DESIGN AND DEVELOPMENT OF AN AUTOMATED URANIUM PELLET STACKING SYSTEM

by

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Bachelor of Engineering, University of Ontario Institute of Technology, 2007

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

The Faculty of Engineering and Applied Science

Mechanical Engineering

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THE UNIVERSITY OF ONTARIO INSTITUTE OF TECHNOLOGY

June 2009

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Abstract

A novel design for an automated uranium pellet stacking system is presented. This system is designed to replace the manual method for stacking uranium pellets for CANDU fuel bundles that is currently used at Cameco Fuel Manufacturing in Port Hope, ON. The system presented is designed as a drop-in solution to the current production line at Cameco. As a result, there are constraints that prevent certain parameters from modification.

The three main goals of this system are to reduce worker exposure to radiation to as low as reasonably achievable, improve product quality, and increase the productivity of the production line. The proposed system will remove the workers from a position of having to handle the uranium pellets and physically place them on the stacks. While the natural uranium currently in production is not a major health risk for short-term exposure, the possibility of production of slightly enriched uranium bundles makes this system a real need. This system also removes the random pellet placement that the manual system uses by taking precise measurements using laser triangulation sensors. These measurements are used to determine which sizes of end pellets are required to complete the stack to within the specified tolerances. A final measurement is done to ensure the stack is within tolerance. All of this information is recorded and can be traced back to the stacks during quality inspection, which is a major improvement over the existing system. This single automated system will replace two manual stations, while increasing the total output production, thus eliminating pellet stacking as a bottleneck in the fuel bundle assembly process. Current production rates can be met by this single, automated station in two shifts per day, while the current manual process requires three shifts using two stations.

Test results of a proof-of-concept prototype indicate that the proposed design meets or exceeds all of the design requirements.
Dedication

This thesis is dedicated to my family and my beloved Korrinne. Without their support, this work would not have been possible.
Acknowledgments

Without the technical support of my advisor, Dr. Scott Nokleby, this work would have been impossible. I would also like to thank Cameco Fuel Manufacturing who provided the funding for this work. In particular I would like to thank Paul Knott and Dave Larkman who served as contacts with Cameco and provided information vital to this project. In addition, I would like to thank Gary Vale from Technical Measures Incorporated of Oshawa for providing services to this project. I would like to acknowledge the following undergraduate students who worked on different subsystems for this project: Brett Weir, Florentin von Frankenberg, Jeff Rembosz, Kannan Dorairaj, Samar Sheikh, and Hussam Malek.
# Table of Contents

Abstract ii

Dedication iii

Acknowledgments iv

Table of Contents v

List of Tables x

List of Figures xi

Nomenclature xvi

1 Introduction 1

1.1 Background ................................. 1
    1.1.1 Background on CANDU Reactors ............... 3
    1.1.2 Background on Uranium Fuel Manufacturing ........ 3
    1.1.3 Current Process of Stacking End Pellets ........... 5

1.2 Thesis Objectives ............................ 6
    1.2.1 Thesis Methodology ............................ 8

1.3 Summary of Contents ........................... 9

2 Requirements and Specifications of the System 10
2.1 Need Statement .................................................. 10
2.2 Problem Statement ............................................... 11
2.3 Functional Requirements ......................................... 12
  2.3.1 Opportunities ................................................. 13
  2.3.2 Assumptions .................................................. 14
  2.3.3 Constraints .................................................. 15
2.4 Physical Requirements ........................................... 15
  2.4.1 Opportunities ................................................. 16
  2.4.2 Assumptions .................................................. 17
  2.4.3 Constraints .................................................. 17
2.5 Additional Requirements ........................................... 17
2.6 Discussion of the Requirements ................................. 18
2.7 Summary of the Requirements ................................... 18
2.8 Functional Decomposition ......................................... 20
  2.8.1 Measurement Subsystem .................................... 21
  2.8.2 Pellet Placement Subsystem ............................... 22
  2.8.3 Work Tray Subsystem ....................................... 23
  2.8.4 End Pellet Handling Subsystem ............................ 23
  2.8.5 Material Tracking Subsystem ............................... 24
  2.8.6 Control Subsystem ......................................... 24
2.9 Development of the Specifications .............................. 24
  2.9.1 Functional Specifications .................................. 25
    2.9.1.1 Automated Pellet Stacking System .................. 25
    2.9.1.2 Measurement Subsystem .............................. 26
    2.9.1.3 Pellet Placement Subsystem ......................... 26
    2.9.1.4 Work Tray Subsystem ................................. 27
    2.9.1.5 End Pellet Handling Subsystem ..................... 27
2.9.1.6 Material Tracking Subsystem ........................................ 27
2.9.1.7 Control Subsystem .................................................. 28
2.9.2 Physical Specifications ................................................. 28
2.9.2.1 Automated Pellet Stacking System ............................. 28
2.9.2.2 Measurement Subsystem ........................................... 29
2.9.2.3 Pellet Placement Subsystem ...................................... 29
2.9.2.4 Work Tray Subsystem ............................................. 29
2.9.2.5 End Pellet Handling Subsystem ................................. 30
2.9.2.6 Material Tracking Subsystem .................................... 30
2.9.2.7 Control Subsystem ................................................. 31

