May 11, 2005

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Dear Mr. Ulrich:

The enclosed report presents our final design solutions and recommendations for the end effector and test stand. Testing of the end effector prototype for effectiveness in performing its design requirements is included in the evaluation section. Lastly, the final drawing package is included in the appendices with a complete bill of materials.

If you have any questions concerning the enclosed report, please contact us at endeffect@uidaho.edu.

Sincerely,

Matthew Robson

Mike Severance

Chris Hallock

Enclosure:  Final Project Report
Design of a Mechanical End Effector for use in a Hot Cell Environment

Prepared for:
Doug Ullrich,
Hanford Bechtel, Inc.

Prepared by:
Matt Robson
Mike Severance
Chris Hallock

May 11, 2005
Executive Summary

This document contains the recommended design solutions for a hot cell end effector. Working concepts for the major components of the end effector have been examined in detail for their ability to meet all of the design specifications and requirements. An end effector prototype, including working compliance, gave insight into the necessary changes for the final design. The design evaluation section of this report identifies the major constraints of the system, as well as suggestions to overcome those constraints. The final recommended design includes a Belleville washer compliance design as well as a dowel pin injection system for connecting the end effector to the Power Manipulator. A detailed drawing package of the Final End Effector, Prototype End Effector, Park Stand, and Test Stand, as well as DFMEA analysis, are included in the appendices of the report.
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1. INTRODUCTION

1.1 Purpose

This report provides Bechtel Hanford, Inc. with the design recommendations for a hot cell end effector that meets the desired functional requirements.

1.2 Problem

The current design of the robotic gripper is capable of handling some of the objects in the hot cell but cannot effectively plug and unplug Staubli® fluid couplings (Figure 1). The wrist mounted camera on the robotic arm cannot view, with any precision, the manipulation of objects by the gripper hand. Alignment of the couplings with the gripper alone is difficult and time consuming to the operator, which is another problem. Therefore, a mechanical end effector that can handle, or manipulate, the Staubli couplings efficiently must be made to attach and work with the robotic gripper hand.

1.3 Objective

This report evaluates conceptual and a final recommended design based on the specifications of the customer. The primary objective of the design recommendations is to facilitate the selection and production of the design which meets the customer requirements, and can be used and easily reproduced by the customer.

1.4 Limits of Design

The end effector is designed to work with RBE 06, RBE 09, RBE 11, and RBE 19 fluid couplings manufactured by Staubli® (Figure 1). These couplings are specifically designed for remote operation within a radioactive hot cell environment. The design of the end effector is recommended only as a custom tool for use with the Power Manipulator (PM) and fluid couplings specified by the customer.

1.5 Methods

The final design recommendations are based on the mechanical engineering principles and theories used in practice and taught at the University of Idaho, complimented by secondary research of similar existing end effectors and test apparatus designs. Fabrication included machine shop application, as well as necessary catalog ordered parts. Testing of the final design was administered using available test apparatuses at the University of Idaho laboratory facilities, as well as the fabricated mock up of the PM, or test stand.
2. SPECIFICATIONS

2.1 End Effector Specifications

The end effector must connect to the PM gripping fingers, and manipulate the Staubli fluid couplings using the applied motion of the PM. A static weight of 60 pounds including the Staubli fluid coupling, Swagelok threaded elbow, and an unspecified amount of hose must be lifted by the end effector. 60 pounds includes the RBE -19 coupling and a ¾ inch threaded elbow, both the largest of their type to be manipulated by the end effector. The connection between the end effector and PM gripping fingers must be able to support this weight without shifting or disconnecting. Dynamic forces are to be ignored in the design of the end effector due to the relatively slow motion of the PM during operation.

Mounted to the wrist of the PM is an operator viewing camera which allows the operator to view an offset pan of the working area (Figure 2, left). In order for the end effector operation to be viewable, it must be designed with an offset. This offset is approximately 7 inches from the center of the PM wrist to the center of the viewing camera.

Staubli fluid couplings are decoupled with the compression of a spring loaded decoupling button mounted on the female end of the coupling and protruding past the outside diameter of the coupling. The end effector must be able to compress the button in order to release the female end of the coupling. It then must be able to hold the female coupling in its grip during removal, transportation, and connection to a male Staubli coupling.

Compliance for operator alignment error must be built into the end effector for efficient operation (Figure 2, center). This compliance should allow the operator as much as 5° of misalignment from the z-axis, or vertical position, when approaching the female Staubli for removal and when approaching the male Staubli for connection with the female Staubli. During connection of the female and male ends of the fluid coupling, compliance must allow for an offset in the x and y axis of motion, or plane perpendicular to the vertical approach, of ¼ off the inside diameter of the female coupling. The end
effector must be able to make this connection inside an operating envelope of 2.5 by 5 inches square in the x and y plane (Figure 2, right). Compliance will allow the operator to successfully manipulate the couplings without spending excess time aligning the end effector with the Staubli fluid couplings.

