the VFD were more consistent than those collected by the torque transducer; the values from the VFD were used when calculating power and displacement for this reason.

The power used by the pump was determined using equation 5.1 [12].

\[
\text{Horsepower} = \frac{\text{Torque} \times \text{Speed}}{63000}
\] (5.1)

In this equation torque must be in in*lb and speed in RPM.

The displacement of the pump was also calculated using equation 5.2.

\[
\text{Displacement} = \frac{\text{FlowRate} \times 231}{\text{Speed}}
\] (5.2)
Where the displacement is measured in \( \frac{m^3}{rev} \), speed in RPM, and flow rate in GPM.

In the 1800 RPM test at open flow \(^2\) pump displacement was calculated to be 119.5 \( \frac{cc}{rev} \), less than the maximum displacement of 140 \( \frac{cc}{rev} \) the pump is rated for. The pump installed has an optional maximum volume set which was calibrated at installation to limit the pump displacement based on the desired power output.

A centered moving average was used to smooth the data collected by the pressure transducer. In this case 15 data points in either direction were used to calculate the average (resulting in 31 averaged points for each sample point) as shown in equation 5.3.

\[
PressureAverage = \frac{15 \text{ previous points} + \text{current point} + 15 \text{ future points}}{31} \quad (5.3)
\]

A filter was added to the high pressure data signal in the control software after performing the constant value tests. The resulting output signal closely matches that of the averaged data with a slight lag.

### 5.5.2 Ramp Tests

Data collected from the ramp tests was similar to that of the constant value tests; speed, pressure, and flow were all collected. Unlike the constant value test however, either the speed or PRV parameter were changed dynamically during the test. These dynamic elements resulted in different behavior from the pump.

A mathematical analysis of the ball valve was performed to determine the amount of flow restriction achieved for a given angle of closure. A Stauff FBV series ball valve, with a pressure rating up to 5,000 PSI was used. The diameter of the internal ball was assumed to be 1.5 times that of the flow diameter. This assumption was

\(^2\)1800 RPM at open flow would result in the greatest flow rate and greatest pump displacement
confirmed with an additional test run with the ramp tests to determine the point
where flow was no longer possible.

To calculate the area of open flow overlapping circular areas were examined. The
geometry of the valve can be seen in figure 5-1. Projecting the ball opening on a plane
normal to the direction of flow provided an accurate area which could be calculated.

Figure 5-1: Sphere showing pipe profile and ball profile oriented 45° apart.
Figure 5-2: Valve angle vs. Area of restriction.

Figure 5-2 shows the relation between valve angle and the area of flow. From this analysis it can be seen that the 20° test was a 92% reduction in area, 15° was a 96% reduction in area, and the 10° test was a 99% reduction in area.

Initially a set of tests was going to be run with the ball valve at 45°. After running a PRV ramp at 1800 RPM though, pressure values were unchanged. It was decided to move directly to the 20° testing at that time instead.

Two additional tests were run after the scheduled tests were completed to determine the edge of the valve limiting flow. At a valve opening of 8° the pump was still able to push approximately 13 GPM through the valve opening when operated between 1000 and 1800 RPM. When the valve was reduced to 6° though, the pump was unable to move more than about 0.5 GPM. Knowing the angle at which both open flow and full closure occur the area of flow can be calculated for any angle the
5.6 Test Results and Conclusions

In general the pump performed very well. As suspected, when trying to sustain the higher pressures at low speeds during constant value testing (450 RPM at 4500 PSI for example) the pump would stall. This behavior was observed when trying to achieve 4500 PSI at 450, 900, and 1800 RPM. While this was anticipated at lower speeds it was unexpected at 1800 RPM. This may be attributed to the manner in which flow restriction was achieved. Future testing should employ a valve designed specifically for restricting flow, in the tests preformed a simple ball valve was partially closed to restrict fluid flow. A ball valve really shouldn’t be used in this manner for two reasons; heat and potential damage to the valve. The restriction created by partially closing a ball valve causes fluid temperature to increase quickly, this requires running an oil chiller to prevent overheating the hydraulic fluid. Large forces imparted by hydraulic fluid can deform the edge of the ball where flow restriction is created.