2.10 Summary of the Specifications ......................................... 31

2.11 Quality Function Deployment ........................................... 32
2.11.1 Planning Matrix - Relating the Requirements to the Specifications 33
2.11.2 Correlation Matrix - Discussing how the Technical Specifications Support or Compromise One Another ........ 35

2.12 Summary ....................................................................... 36

3 Literature Review ............................................................ 38
3.1 Fuel Bundle Production Methods ....................................... 38
3.2 Measurement Technologies ............................................... 43
3.2.1 Contact Measurement Devices ................................. 44
3.2.1.1 Coordinate Measurement Machines ...................... 44
3.2.1.2 Transducers ......................................................... 46
3.2.2 Non-Contact Measurement Devices ......................... 47
3.2.2.1 3D Light Measurement ........................................ 47
3.2.2.2 Laser Triangulation Measurement ......................... 48
3.2.2.3 Doppler Measurement ........................................... 51
3.2.2.4 Differential Interferometer .................................... 52
3.3 Pellet Placement ........................................ 54
    3.3.1 Cartesian Robots ................................. 54
    3.3.2 Articulated Robots ............................. 55
    3.3.3 SCARA Robots ................................. 56
    3.3.4 Existing Cameco Technologies .................. 58
3.4 Material Tracking ..................................... 58
    3.4.1 Elecsys Corporation .......................... 60
    3.4.2 Escort Memory Systems ....................... 60
    3.4.3 Titan Tag ..................................... 60
3.5 Summary ............................................... 61

4 Concept Generation and Evaluation ..................... 62
4.1 Proposed Solutions to the Problem ................. 62
    4.1.1 Concepts for Measurement of the Stacks ...... 63
        4.1.1.1 Concepts for Compressing the Stacks .... 63
        4.1.1.2 Concepts for Measuring the Stacks ...... 65
    4.1.2 Concepts for the Work Tray Subsystem ...... 68
        4.1.2.1 Concepts for Indexing the Work Trays .. 68
        4.1.2.2 Concepts for Sorting and Storing the Work Trays . 70
    4.1.3 Concepts for the Pellet Placement Subsystem . 74
    4.1.4 Concepts for the End Pellet Handling Subsystem . 77
        4.1.4.1 Concepts for the End Pellet Unloading Subsystem . 78
        4.1.4.2 Concepts for the End Pellet Conveyor Subsystem . 81
        4.1.4.3 Concepts for Disposing of the Empty Trays .. 82
    4.1.5 Concepts for the Material Tracking Subsystem . 84
    4.1.6 Concepts for the Control Subsystem .......... 85
4.2 Concept Evaluation and Selection .................. 85
    4.2.1 Measurement Subsystem Concept Evaluation ... 85
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.1.1</td>
<td>Compression Subsystem Concept Evaluation</td>
<td>86</td>
</tr>
<tr>
<td>4.2.1.2</td>
<td>Measurement Subsystem Concept Evaluation</td>
<td>87</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Work Tray Subsystem Concept Evaluation</td>
<td>89</td>
</tr>
<tr>
<td>4.2.2.1</td>
<td>Work Tray Indexing Concept Evaluation</td>
<td>89</td>
</tr>
<tr>
<td>4.2.2.2</td>
<td>Work Tray Sorting and Storing Concept Evaluation</td>
<td>90</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Pellet Placement Subsystem Concept Evaluation</td>
<td>91</td>
</tr>
<tr>
<td>4.2.4</td>
<td>End Pellet Handling Subsystem Concept Evaluation</td>
<td>93</td>
</tr>
<tr>
<td>4.2.4.1</td>
<td>End Pellet Unloading Concept Evaluation</td>
<td>93</td>
</tr>
<tr>
<td>4.2.4.2</td>
<td>End Pellet Conveyor Concept Evaluation</td>
<td>94</td>
</tr>
<tr>
<td>4.2.4.3</td>
<td>Empty Tray Disposal Concept Evaluation</td>
<td>95</td>
</tr>
<tr>
<td>4.2.5</td>
<td>System Control</td>
<td>96</td>
</tr>
<tr>
<td>4.3</td>
<td>Chosen System Design</td>
<td>97</td>
</tr>
<tr>
<td>4.4</td>
<td>Remarks on the Selected Concept</td>
<td>100</td>
</tr>
<tr>
<td>4.5</td>
<td>Summary</td>
<td>101</td>
</tr>
</tbody>
</table>