2.2 Test Stand Specifications

The test stand is a direct mock up of the driving linkage for the PM robotic arm used in the hot cell. It should be capable of testing the end effector prototypes for successful connection and disconnection of the Staubli fluid couplings. In order to meet this requirement it must simulate the motion of the PM arm used in the hot cell. Also important in the design of the test stand is the fabrication to specification of the gripper fingers and its moving links to insure proper simulation of the connection and motion between the gripper fingers and end effector. Each gripper finger will feature a ¼ inch extruded hole that will be used for the connection of the end effector to the PM. The location of the hole will be determined by the optimal position necessary for the design of the end effector, so long as the location of the hole does not effect the performance of the PM gripper.

2.3 Park Stand Specifications

The park stand will be used to place, or park, the end effector when not in use by the operator. It will function as a means to connect and remove the end effector from the PM gripper fingers. To make placement within the hot cell less obtrusive, the design should be simple and movable.

The design of the park stand is highly dependent on that of the end effector, and how the end effector attaches to the PM. The park stand’s dependence on the end effector design implies that the park stand should be built subsequent to the end effector. However, the selection of the end effector design should consider the easiest possible pick and placement from the park stand.

2.4 Materials

Stainless steel will be used for the major components of the final end effector and park stand designs. Radiation has no significant effect on the material properties of stainless steel, but more importantly, stainless steel resists the corrosive chemical effects from the radiation decontamination process undergone by materials leaving the hot cell. Design analysis will use the properties of stainless steel; however, to reduce material and fabrication costs, aluminum and mild steel should be used for prototyping.

In order to meet grip requirements, we will be using an elastic polymer. This material must display a sound resistance to radioactive exposure and corrosive chemicals, and have a minimum life span of five years under these conditions. The selection of the specific polymer must consider its resistance to radioactive nuclear breakdown, cracking, tear propagation, adhesiveness to metal alloys, and flexure properties. Based on the
material selection sheet provided by Bechtel, it is our recommendation that rubber is used. Synthetic rubber displayed high markings in all of the selection criteria, and will work well for compliance and grip in the end effector design given its highly elastic properties.

3. Concepts Considered

Included in this section are all relevant concepts considered meeting the functional requirements set for each design component. The process of concept development is discussed as well as possibilities for further development.

3.1 End Effector

To properly analyze the design of the end effector it must be broken down into its three primary components: compliance, gripper connection, offset, and grip (Figure 3).

3.1.1 Compliance

Belleville Washer Design

Addressing the compliance functional requirement of the end effector requires a design which can translate and rotate while allowing sufficient force to be applied to the Staubli couplings to compress the decoupling button and grip the couplings for transport. The Belleville washer design implements the use of Belleville washers capable of compressive spring characteristics while allowing the spring rate and compressive length to be adjusted as needed for the design. Three basic components of the design include the deflection rod, shoulder bolt, and Belleville washers (Figure 4). The design is implemented at the grip, as opposed to the gripper connection, in order to avoid excessive compliance motion which may be amplified by a large moment arm applied from the gripper connection to the grip.

This design is simplified using a shoulder bolt as the connection from the down beams to the grip. Belleville washers are placed on the shoulder bolt in series. During connection to the grip a small compressive force is applied to the Belleville washers. This compressive force keeps the grip in its proper stationary position. In the case that a translational adjustment must be made for the end effector to connect or disconnect a coupling, the Belleville washers can compress in the x-direction and move in the y-
direction due to a maximum allowed tolerance between the down beams and the shoulder bolt. Rotational motion is achieved due to the tolerance between the down beams and the shoulder bolt as well. A deflection rod, essentially a dowel pin, is used to limit the rotational motion of the grip to the specified 5° misalignment. The Belleville washer design is simple and effective in meeting its functional requirements.

**Four-Spring Box Design**

A design also applied at the grip includes the use of compressive springs and motion limiting grip connection boxes. Four high spring rate compressive springs form the contact points between the beam connection boss and the grip connection box (Figure 5). Dimensions between the beam connection boss and the grip connection box limit the translation in the x, y, and z-directions. The amount of spring compression can be adjusted by the positioning of the spring mounting dowels. Rotational motion is accomplished through the freedom of motion of the four springs used in the design. Although this design was never tested, in theory it is capable of meeting the functional requirements of compliance, but may not provide enough support in transportation of the Staubli couplings and attached hoses.

**3.1.2 Gripper Connection**

**Dowel Injection Design**

As part of the design specifications, a ¼ inch hole in the gripper fingers can be manipulated as needed for the design. The most reliable connection of the end effector to the gripper fingers can be identified as a dowel insert into the specified ¼ inch hole. A spring loaded dowel injection design utilizes the ¼ inch hole to firmly connect the end effector to the PM.