High pressure values were plotted, using the centered moving average, along with the speed set and recorded by the VFD, as shown in figure 5-3.
Figure 5-3: Pressure and Speed (1350 RPM, open flow)

Power, calculated from the torque and speed read by the VFD, was plotted with the VFD recorded torque, as shown in figure 5-4.
Similar plots were generated for each test case and can be found in Appendix C. Figures 5-5 and 5-6 show the system response, both pressure and torque, during a test scenario where the pump stalled.
Figure 5-5: Pressure and Speed (450 RPM, 4500 PSI)
Figure 5-6: Power and Torque (450 RPM, 4500 PSI)

The relationship between speed and pressure for a typical ramp test can be seen in figure 5-7, speed is measured in RPM and pressure in PSI.
Similarly the pressure profile for a PDV ramp test is shown in figure 5-8, pressure is measured in PSI.
Figure 5-8: PDV ramp, 1400 RPM, 15°

Pressure and torque data was plotted for each RPM value tested to more easily show the effects of the valve angle. Figures 5-9 and 5-10 show these respectively at 600 RPM.
Figure 5-9: Pressure (PSI) curves at 600 RPM
Figure 5-9 shows the significant impact valve closure has on pressure and figure 5-10 shows the corresponding increase in torque required to maintain flow through the reduced valve area at this elevated pressure.

Observations were made during high pressure tests that the pump had a tendency to begin cycling, or stall out entirely while unloading in the range of 800 - 900 RPM. An additional test was run in an attempt to single out the parameters that caused the pump to stall. This test was run at 800 RPM ramping the proportional pressure controller. It was discovered that the rate of loading and unloading was to blame. If the pump was loaded or unloaded slowly it performed satisfactorily; however, if the loading or unloading was rapid it would cause the pump to cycle and eventually stall. This can be seen in figure 5-11, pressure is measured in PSI.
In each of the constant value tests run pressure and speed were controlled values; flow however, was measured not set at a specified value. Plotting Pressure vs. Speed vs. Flow generates a profile which can be used in future testing to determine speed and pressure values to achieve a desired flow rate.

The results from constant value testing gave a rough baseline for the performance characteristics of the 75 HP test cell, however this was not a very smooth profile. Using the results of the ramp tests a profile was created relating pressure, flow, speed, and PRV value. This profile can be seen in figure 5-12.
Figure 5-12: Speed vs. Pressure vs. Flow vs. PRV value

5.7 Summary

An Oilgear PVK 140 P/M was operated in pump mode to collect data used to generate a performance profile. Torque values were collected from the VFD and torque transducer. Pressure and flow rate values were also collected. This data was then used to calculate power and displacement for each of the constant value tests. Surface plots comparing pressure, speed, and flow were generated.

The 75 HP test cell is designed primarily as a supply source for the rest of the lab. Since this cell supports the rest of the lab it does feature some components which are not found in other cells.

The pump mounted in the 75 HP cell is capable of producing up to 4500 PSI or 50 GPM depending on the requirements of the test being conducted. Both 4500 PSI and 50 GPM are not possible concurrently with this unit; at 4500 PSI approximately
22 GPM can be achieved and at 50 GPM roughly 2500 PSI can be maintained [17].

When using the 75 HP supply unit to power future tests the pump should be operated between 1500 and 1800 RPM for best results. Operation as low as 1200 RPM is acceptable for lower pressure or torque requirements, any operation below this may result in the unit stalling or possible damage.

At high pressures a limitation was discovered when high rates of loading and unloading are experienced in the 800 - 900 RPM range. This appears to be a result of the torque required to maintain pressure and flow is greater than the pump and dynamometer are capable of providing.
Chapter 6

Conclusions and Future Work

In this work, the process of designing and constructing a high pressure hydraulic test facility was examined. Details ranging from the initial concept, to budgeting and contracting, to performing a series of tests to characterize the supply pump were discussed.

A review of current literature and technology revealed the need for a test facility capable of testing hydraulic components up to 5,000 PSI. The ability to collect data on pressure, flow rate, rotational speed, and fluid temperature was critical. This data can be used to generate efficiency maps of production P/M’s, verify manufacturer specifications, and test control strategies.

Layouts and possible locations of the HTF at the University of Toledo College of Engineering was reviewed in detail. Components of the hydraulic, electrical, and data acquisition system were selected. The construction process, including modifications to the lab, was explained. Safety equipment as well as safe operating procedures for lab users were defined. Finally, a test procedure was defined and the results of characterization testing on the 75 HP supply pump were documented.
6.1 Conclusions

A fully functional hydraulic test facility capable of testing components up to 5,000 PSI or 50 GPM was constructed.

The 75 HP supply unit was tested and a performance map developed. From tests performed on this unit a recommended operating range of 1500 - 1800 RPM was determined.

A Stauff FBV ball valve was analysed to determine the flow restriction imparted through its full range of motion.

6.2 Future Work

6.2.1 Flow Control Valve

A standard ball valve was used to restrict flow, testing the 75 HP supply pump. This method works, however it is not ideal; accurately measuring the open area of the valve while partially open is difficult. Using a valve of this style to restrict flow also generates a great deal of heat in the oil. Replacing this with a valve designed specifically for restricting flow in a hydraulic line would enable more accurate testing parameters and tests which are easily repeatable.