5 Form Design and Analysis

<table>
<thead>
<tr>
<th>Sections</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Introduction to the System</td>
<td>104</td>
</tr>
<tr>
<td>5.2</td>
<td>Measurement Subsystem</td>
<td>106</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Measurement Subsystem Proof-of-Concept Prototype</td>
<td>110</td>
</tr>
<tr>
<td>5.3</td>
<td>Pellet Placement Subsystem</td>
<td>112</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Pellet Placement Subsystem Proof-of-Concept Prototype</td>
<td>116</td>
</tr>
<tr>
<td>5.4</td>
<td>Work Tray Subsystem</td>
<td>118</td>
</tr>
<tr>
<td>5.4.1</td>
<td>Work Tray Subsystem Proof-of-Concept Prototype</td>
<td>120</td>
</tr>
<tr>
<td>5.5</td>
<td>End Pellet Handling Subsystem</td>
<td>122</td>
</tr>
<tr>
<td>5.6</td>
<td>Material Tracking</td>
<td>127</td>
</tr>
<tr>
<td>5.7</td>
<td>Control Algorithm</td>
<td>127</td>
</tr>
<tr>
<td>5.8</td>
<td>Safety Guarding</td>
<td>131</td>
</tr>
<tr>
<td>5.9</td>
<td>Summary</td>
<td>132</td>
</tr>
</tbody>
</table>
6 Test Plan and Results

6.1 Measurement Subsystem ........................................ 133
   6.1.1 Measurement Repeatability ............................... 133
   6.1.2 Measurement Accuracy .................................. 135
   6.1.3 Compression Test ........................................... 137

6.2 Pellet Placement Subsystem .................................... 138
   6.2.1 Pick-and-Place Consistency ............................. 138
   6.2.2 Gripper Ability at High-Speed Motion ................. 140
   6.2.3 Gripper Pick-and-Place on a Full Tray ............... 141

6.3 Work Tray Subsystem ........................................... 141
   6.3.1 Indexing Accuracy ....................................... 141

6.4 Control Algorithm .............................................. 144

6.5 Summary .............................................................. 145

7 Conclusions and Recommendations for Future Work 148

7.1 Conclusions ........................................................... 148

7.2 Recommendations for Future Work ............................... 150

Appendices 157

A House of Quality 157

B Test Plan and Results 159

B.1 Measurement Repeatability Test ............................... 159
B.2 Measurement Accuracy Test .................................... 160
B.3 Pick-and-Place Repeatability Test .......................... 161
B.4 High-Speed Robot Test ......................................... 162
B.5 Indexing Accuracy Test ......................................... 163
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Cycle times</td>
<td>25</td>
</tr>
<tr>
<td>4.1</td>
<td>Compression Component Decision Matrix</td>
<td>87</td>
</tr>
<tr>
<td>4.2</td>
<td>Measurement Subsystem Decision Matrix</td>
<td>88</td>
</tr>
<tr>
<td>4.3</td>
<td>Work Tray Indexing Decision Matrix</td>
<td>90</td>
</tr>
<tr>
<td>4.4</td>
<td>Sorting and Storing Decision Matrix</td>
<td>91</td>
</tr>
<tr>
<td>4.5</td>
<td>Pellet Placement Subsystem Decision Matrix</td>
<td>92</td>
</tr>
<tr>
<td>4.6</td>
<td>End Pellet Unloading Decision Matrix</td>
<td>94</td>
</tr>
<tr>
<td>4.7</td>
<td>End Pellet Conveyor System Decision Matrix</td>
<td>95</td>
</tr>
<tr>
<td>4.8</td>
<td>Empty Tray Disposal Decision Matrix</td>
<td>96</td>
</tr>
</tbody>
</table>
List of Figures