The dowel injection design consists of five total parts which contribute to its functional and DFMEA applications including the dowel pin, lever pin, compression spring, dowel housing, and mounting plate (Figure 6). A tolerated dowel pin with a press fit hole for the lever pin is inserted into the dowel housing following the compression spring. The lever pin is press fit into the dowel pin while the spring, dowel pin,
and dowel housing assembly is in place. This operation allows the dowel housing to be press fit into the mounting plate, which would not be possible if the lever pin slot, machined into the dowel housing, extended to the end of the dowel housing. After assembly, the dowel injection system is then mounted to the gripper wedge.

A very simple design concept, the dowel injection system works principally on the force exerted by the compression spring. The dowel pin can be removed or inserted into the gripper wedge and gripper fingers by moving the lever pin forward and backward. The dowel injection system works in congruence with the dowel removal park stand design explained in detail on page 9 of this report. Another feature of this design concerning potential failure modes includes the potential of the system to be removed via MSM assistance by removing the the mounting plate from the gripper wedges. This would allow the dowel pin to be removed from the PM, essentially avoiding the potential for entrapment of the end effector on the PM.

**Spring Force Design**

Connecting the end effector to the grip of the PM has proved conceptually challenging due to the geometries and loading specifications required. The triangular shape of the PM gripper fingers makes the resistance to gravity (i.e. hooks, wedges, flats, etc.) in the design nearly impossible. However, there are three geometry features of the gripper fingers which must be considered: dowel holes, manipulator grooves, and flat faces (Figure 7). These are the primary features used in the conceptual design for the spring force gripper connection.

First, the dowel holes, which extrude through the side of the gripper fingers, can be used to place any object in which may help suspend the end effector and/or stabilize it. The complexity of designing a mechanism, which can insert and remove a dowel into the dowel hole, made this design too difficult to pursue in the time being. However, an idea for a mechanism acting as a teeter-totter lever, which moves in and out of place as the gripper moves into place, has been considered. More effective use of the dowel hole may be in stabilization and connection alignment of the gripper-to-end effector connection. This function prompted the idea for the use of an expansion plug, which uses a spring loaded bearing to snap into the dowel hole.

Second, the groove notch already machined out of the PM gripper fingers would work well with the use of a wedge fitting on the end effector. The notch initially created for use in handling pipes, hoses, and other objects within the hot cell, allows for alignment of the end effector. Working in conjunction with the expansion plugs, the groove notch would also create the needed fit for stability during movement.
Lastly, the flat face of the PM gripper fingers creates a surface ideal for a compression friction fit. This means that a force can be applied normal to the parallel moving gripper fingers to hold the end effector onto them. Applying a force normal to the gripping surface can be accomplished mechanically through the use of spring force. Two springs consider for this conceptual design are the torsion and compression spring. Both springs apply a force opposite to the force compressing them, which can be used as the necessary normal force to keep the end effector on the gripper fingers.

CAD testing of the compression spring design proved successful despite concerns posed by the arch motion transcribed by the PM gripper fingers. Because the two fingers are parallel in their relative motion to each other, a spring housing placed between the two sides of the end effector mounting connection will not experience any bending moments. As seen in Figure 4, the spring would be placed inside of a tube housing which in turn would be placed inside of two tube stops mounted to the end effector. The tubes mounted to the end effector would act as a stop to ensure that the gripper cannot compress the spring past its solid length.

3.1.3 Offset

The offset, as described in its specifications, serves the functional requirement of placing the working portion of the end effector, the grip, directly below the viewing pan of the operator’s camera mounted to the wrist of the PM. In order to increase the overall viewing field of operation, a narrow reinforced beam design has been implemented (Figure 8). The beam is constructed as a T-beam to minimize bending stresses and to act as an alignment channel. Other concepts for increasing the viewing area were considered, such as a circular opening on the beam, but were impractical.

To improve alignment success and efficiency to the operator, an alignment marking system can be incorporated into the offset and on the mounted surface of the male Staubli coupling. In concept, hash marks on the x and y axis would be placed on the top offset beam of the end effector. These hash marks would line up with horizontal and vertical lines around the male Staubli. Hash marks on the offset would indicate the center point of the four different sizes of Staubli couplings when the end effector grip is completely closed. This alignment system would be used primarily in aligning the connection of the two ends of the Staubli.

Alignment of the end effector parallel to the offset is important in avoiding unevenly placed moments on the two individual pieces of the end effector, the right and the left. This is where a keyway channel, trough channel, or linear bearing may be necessary in the design. A dovetail was considered for a keyway channel, but initial modeling of the
PM gripper linkage proved that its arch motion would not allow for a tight design because of the displacement between the offsets during motion. This same constraint would prove true for a linear bearing design. The T-beam keyway channel, or a basic block channel as seen in Figure 9, allows for the displacement of the offsets while keeping them aligned parallel to each other. To ensure complete stability during movement, a sliding link could be fixed to the top or left offset and allowed to slide with the motion of the end effector in a groove machined into the bottom or right offset.