6.2.2 Signal Noise

Reducing the noise present in the pressure and temperature signal would make data analysis more accurate. Ground loops, or faulty grounds could be a contributing factor to this issue. Verifying the sensor wiring to the DAQ and accompanying grounds should be the first step. If noise is still an issue with wiring and grounds properly connected an analog filter may be required.
6.2.3 Mounting Hardware

Currently any new components to be tested require new mounting holes drilled and tapped into the work surface. Replacing this with a modular system would make changeover from one test to another simpler while leaving the work surface unmodified. There are several viable options for modular mounting; a sacrificial plate to bolt to, T-slots machined into the work surface, or some form of sliding track that can be fastened to the surface with fixtures that are easily interchanged.

The most economical to implement and simplest design would be adding a sacrificial plate to the work surface. This would only need to be bolted to the table at a few points so as to not shift or allow vibration. Periodically, the plate would need to be replaced as mounting holes may interfere and compromise the rigidity of the test assembly.

Machining T-slots into the work surface after the tables have already been installed in each cell would present a significant challenge. If it were practical to machine the work surfaces with T-slots this would be a very strong clamping method to secure equipment. Precautions would need to be taken to prevent build up of oil and dirt in the slots causing hardware to bind.

Bolting or welding a track mechanism to the work surface presents a strong mounting that would be easily configurable, reasonably easy to implement, and have no components that would require regular replacement. Given cost is not prohibitively expensive a modular track assembly would appear to be the most favorable solution to install preserving the work surface.

6.2.4 Hardware Inventory

With the large selection of hardware and fittings needed in the lab at all times keeping track of what is available and items that need to be replaced can be quite
challenging. Implementing an inventory system would aid in tracking in stock hardware. This could be done with a computer database, simply checking out items as they are used and checked back in when no longer installed. Alerts can be triggered for low levels of an item reminding lab users to order replacements.
References


Appendix A

DAQ Wiring & Hydraulic Schematics
UT Hydraulics Lab DAQ Wiring
75 hp cell  December 2, 2009
MWW  Rev - D
Appendix B

Operational Sequence
Operational Sequence

Hydraulic Test Cell Rooms

The Hydraulic Test Cell Rooms have a dual function; they can be set up to test Hydraulic Motors or Hydraulic Pumps. Multiple Test Cell Rooms can operate at the same time depending on the components being tested in each cell. When leaving a Test Cell Room, ALL ball valves must be in the closed position, except for Item #33 which is the sump unit ball valve, which must remain open to allow sump oil to be transferred back to the reservoir. Before a test may be performed, make sure the following sequence is followed. Reference the Hydraulic Schematic, 20348-B-H2, H4, HS-0 for item numbers. Failure to follow the proper Operational Sequence may result in product damage and or severe personal injury. Pressurized oil is VERY DANGEROUS, MAKE SURE all pressure has decayed from the system and power is locked out and tagged before any work is performed.

Testing a Hydraulic Pump

- Once the test pump is mounted and all connections have been made to it, move the lever on the selector valve, item #76 to allow test pump flow to be ported to the pressure filter, item #74 and pressure test manifold, item #72.
- Open ball valve, item #17 to communicate the reservoir to the suction of the test pump.
- Open ball valve, item #66 to allow test pressure manifold, Item #72 to flow back to the return header and ultimately the reservoir.
- "Bump" the inverter drive to verify rotation of the test pump. Once rotation has been verified, allow inverter drive to ramp up to test speed required for the test pump.
- Test pressure is now applied via a command signal from the DAC system to the proportional pressure control valve, item #69. Pump output flow is verified by item #75 back to the DAC system.

Testing a Hydraulic Motor

- Once the test motor is mounted and all connections have been made to it, move the lever on the selector valve, item #76 to allow test motor flow to be ported to the pressure filter, item #74 and test manifold, item #72.
- Close ball valve, item #65 and open ball valves, items #66 and #55. This allows pump flow from the Hydraulic Test Room to enter the test cell and test oil from the motor to flow back through item #72, item #75, and item #66 back to the reservoir.
- A command signal from the DAC system to item #69 will determine the drive pressure that is fed into the test motor. The torque generated by the test motor will be absorbed through the electric motor and inverter drive.
- Drive pressure is monitored through item #24 while flow is monitored through item #75.
To test a hydraulic motor, the Hydraulic Pump Room system must also be running to supply the test oil to the test motor. Follow the below sequence to get the Hydraulic Pump Room system operational.

**Hydraulic Pump Room**

The sole function for the Hydraulic Pump Room is to supply a flow at a selectable pressure to the other test cells. No "product" testing will be conducted in the Hydraulic Pump Room.

Before power is applied to start the pump, make sure the following sequence is performed. Reference the Hydraulic Schematic, 20348-B-H3-0 for item numbers.