1.1 Photo of fuel pellets before being placed into a stack (Courtesy Cameco) 4
1.2 Figure of a fuel bundle (Courtesy Cameco) 5

2.1 Relationships of the subsystems 21
2.2 Functional decomposition to show the flow of energy, material, and information through the process 22

3.2 Stack with different enrichments of uranium [1] 39
3.3 Bridge Style CMM machine [2] 45
3.4 Gantry Style CMM machine [3] 46
3.5 Transducer that is capable of taking linear measurements [4] 46
3.6 AR600 Laser Triangulation Unit from Acuity [5] 48
3.7 LAP Antaris S500 Measurement Unit [6] 49
3.9 Example of a cartesian robot [8] 55
3.10 Fanuc M-20iA, an example of an articulated robot [9] 56
3.11 Fanuc LR Mate 200iC/5L [9] 57
3.12 Example of a SCARA robot [10] 57
3.13 Cameco cartesian gantry system used for loading/unloading the grinders 58
4.1 Compression Concept 1-1 using two pneumatic pistons .......................... 64
4.2 Compression Concept 1-2a using a fixed wall to raise and lower ........ 64
4.3 Compression Concept 1-2b using two pneumatic pistons and two staggered, fixed, reference points ................................................................. 65
4.4 Measurement Concept 1-5 using two triangulation sensors ............... 67
4.5 Measurement Concept 1-7 using one triangulation sensor and a fixed reference point ................................................................. 68
4.6 Measurement Concept 1-8 using Doppler laser measurement unit ...... 68
4.7 Work Tray Concept 2-1 using the conveyor system ............................ 69
4.8 Work Tray Concept 2-2 involving the cart system ............................. 70
4.9 Geneva wheels used in Concept 2-3 .................................................... 70
4.10 Dual output sorting conveyor (Concept 2-4) ..................................... 71
4.11 Dual hopper on a single output conveyor (Concept 2-5) .......... 72
4.12 Work tray sorting concept for a raised conveyor (Concept 2-6) .... 72
4.13 Work tray sorting concept with a trap door and two tiered conveyors (Concept 2-7) ........................................................................... 73
4.16 Pellet placement Concept 3-1 involving one SCARA robot arm ...... 75
4.17 Pellet placement Concept 3-2 involving two SCARA robot arms .... 76
4.18 Pellet placement Concept 3-3 involving one FANUC LRMate 6-axis robot 76
4.19 Custom Gripper designs for pellet placement Concept 3-4, a) Carousel custom gripper design for pellet placement Concept 3-4a, b) Ferris wheel custom gripper design for pellet placement Concept 3-4b .... 77
4.20 Custom gripper able to hold two end pellets at a time .................... 78
4.21 Cartesian robot used in Concept 4-1 ............................................... 79
4.22 Individual gantry design for unloading end pellets trays (Concept 4-2) 80
4.23 Using a FANUC M-10iA robot to pick-and-place end pellets on the conveyors (Concept 4-3) .................................................. 80
4.24 End pellet placement Concept 4-5 showing a SCARA on a track . . 81
4.25 Single infeed conveyor with lanes for pellets (Concept 4-7) ........ 82
4.26 Tray disposal Concept 4-9 ................................................... 83
4.27 Tray disposal Concept 4-10 .................................................. 84
4.28 Final system concept with all components ............................... 97
4.29 Measurement system final concept ....................................... 98
4.30 Work tray sorting and storing final concept .............................. 99
4.31 End pellet unloading final concept ........................................ 99
4.32 Final end pellet unloading layout ....................................... 102
4.33 Final output layout with one hopper ................................... 103
5.1 Complete automated pellet stacking system ............................. 105
5.2 Measurement and compression system with third pneumatic unit for aligning the pellets on the trays ................................. 108
5.3 Setup of laser measurement units with the compression pistons .... 109
5.4 Photos of the proof-of-concept prototype for the measurement subsys-
tem, including (a) the main compression side, (b) the laser measure-
ment side, and (c) a system overview ....................................... 111
5.5 Compression valve block with two inputs for separate control of the grippers and the compression pistons ............................... 112
5.6 Pellet placement robot with the gripper attached to Joint 6 ........... 113
5.7 Pellet placement robot path from simulation .......................... 114
5.8 Teach Pendant from simulation software, used to program the robot . 115
5.9 Robot mounted over the workspace ...................................... 115
5.10 Platform designed to mount the robot over the output conveyor ... 116
5.11 Prototype gripper attached to the Epson robot for testing ........... 117
5.12 Pellet placement subsystem prototype setup .......................... 118
5.13 V-Belt design for the conveyor to ensure the belt stays straight [12] . 119
5.14 Slot sensor used for indexing the trays [13] ............................... 119
5.15 Index sensor mounted during testing ................................. 120
5.16 Index sensor mounted for the final design ............................. 121
5.17 Conveyor used to transport the end pellets into the reach of the pellet placement robot ................................. 123
5.18 Final end pellet unloading layout ................................. 124
5.19 Section of the belt used on the end pellet conveyors [14] ............. 124
5.20 Cover designed to ensure end pellets do not flip on their ends during pick-up ........................................ 125
5.21 Pellet Sensor mounted to the cover ........................................ 126
5.22 Cover and sensor mounted to an end pellet conveyor ................. 126
5.23 Flowchart of the control algorithm for the prototype, specifically for the measurement subsystem, the pellet placement subsystem, and the work tray subsystem ........................................ 128
5.24 Sequence of indexes based on the control algorithm ................. 130
6.1 Measurement repeatability test setup ................................. 134
6.2 Measurement accuracy test setup at the (a) measurement end and (b) compression end ........................................ 136
6.3 Test setup for the pick-and-place test .................................... 139
6.4 Test setup for the high speed robot motion test ......................... 140
6.5 Gripper pick-and-place on a full tray test setup ........................ 142
6.6 Test setup for the tray indexing test ....................................... 143
6.7 Graph showing the relationship of standard deviation of indexing vs. conveyor speed ........................................ 144
Nomenclature