3.1.4 Grip

Direct contact between the Staubli fluid couplings and the end effector will occur at the grip of the end effector. This design must be able to hold the coupling firmly without slipping during movement. Any interference due to snag points will likely occur at the grip, and this is why its geometry is important. To support the static load applied during movement of the couplings, the Master-Slave Manipulator (MSM) flat on the female Staubli fluid couplings must come in contact with a flat surface on the grip. In addition, if the operator overshoots the MSM flat or comes onto the Staubli offset, the grip must have a curved or angled contact surface to allow the end effector’s compliance to correct the error.

Furthermore the grip has the duty of compensating for the difference in diameter between the four fluid couplings to be used in the hot cell. This requires a special geometry which can utilize the most amount of contact surface between the grip and coupling. As seen in Figure 10, the button compressing flat surface of the grip is smaller than its counterpart, which completes a 180° semicircle. This will allow for the largest amount of surface contact on the largest RBE-19 Staubli as necessary. A rubber insert on the contact surface of the grip will allow a high friction contact, and assist in conforming to the different diameters of the couplings while allowing minor compliance. A design under consideration for the grip includes a hinged spring loaded grip, which would conform to the different couplings with greater surface area contacted.

Figure 9. Beam design of end effector offset.

Figure 10. Cross section profile of the grip.
3.2 Park Stand

Dowel Removal Design

In the search for an optimized design in attaching the end effector to the gripper, a simple design for the park stand prototype resulted. Figure 11 illustrates the basic design of the park stand with the prototype end effector in place. Two angled slots in a plate allow the end effector dowels to be removed as the end effector is moved into its resting position as seen in Figure 11. A sharp edge engages the dowel levers which are attached to the injection dowels. When the end effector is moved into place, the dowel levers are held in place by a flat trough at the end of the angled slots. At the resting point the spring which injects the dowel into the gripper is fully compressed. Connection of the end effector to the PM consists of aligning the gripper fingers into the end effector wedges and simply moving the end effector forward out of the park stand.

Spring Force Relief Design

Another potential design for the park stand has been explored in combination with the spring force design for the gripper connection. This design, as seen in Figure 12, uses the spring force in the end effector to release against a flat surface. Once the end effector is fully released, the PM grippers can then fully extend releasing them from the end effector. Attaching the PM grippers to the end effector works in reverse order using the spring housing stops to allow the gripper fingers to snap into place. Alignment of the fingers would come from the expansion plugs and groove wedges discussed in conceptual design of the gripper connection of the end effector.

Figure 11. Dowel removal design of park stand.

Figure 12. Spring force relief design of park stand.
4. Design Evaluation

4.1 Testing Concept Development

Initially, the compliance design was to be evaluated using confidence intervals. The chosen interval included that compliance would work 95% of the time at a confidence of 95% within the required compliance range. Further research revealed that it would not be possible to use confidence intervals or any further statistical analysis. This was due to the fact that there was to be no measured result, a governing equation, or more than one prototype to compare results with. The result was observed and there were only two outcomes, success or failure. Although simple, the chosen technique to evaluate the design was effective. It was decided to gradually offset and misalign the connection, and at each increment take samples and find the percentage of successful connections at each point (Equation 1).

Although the end effector was designed to work with four different sizes of fluid couplings only the largest, RBE 19, and the smallest, RBE 06, were tested. The reasoning supporting this approach was that if the end effector functioned at its maximum limits then there was no reason it would not function within its bounds.

4.1.1 Test Protocol

A testing protocol was developed in order to achieve consistent results. This is important so that results could be compared from different testing runs. This procedure was updated during testing once the testing team started to record results to streamline the process and save time.

Each axis is tested independently. This is done to show what parts of the compliance worked and what failed to meet the functional requirements. Before testing began each axis was calibrated to a zero position. This was done by attempting to couple the couplings and observing the compliance. The couplings have a tolerance and any offset would result in the compliance engaging.

Once the couplings were calibrated, the offset was adjusted in 0.05 inch increments until the max required offset was reached or the connection/disconnection failed at the offset. If the connection/disconnection failed the offset was moved back to the where it worked and tested 4 more times. Initially the testing protocol called for 20 attempts at each offset to see if it worked 95% of the time. This was changed during testing because of the observation that the compliance either worked or failed 100% of the time at each offset.

This process was repeated for misalignment of zero, three, and six degrees. Due to the fact that the compliance design is not symmetric, the misalignment had to be tested with rotation in the positive and negative direction about each axis for each misalignment. It is difficult to zero the couplings when there is a misalignment because of the fact that the compliance has to engage even at zero offset. There may be some error in our results due to this.
4.1.2 Variables

In the test there are two independent variables and one dependent variable. The independent variables are linear offset and degrees of misalignment. The dependent variable is whether the end effector was able to couple and decouple the coupling at the prescribed offset and misalignment. A data reduction technique was necessary to evaluate the correlation between the variables.