- On the reservoir, open the suction balls, items #16 and #17.
- In the Pump Room, open the suction ball valve, item #17 that supplies the Oilgear pump.
- Close pressure header ball valve, item #55 on header block.
- On the sump unit, open ball valve #66 to allow sump oil to be transferred back to the reservoir.
- In the Pump Room, open the ball valve that is on the return header, also item #66.
- Make sure there is no pressure command signal going to the proportional pressure control, item #25.
- With the entire above confirmed, "bump" the inverter drive to verify correct rotation of the Oilgear pump, item #28.
- Once the correct rotation has been established, allow the pump to ramp up to its programmed running speed.
- At this point, the pump should be compensated at its minimum operating pressure.
- Once a Test Cell Room is set up and ready to conduct a Hydraulic Motor test, open ball valve, item #55 which will allow Hydraulic Pump Room oil to go out to the selected test cells.
- The DAC unit will determine the pressure the Oilgear pump will operate at via a command signal.
Hydraulic Pump Room Reservoir Assembly

Reference Drawing #20348-B-H3-0
Sump Unit Assembly

Reference Drawing #20348-B-H3-0

Relief valve, item #50
Low Level Switches, item #49
Pump, item #44
Filter assembly, item #53
Electric motor, item #43
Test Cell Valve/Filter Assembly
Reference Drawing #20348-B-H2-0
Test Cell Header Piping

Reference Drawing #20348-B-H2-0

PSI header and ball valves, Item #55

Return header and ball valves, Item #66

Suction header and ball valve. Item #65
Hydraulic Pump Room Pump

Reference Drawing #20348-B-H3-0

Oilgear pump, Item #28
Hydraulic Pump Room Reducing Valve Assembly

Reference Drawing #20348-B-H3-0

Pump proportional PSI control, item #20-25
Hydraulic Pump Room Accumulator System
Reference Drawing #20348-B-H3-0
Hydraulic Pump Room Header Piping

Reference Drawing #20348-B-H3-0
Appendix C

Test Results

Pressure and Speed, and Power and Torque plots from constant value testing.

(a) Pressure and Speed
(b) Power and Torque

Figure C-1: 450 RPM, open flow constant value test.
(a) Pressure and Speed  
(b) Power and Torque

Figure C-2: 450 RPM, 2400 PSI constant value test.

(a) Pressure and Speed  
(b) Power and Torque

Figure C-3: 450 RPM, 3600 PSI constant value test.
(a) Pressure and Speed  
(b) Power and Torque

Figure C-4: 450 RPM, 4500 PSI constant value test.

(a) Pressure and Speed  
(b) Power and Torque

Figure C-5: 900 RPM, open flow constant value test.
(a) Pressure and Speed            (b) Power and Torque

Figure C-6: 900 RPM, 2400 PSI constant value test.

(a) Pressure and Speed            (b) Power and Torque

Figure C-7: 900 RPM, 3600 PSI constant value test.
Figure C-8: 900 RPM, 4500 PSI constant value test.

Figure C-9: 1350 RPM, open flow constant value test.
Figure C-10: 1350 RPM, 2400 PSI constant value test.

(a) Pressure and Speed

(b) Power and Torque

Figure C-11: 1350 RPM, 3600 PSI constant value test.

(a) Pressure and Speed

(b) Power and Torque
(a) Pressure and Speed  
(b) Power and Torque

Figure C-12: 1350 RPM, 4500 PSI constant value test.

(a) Pressure and Speed  
(b) Power and Torque

Figure C-13: 1800 RPM, open flow constant value test.
(a) Pressure and Speed

(b) Power and Torque

Figure C-14: 1800 RPM, 2400 PSI constant value test.

(a) Pressure and Speed

(b) Power and Torque

Figure C-15: 1800 RPM, 3600 PSI constant value test.
(a) Pressure and Speed
(b) Power and Torque

Figure C-16: 1800 RPM, 4500 PSI constant value test.

Pressure plots for PRV ramp testing.
Figure C-17: Valve open 90°, PRV ramp test.
(a) Pressure in PSI (600 RPM)
(b) Pressure in PSI (1000 RPM)
(c) Pressure in PSI (1400 RPM)
(d) Pressure in PSI (1800 RPM)

Figure C-18: Valve open 20°, PRV ramp test.
Figure C-19: Valve open 15°, PRV ramp test.
Figure C-20: Valve open 10°, PRV ramp test.

Pressure plots for speed ramp testing.
Figure C-21: Valve open 90°, speed ramp test.
Figure C-22: Valve open 20°, speed ramp test.
Figure C-23: Valve open 15°, speed ramp test.
(a) Pressure in PSI (0 PRV set point)  
(b) Pressure in PSI (2.5 PRV set point)  
(c) Pressure in PSI (5.0 PRV set point)  
(d) Pressure in PSI (7.5 PRV set point)  
(e) Pressure in PSI (10.0 PRV set point)  

Figure C-24: Valve open 10°, speed ramp test.