ALARA  As Low As Reasonably Achievable

BWR  Boiling Water Reactor

CANDU  Canada Deuterium Uranium

CMM  Coordinate Measurement Machine

CSA  Canadian Standards Association

DI  Differential Interferometer

DOF  Degree-of-Freedom

JIT  Just-in-Time

PHWR  Pressurized Heavy Water Reactor

PWR  Pressurized Water Reactor

QFD  Quality Functional Deployment

RFID  Radio Frequency Identification

RIA  Robotics Industry Association

SLAPS  Stack Length Adjustment Pellets
Chapter 1

Introduction

1.1 Background

Cameco Corporation is one of the world’s largest producers of natural, low-cost uranium, accounting for 15\% of the world production from its mines spread across the globe. Cameco is also a leader in processing services required to produce fuel for nuclear power plants [15]. At the Cameco facilities in Port Hope, Ontario, much of the processing of uranium is done, including the manufacturing of fuel bundles for CANDU reactors. The current manufacturing process has a mix of automated and manual systems working together to turn uranium powder into pellets, which get placed in fuel rods, which form the basis of a fuel bundle.

In the production of these fuel bundles the uranium powder is pressed into solid pellets which are sintered and ground to the proper diameter. End pellets are produced with a slightly smaller diameter to allow for the placement of end caps on the fuel rods. There are three different lengths of end pellets, which are used to ensure the final stack length is within the required tolerances. Stack length adjustment pellets (SLAPS) are produced with the same diameter as standard pellets, but in the lengths of the end pellets. These SLAPS are used to adjust the length of a stack when the placement of
end pellets alone cannot meet the dimensional requirements of the stack.

The regular stack pellets are placed on trays, with 16 stacks of pellets on a tray and 28 pellets per stack before end pellet placement. These trays are placed in a storage area until they are measured and stacked with the appropriate end pellets and SLAPS. After this process, the pellet stacks are inserted into Zircaloy tubes and welded shut so they can be assembled into fuel bundles.

The major problem with automating this system is that each stack must be approximately 500 mm plus or minus a few milimeters, but each individual pellet has a nominal tolerance of ±0.5 mm. Therefore, with 30 pellets making up a stack, the sum of the tolerances for the individual pellets is much greater than the overall tolerance on the stack.

One method that could potentially reduce this problem is to re-evaluate the manufacturing process of the individual pellets in order to reduce the tolerances on them. However, the system requested by Cameco for this project was requested as a drop-in solution to their existing manufacturing line, so at this time, possible modifications for the manufacturing of the pellets will not be discussed.