The data reduction technique uses five samples of the dependent variable, coupling connection, were recorded from the independent variables of linear offset and degrees of misalignment. To reduce the data the 5 samples were converted into a success percentage by using Equation 1, Percent_Success (3). This equation allowed the 5 samples to be represented as one point on the data plot.

\[
Percent\_Success = \frac{\text{Sum\_of\_data}}{\text{Samples\_of\_data}} \times 100\%
\]  

(Equation 1)

The equation Percent_Success refers to the success percentage of the coupling connection. Sum_of_data refers to the numerical sum of the data at that location. Samples_of_data refers to how many samples were taken at the data location. The Percent_Success equation determines if the objectives set by Bechtel are being met.
4.2 Test Stand Design

Such as in the end effector, the test stand is broken down into its three design components. They include: driving the gripping motion, driving the test stand, and the rotation of the gripper (Figure 13). The following goes through the individual conceptual designs of these three areas of focus.

4.2.1 Driving the Gripper

A gripper was designed and fabricated using the PM assembly drawings (Figure 13). There was not enough dimensions to make it exact, however, the design is similar so only minor changes will have to be made to make the end effector function with the PM used in the hot cell.

The gripping motion is driven by a screw and crank wheel. To allow the screw to push and pull and still allow it to rotate freely required a unique design (Figure 14). Using a clamp on collar that fits within a housing that limits it travel in the z direction and allows it to rotate freely within the housing, the screw is able to push and pull the linkage when it is threaded up and down.

Figure 14. Gripper assembly (left), driving linkage assembly (right).
4.2.2 X and Y-Axis Motion Device

In order to decouple the test stand design, the x and y motion device adjusts the position of the fluid coupling plug rather than moving the end effector. The X and Y motion device includes two linear rail systems that are stacked on top of each other (Figure 15). The offset is adjusted by turning either the x or y axis crank wheel. The coupling is attached using a threading plug bolted to the table.

The X and Y motion device also had a role in rotating the plug, again it was easier to rotate the plug than rotate the gripper. Rotation was achieved by placing spacers under plug attachment table. This allowed the plug to rotate up ±6 degrees about the x or y axis.

4.2.3 Z-axis motion

The Z-axis motion is driven by a linear motion device. It is unique because it uses two screws on either side that are connected by a timing belt (Figure 16). This was necessary because of the fact that the screw was not in the center of gripper. Having only one screw would cause binding and non-uniform motion.
4.3 Test Results

The results from the testing are surprising and helpful. The RBE 06 was not tested because of a flaw in the grip design. A taper on the inside of the grip initially designed to allow the coupling to move when the couplings were aligning is more of a hindrance than help. The RBE 06 socket would be pushed out of the grip when attempting to make the connection. The RBE 19 has enough gripping area that the taper did not create a problem when testing it.

Another problem that was discovered is with the profile of the fluid coupling plug. Located on the plug is a lip that is only tapered on the top (Figure 17). The diameter of the lip is approximately equal to the inner diameter of the socket fluid coupling. This does not create a problem when attempting to couple the Staublis because of the taper, but when the end effector is decoupling the fluid couplings the lip catches on the inner profile of the socket. The inner profile of the socket is normally smooth but when the release button is depressed the edges are exposed and grab the lip. In the final design of the end effector the release button is always depressed when handling the socket.

Offset Success or Failure

The following results represent the testing of the RBE 19 fluid coupling when there is no misalignment.
The compliance worked to the maximum required offset when there was an offset in the positive y-direction. The compliance worked only -0.05 inches in the negative y-direction because of the lip located on the plug catching on the inner profile of the socket.

The compliance worked to the maximum offset in the positive and negative x-direction when there was no misalignment.

**Misalignment and Offset Success or Failure**

The following results represent the testing of the RBE 19 fluid coupling with a misalignment of negative 3 degrees about the x-axis.
The compliance worked to an offset of 0.2 inches in the positive y-direction. The compliance failed when there was any offset in the negative y-direction because of the lip located on the plug catching on the inner profile of the socket.

The compliance worked to the maximum required offset when there was an offset in the positive x-direction. The compliance only worked to -0.15 inches in the negative x-direction because of a tolerance stacking problem with the prototype end effector. When the grip was closed it did not line up exactly, and when gripping a coupling the compliance engaged in order to completely close.

### 4.4 Prototype Functional Results

The prototype functioned to the maximum offset with an offset on either side of the plug in the x-direction or an offset in the positive y-direction. It did not function in the negative y-direction because the lip on the plug catches on the inner profile of the socket. The lip also caused problems when there was misalignment of ± 3 degrees or greater about the y-axis, or when there was a misalignment of 3 degrees or greater about the x-axis.

Testing of the gripper connection showed that binding occurred when the dowel was removed from the gripper fingers. The identified problem was that the dowel pin lever created a large moment causing the dowel to bind with the gripper finger and the inside of the dowel housing. Attempts to remove the end effector prototype using the park stand were unsuccessful due to tolerance issues and the described binding of the dowel. All other components of the end effector worked with no binding or tolerance stacking issues.
4.5 FEA Structural Analysis

In the conceptual design of the end effector it was necessary to validate the structural integrity of the design before fabrication. Initial static analysis of the end effector in a point load model proved the design to be satisfactory. However because of the complexity of the geometry of the end effector the use of an FEA analysis program gave more accurate results. Figure 17 shows the Algor® model of the end effector with the grip hidden from the view.