Another problem with automating this process is the actual pellets. Once the uranium dioxide powder is sintered into the pellet shape, they become a ceramic-like material, which is very brittle. The pellets have to be handled with care throughout the fuel bundle assembly process in order not to damage them. The sintering process is done to significantly increase the density of the pellets and converts the powder to the ceramic material required. The overall shape of the pellet is retained throughout sintering, however voids and gaps are removed as the particles become the crystalline structure [16]. It is difficult to control the amount of shrinkage that will occur during sintering since it depends on the density of the green pellet (the pellet prior to sintering), as well as the pellets location in the sintering oven. Since the diameter of the pellets is required to be within tight limits, the pellets are ground to specific diameters after the
sintering process to ensure they are correct. Currently, there are no steps in place to rework the lengths of the pellets after the sintering process. Thus there is variation in the pellet lengths. Redesigning the manufacturing of the pellets or providing solutions to the length variation is not part of this thesis. The task of this thesis is, taking into consideration the length variance, design a system that can automatically stack the uranium pellets.

1.1.1 Background on CANDU Reactors

The Canada Deuterium Uranium (CANDU) reactor is a Canadian-designed power reactor of the Pressurized Heavy Water Reactor (PHWR) type that uses heavy water for both the moderator and coolant and natural uranium for fuel [17]. CANDU is the most efficient of all current reactors in terms of uranium consumption as it uses approximately 15% less uranium than a pressurized water reactor for each megawatt of electricity produced. By using natural uranium, it makes the manufacturing of fuel easier due to the supply of natural uranium available [17]. Cameco is one of the world’s largest producers of natural uranium, and is one of two companies responsible for the production of fuel bundles for the CANDU reactors in Canada, the other being GE Energy [15].

1.1.2 Background on Uranium Fuel Manufacturing

Uranium is one of the most abundant elements found in the Earth’s crust, however concentrated uranium ores are found in just a few places, usually in hard rock or sandstone [15]. Uranium deposits suitable for mining are found all over the world, but the largest deposits are in Australia, Kazakhstan, and Canada, with high-grade deposits being found only in Canada. In Canada, uranium mining began in 1931 at Great Bear Lake in the Northwest Territories. Today, Cameco dominates the uranium market as the majority owner of the world’s largest and highest-grade uranium
deposits, most of which are located in Saskatchewan [15]. After the uranium ore is mined, it undergoes a series of operations in order to make it usable for nuclear fuel. After mining, the uranium ore is first milled to produce the concentrate known as yellowcake. It is then refined and converted into either uranium dioxide (UO$_2$) for heavy water reactors or uranium hexafluoride (UF$_6$) for light water reactors. If the uranium requires enrichment, it is done at this stage. Enrichment is the process that increases the Uranium-235 concentration from 0.7%, which is its natural state, to 3-5% [15]. In the case of the CANDU reactors, UO$_2$ is used to produce the pellets. The UO$_2$ arrives in a powder form, where it is pressed into pellet-form and sintered in a furnace to form ceramic pellets. A typical pellet weighs about 20 g and can generate as much electricity as 3.5 barrels of oil, 17,000 cubic feet of natural gas, or 1,780 pounds of coal. Figure 1.1 shows a picture of uranium pellets after having been processed.

Once the pellets have been formed, they are placed on trays that hold 16 rows of stacks. Each stack has 28 regular pellets plus two end pellets. These end pellets have a slightly smaller diameter in order to allow for assembly of the tubes. Once the end pellets are placed, the stacks are placed in zircaloy tubes and are sealed by welding end caps onto the tubes. These tubes are then placed in bundles using pre-manufactured spacers and ends so that the tubes form the structure of a fuel bundle. For the PHWR, each fuel bundle has 37 tubes and they are arranged in the configuration as shown in Figure 1.2.

Figure 1.1: Photo of fuel pellets before being placed into a stack (Courtesy Cameco)
1.1.3 Current Process of Stacking End Pellets

The process of placing end pellets on the stacks is currently an entirely manual process. Three different end pellet lengths are used. The stacking operation involves an operator placing one size of end pellet on all 16 stacks, taking measurements with a Go/No-Go gauge, and then changing end pellet sizes should the final stack length not fit within the tolerances. Should there be no combination of the three end pellet sizes that would allow the stack to meet the final stack length tolerance, then the operator would replace regular stack pellets with SLAPS to change the length of the stack. These SLAPS can be placed anywhere in the stack except at the end or next to an end pellet.