![Image](image_url)

Figure 17. FEA analysis of the end effector using Algor® software.

The model is constrained at the end effector wedges which function as the attachment to the gripper. A surface force is applied to the compliance plates at the location where compression of the fluid couplings by the grip is balanced. This force consists of a 60 lbf load in the y-direction, or downward direction, simulating the maximum weight load of the RBE 19 and its free hanging hose. The x-component, in the direction perpendicular to the compliance plates, is set to 125 lbf simulating a combined clamping force from the power manipulator of 250 lbf. A relatively fine mesh setting gives reliable results.

The end effector was modeled as an annealed 304 Stainless Steel. This particular stainless steel has a yield strength of 40 kpsi and an ultimate tensile strength of 82.4 kpsi (Shigley, Mischke. *Mechanical Engineering Design*. McGraw-Hill, New York, 2001. 6th Ed. pg. 1208). FEA analysis gave a maximum stress of 32.2 kpsi. This essentially proves, with respect to accuracy of the software, that the geometry can function under the maximum applied loads without failure or even plastic deformation.
4.6 DFMEA Analysis

Design Failure Modes and Effects Analysis is necessary in avoiding potential failures of the end effector and park stand system (refer to Appendix D for complete DFMEA). Given the expected substantial operating cost of the Hanford waste treatment facility, it is important that failure of the end effector is not the cause of extensive down time during the changing of the vitrification boilers. This section also considers a potential point for inefficient operation of the end effector tool.

In order to avoid the potential for failed connections of fluid couplings, as identified in design evaluation, the operator should be aware of the offsets and misalignment approaches which most result in a failed connection. The test results section of design analysis should be understood thoroughly by the operator to better understand the limits of both the end effector and Staubli fluid coupling designs. This will ultimately help the operator increase the success and efficiency of manipulating the fluid couplings.

Identified in FEA analysis, the highest stresses seen in the end effector design under the load bounds occurs at changes in geometry of the offset beams, in other words, at stress concentrations. Although this analysis also shows that the design can withstand the applied stresses, potential failure could come from monotonic or fatigue loading. Triangular additions to the beam flanges located at the connection between the down beams and the offset beams and between the gripper wedge and offset beams may add the necessary support to avoid failure. These structural supports must not interfere with the motion of the end effector. Avoiding right angles at the intersection between beams will also help avoid stress concentrations. These geometries may be more easily attainable in the casting process to be used in the final prototype. These measures should be observed as important because the implications of a failed end effector could result in substantial downtime costs if a back-up end effector tool is not available.

Test results revealed the potential for binding of the dowel injection design during removal of the end effector. This can be avoided by allowing a higher tolerance between the gripper attachment hole and the dowel pin. It can also be avoided using a design having less or no moment acting on the dowel pin as it is retracted. A recommendation for this design is found in the conclusion section of this report.
5. Economic Analysis

End Effector

<table>
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<tr>
<th>Labor</th>
<th>Time (hours)</th>
<th>Pay Rate ($/hour)</th>
<th>Total Cost ($)</th>
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<td>1,480.00</td>
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Total: $ 8,880.00

Parts

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<tr>
<th>Description</th>
<th>Cost ($)</th>
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</thead>
<tbody>
<tr>
<td>Rubber with Adhesive Back, 1/16&quot; Thick, 12&quot;X12&quot; Sheet</td>
<td>9.74</td>
</tr>
<tr>
<td>Belleville Disc Spring, .255 ID, .5 OD, .018&quot; Thick, Pack of 12</td>
<td>21.18</td>
</tr>
<tr>
<td>Steel Shoulder Bolt, 1/4&quot; Should Diameter, 1-1/4&quot; Shoulder L, 10-24 Thread</td>
<td>4.56</td>
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<tr>
<td>2&quot; - 0.24&quot;, 3.65lb/in Ground Ends-Music Wire Spring</td>
<td>24.90</td>
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Total: $ 60.38

Materials

<table>
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<tr>
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<tbody>
<tr>
<td>3.5&quot; X 12&quot; Aluminum Round</td>
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<tr>
<td>.75&quot; X .75&quot; X 2' 1020 Steel Bar</td>
<td>17.00</td>
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<tr>
<td>.75&quot; X 1.25&quot; X 3' 1020 Steel Bar</td>
<td>24.90</td>
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Total: $ 87.80

Total Cost of End Effector $ 9,028.18

Park Stand

<table>
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<tr>
<th>Labor</th>
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<th>Pay Rate ($/hour)</th>
<th>Total Cost ($)</th>
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<tbody>
<tr>
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<td>400.00</td>
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<tr>
<td>Fabrication</td>
<td>12</td>
<td>20.00</td>
<td>240.00</td>
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<td>Testing</td>
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<td>20.00</td>
<td>40.00</td>
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Total: $ 680.00

Materials

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<tr>
<td>1&quot; X .25&quot; X 5' Steel Bar Stock</td>
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<tr>
<td>1.5&quot; X .25&quot; X 20&quot; Steel Bar Stock</td>
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<tr>
<td>2&quot; X .5&quot; X 7&quot; Aluminum</td>
<td>1.50</td>
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Total: $ 6.00

Total Cost of Park Stand $ 686.00
## Test Stand

### Labor

<table>
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<tr>
<th>Labor</th>
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<td>Design</td>
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<td>20.00</td>
<td>14,000.00</td>
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<td>Fabrication</td>
<td>160</td>
<td>20.00</td>
<td>3,200.00</td>
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<td>Testing</td>
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<td>20.00</td>
<td>160.00</td>
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<td><strong>Total</strong></td>
<td><strong>17,360.00</strong></td>
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<td>$17,360.00</td>
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### Test Stand Parts

<table>
<thead>
<tr>
<th>Description</th>
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<tbody>
<tr>
<td>RH Clamp on Collar, 10-32 Thread</td>
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<tr>
<td>Chrome Plated Steel Shaft 3/8&quot; OD 12&quot; Long</td>
<td>21.34</td>
</tr>
<tr>
<td>Chrome Plated Steel Shaft 3/8&quot; OD 36&quot; Long</td>
<td>20.79</td>
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<tr>
<td>Chrome Plated Steel Shaft 1/2&quot; OD 18&quot; Long</td>
<td>38.40</td>
</tr>
<tr>
<td>Linear Ball Bearing, 1/2&quot; ID, 7/8&quot; OD, 1-1/4&quot; Long</td>
<td>158.40</td>
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<tr>
<td>Bronze Round Nut, 10 TPI, RH, 1/2&quot;-10 Sz</td>
<td>23.59</td>
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<tr>
<td>Mounting Flange for Bronze Round Nut</td>
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</tr>
<tr>
<td>Steel Threaded Rod, RH, 10 TPI, 1/2&quot; OD, 3' Long</td>
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<tr>
<td>Hand Wheel, 1/2&quot; Bore</td>
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<tr>
<td>Machinable Acme Round Nut, 1/2-10 Acme Thread, RH</td>
<td>79.20</td>
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<tr>
<td>Pillow-Block, Bearing Tight Clearance, 3/8&quot; ID</td>
<td>286.40</td>
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<tr>
<td>Stainless Steel Dowel Pin, 1/4&quot;D, 3&quot; Length</td>
<td>13.89</td>
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<tr>
<td>Stainless Steel Dowel Pin, 1/4&quot;D, 1-3/4&quot; Length</td>
<td>11.22</td>
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<tr>
<td>SAE 841 Bronze Thrust Bearing, 1/2&quot; ID, 1&quot;OD, 1/16&quot; Thick</td>
<td>5.60</td>
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<tr>
<td>Timing Belt Pulley, Fit 1/2&quot; Belt Width, 2.156&quot; OD, 16 Teeth</td>
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</tr>
<tr>
<td>Idler Pulley 3/8 Bore, 3/4&quot; Belt Width, 3-1/2 OD</td>
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<tr>
<td>Belt that works</td>
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<td><strong>Total</strong></td>
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### Testing Parts

<table>
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<tr>
<td>Hex Nipple, 3/4 NPT</td>
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<tr>
<td>Street Elbow</td>
<td>61.20</td>
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<tr>
<td>Brass Hex Nipple Reducer, 3/4&quot; Male x 1/2&quot; Male Pipe Size</td>
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</tr>
<tr>
<td>Brass Hex Nipple Reducer, 1/2&quot; Male x 1/4&quot; Male Pipe Size</td>
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<tr>
<td>.09&quot; Thick Spacer for 1/4&quot; Screw, 5/8&quot; OD, Pack of 100</td>
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<td>3/16&quot; Thick Spacer for 1/4&quot; Screw, 5/8&quot; OD, Pack of 10</td>
<td>6.10</td>
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<tr>
<td>RBE 06 Valved Socket for remote operation, 1/4&quot; FNPT</td>
<td>Donated</td>
</tr>
<tr>
<td>RBE 06 Plug, 1/4&quot; FNPT</td>
<td>Donated</td>
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<tr>
<td>RBE 19 Valved Socket for remote operation, 3/4&quot; FNPT</td>
<td>Donated</td>
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<tr>
<td>RBE 19 Plug, 3/4&quot; FNPT</td>
<td>Donated</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>99.76</strong></td>
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### Test Stand Materials

<table>
<thead>
<tr>
<th>Description</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12&quot; X 12&quot; X .5&quot; Aluminum</td>
<td>56.46</td>
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<tr>
<td>12&quot; X 12&quot; X .75&quot; Aluminum</td>
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</tr>
<tr>
<td>12&quot; X 12&quot; X 1&quot; Aluminum</td>
<td>81.12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>201.08</strong></td>
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**Total Cost of Test Stand** | **$18,651.78**
**Estimated Value to the Customer**