There are a few issues with this manual method that are addressed in this thesis. First, the trial-and-error method of placing the end pellets is inefficient and can lead to errors in stack length, which can cause problems further down the production line. In addition, in the current arrangement, it is possible for an operator to mix-up end pellets with SLAPS, possibly resulting in SLAPS being placed on the ends or end pellets being placed in the wrong parts of a stack. Either scenario can cause a bundle
to fail. An automated system would reduce or eliminate the possibility of errors.
Second, having a person physically moving and placing pellets on the trays poses a
health risk to operators due to radiation exposure. With the possibility of production
of bundles using slightly enriched uranium fuel coming in the future, it is important
to limit human exposure. An automated system would reduce worker exposure. This
system would help keep worker exposure “as low as reasonably achievable” (ALARA),
a nuclear industry requirement.
Third, Cameco currently has two manual stacking stations that produce a total of
5,120 stacks per eight hour shift. An automated system would be able to exceed that
production, while eliminating the need for two stations.

1.2 Thesis Objectives

The need for an automated end pellet stacking system was expressed by Cameco to
integrate into their existing production line. This system is designed to be dropped
into the existing line, and as a result there are certain parameters that cannot be
altered.

There are three main goals for this system:

1. Reduce worker exposure
2. Improve quality
3. Increase productivity

The first goal is very important due to the industry regulations on worker exposure
to uranium per year. Although the natural uranium currently in production is not
a major health risk for short-term exposure, Cameco is considering the possibility of
producing a slightly enriched compound of uranium, making an automated system
more desirable. It is critical to keep radiation exposure ALARA.
The second goal stems from flaws in the bundles as a result of the manual stacking process. With the manual process, the pellets are placed randomly and then measured with a gauge. No measurement numbers are ever recorded, and measurements may not always be accurate. Also, with the inclusion of SLAPS in a stack, workers have been known to use SLAPS instead of end pellets, which causes problems when the end caps are welded on to the zircaloy tubes. With an automated system, the possibility of mixing SLAPS with end pellets can be eliminated. In addition, measurements of every stack could be recorded into a database to be used for quality control. There would also be a record of each lot of uranium that went into each stack, which is important for bundle recalls and quality control.

The third goal is fairly simple to see: increased productivity equals increased profit. This single automated system is designed to replace two manual stations, while increasing the output of the two stations and eliminating the pellet stacking station as a bottleneck in the fuel bundle assembly process. Currently, the manual stations are producing 5,120 stacks per day, where a day has three, eight hour shifts. The goal of the automated station is to increase output of this system by a minimum of 1.5 times. This would keep the concept of just-in-time (JIT) in place between the automated stacking station and the end-cap welding stations.

Additional design constraints that are not part of the main problem are also present. As mentioned above, the current manual stacking method uses two stations to achieve the output that Cameco is currently producing. One automated system will be required to replace both manual stations, and the overall footprint of the automated station should be less than what is currently used by the manual method. As previously stated, the output of this single automated system should also exceed the output of the two manual stations.

There are also certain areas that cannot be changed to fit this system. Since this system is designed to be placed in the current manufacturing environment, the man-
ufacturing of the pellets, the transportation of the pellets throughout the plant, and the materials that can be used to contact the pellets must not be altered. The materials that can be used to contact the uranium are limited to stainless steel and chrome plated steel. At no point can aluminum or plastics contact the uranium.

1.2.1 Thesis Methodology

In order to develop a solution to this problem, a formal engineering design process was used. At the outset, a meeting was arranged between Cameco and the team at UOIT. In this meeting, a clear understanding of what the Cameco team was looking for was developed and a list of customer requirements for the project was generated. From the list of customer requirements, the specifications were developed to meet these requirements through Quality Functional Deployment (QFD) and the assistance of design tools such as functional decomposition and the House of Quality. Once these specifications had been determined and discussed with the Cameco team, a set of feasible working concepts were developed for each of the required subsystems, and these concepts were refined through multiple discussions with the UOIT and Cameco teams. Once a set of refined concepts was presented, a series of selection methods including decision matrices and Go/No-Go criteria were used to determine the best concept for each subsystem. At this point, each of these concepts was analyzed in a global context to determine the best combinations to design the overall automated pellet stacking system.

Once the final form design was made, final dimensions, tolerances, material selection, and standard components needed were determined and purchased in order to construct a physical prototype. The design was created using the 3D modeling software Solidworks 2008 so that analysis could be performed on critical parts and components, and motion studies could be done where necessary.

\[1\text{Discussion with CFM Personnel}\]
Once the analysis of the system had been completed and it was confirmed that the system would operate as designed, the physical prototype was built and testing was conducted to demonstrate that the requirements of the design were met.