Total Estimated Labor Hours (including design, fabrication, and testing): 1,346  
Total Labor Cost at $20/hour: $26,920  
Total Cost of Materials and Parts: $1,445.96  
Total Estimated Value Delivered to Customer: $28,366

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**6. Conclusions and Recommendations**

A final design recommendation based on testing results and developed concepts utilizes many of the prototype design concepts with specific alterations. Figure 18 represents a solid model of the final design. Addressing compliance is the Belleville washer design, and connection to the gripper is the dowel injection design corresponding to the park stand design. Also considered in this recommendation section are operator procedures and/or tips to ensure the greatest success for connection and disconnection of the Staubli fluid couplings. Lastly, structural design recommendations are included for consideration in fabrication of the final end effector prototype.

![Figure 18. Top view of end effector showing the desired offset.](image)

As previously described, the major functional requirements of the end effector include compliance, connection to the PM, an offset for operator viewing, and the ability to handle four sizes of Staubli fluid couplings. Multiple iterations of the compliance design, considered at the grip, gripper connection, and wedge to beam connection, converged on the Belleville washer design. The design uses the down beam for connection of the shoulder bolt and deflection rod, which reduces the necessary offset of the design by 0.5 inches. Belleville washers possessing greater individual displacement but with a similar load rating, approximately 47 pounds, may be used to reduce the overall gripping offset in return reducing the length of the top sliding t-beam. Testing proves that this design is capable of meeting all offset requirements and up to 3° misalignment, the only constraint of which comes from the Staubli fluid coupling design.

Attachment of the end effector to the PM should incorporate a dowel injection design. This design will work in the manner described in the concepts considered section. The dowel will be injected using the force of a compressive spring. The specified spring
should have a spring constant of approximately 5 lbs/in., and have an overall length allowing constant compression of the spring in the assembly. The compressed length of the spring must allow the dowel pin to be extracted to a flush position with the inside of the gripper wedge. The park stand will act as the means by which the dowel pin lever is engaged to release and insert the dowel pin into the PM gripper fingers. As depicted in Figure 19 the left mounting plate must be offset to allow the lever pins to be engaged more easily by the park stand. The lever pin will be engaged by two slotted plates which will uniformly extract the dowel pin by applying an equal distributed load to the lever pin (Figure 19). Ultimately, this design will prevent binding when the dowel pin is removed by the park stand.

Figure 19. Assembly view of dowel injection system (left), transparent top view of dowel injection system (right).

The essential counterpart to the dowel injection design is the park stand design. A stepped offset allows the dowel levers to engage the top and bottom sliding plates with a straight alignment approach by the operator (Figure 20). The location of the sliding plate grooves should be determined by the distance between the lever pins when the end effector is completely closed; in other the words, the grips are in contact.

Figure 20. Park stand assembly view (left), view of park stand sliding plate stepped offset (right).
The final assembly of the end effector must allow a specific distance for complete compression of the Bellville washers as part of the compliance. A distance of 0.5 inches between the faces of the gripper wedges when the opposing grips are in initial contact will ensure enough distance for complete compression of the washers when necessary. This distance may change as a result of using Bellville washers with different loading properties for the compliance. The lengths of the offset beams are optimized to allow a 7 inch offset from the gripper axis to the camera viewing axis. These optimized lengths correlate to the 0.5 inch compression distance and the combined dimensions of the grip and compliance (Figure 21).

![Figure 21. Top view of end effector showing the desired offset.](image)

The grip contact with the Staubli fluid couplings is an integral part of the end effector design. The grip geometry should remain the same with one change to the manipulator flat groove. A flat upper ledge will allow the grip to resist any slipping that can occur during gripping of the Staublis, as observed in testing (Figure 10). A rubber insert of 1/8 inch thickness when added to the left grip creates an inside radius equal to the outside radius of the RBE 19 Staubli. The rubber insert reduces point contact between the grip and Staubli, providing more friction for a stronger grip. In applying the rubber to the grip surface, the adhesive and or method used must ensure that the rubber does not delaminate from the grip, a common problem found during testing due to poor adhesive backing.

In reaching the goal of efficient manipulation of the Staubli fluid couplings, a final recommendation should be considered. Testing revealed that manipulating the RBE 06, or smallest, Staubli was achievable but difficult using the prototype grip geometry. Efficient manipulation of the RBE 06 Staubli might better be achieved by designing an end effector specifically for this task. An end effector designed specifically for the RBE 06 Staubli would use all of the same features as previously described. The primary differences would include a reduced length of the down beams, an optimized grip geometry, and smaller allowable offset in the compliance design.
Appendix A

a. Final End Effector Drawing Package
b. Prototype End Effector Drawing Package
Appendix B

Park Stand Drawing Package
Appendix C

Test Stand Drawing Package
Appendix D

Full DFMEA
Appendix E – Gantt Chart Project Schedule (MS Project)