1.3 Summary of Contents

In Chapter 2, the requirements from the customer are defined and the specifications are developed. This information is used to further define the problem and provide a basis to develop concepts for the solution. Chapter 3 presents a review of literature related to this topic. Chapter 4 describes the concepts that were developed in order to solve the problem. In this chapter a thorough analysis of each concept is performed and final concepts are determined for each subsystem. Chapter 5 describes in detail the final system design and presents engineering analysis of the design. Chapter 6 presents the results from testing the physical prototype in a lab setting. Chapter 7 finishes the thesis with conclusions and a discussion of potential future work and integration with the existing line at Cameco.
Chapter 2

Requirements and Specifications of the System

This chapter presents the requirements as determined by Cameco. The specifications are developed and through Quality Functional Deployment (QFD) and functional decomposition these specifications are analyzed and the system is broken down to its base functions. A House of Quality is presented and discussed in this chapter and target values are assessed to the specifications in order to have parameters to design to.

2.1 Need Statement

In any industry, safety is always a concern. In the nuclear industry, safety is the overriding factor that controls every detail. In the case of building the fuel bundles, each stack needs to be built to very tight specifications, and needs to be done so in a timely fashion. For humans, overexposure to elements such as uranium can lead to serious health complications later in life. The idea of automating the process of manufacturing fuel bundles helps to reduce human exposure to these materials, as well as increase the overall speed and accuracy of the system. The system not only needs to
have a fast cycle time, but must also be accurate to within sub-millimetre resolution. If the system is not accurate to within the required tolerances, and these bundles are placed within a nuclear reactor to generate power, the bundle may fail which could lead to catastrophic results. The current process that is in place is effective, however by automating the process worker safety, product quality, and productivity can be improved.

There is also a need to verify that the end pellets that are being placed are actually end pellets, and not the SLAPS. To be sure of this, an idea is proposed to increase the types of end pellets from three to five, and eliminate the need for SLAPS altogether.

2.2 Problem Statement

There are several problems that arise when developing any automated system, including component selection, shielding of sensitive components, overall layout of the work zone, and safety constraints. There are many such safety constraints that will need to be examined and observed when implementing this system, including guards around the work cell that abide by the six and six principle; the guard must be six inches off the floor, and six feet high. There are many other safety standards that will be considered throughout the design of this system in order to meet the quality standards of Cameco. Another problem that will arise in the automation of this system is the shielding of the components to protect them from the uranium dust that is in the facility. Companies such as FANUC Robotics currently supply this shielding for their robotic components, but for the measurement systems that will be required, this will need to be examined.

With regards to the layout of the work zone, the current setup works well for the manual process when there is a worker unloading the trays from the conveyor as they need them, placing them on the station, and picking which pellets they need. A new
system layout will need to be designed in order to allow for the automatic indexing of trays, the sorting of trays where certain stacks are outside the tolerance limits, and the storage of the end pellets that are available for automated pick-and-place procedures.

Throughout the entire design process, safety will be the number one concern, and will be considered at every step in order to ensure that the process is indeed being made safer, not harmful to the workers in the plant or the environment.

To have a successful system, the following three goals must be met:

- Reduce worker exposure to uranium
- Reduce number of errors that occur
- Increase productivity

Another problem with automating this system is that each pellet has a nominal tolerance of $\pm 0.5$ mm, and with 30 pellets making up a stack, the sum of the tolerances for the individual pellets is much greater than the overall tolerance on the stack. As discussed in Chapter 1, one way to correct this would be to tighten tolerances on the individual pellets and have greater control over the process. There are various difficulties with this and, as such, the system requested by Cameco for this project was requested as a drop-in solution to their existing manufacturing line. It is also important to note that the trays that the uranium pellets are transferred through the plant on must remain in use and cannot be altered. There are other constraints that are a result of this being a drop in solution, and they will be discussed in this chapter.

2.3 Functional Requirements

The main functions of this system are as follows:
• Index the tray so that it is in the proper position for measuring the first stack. There are 16 stacks in total that need to be measured per tray.

• Accurately measure the stack length.

• Determine if the current stack is acceptable.

• If at least one stack on a tray is unacceptable, flag the tray.

• If acceptable, determine the proper combination of end pellets from the available selection.

• Pick the proper end pellets and place them on the ends.

• Measure the final stack length of each stack to ensure it is within tolerance.

• Record the tracing data for the pellets that were chosen for each stack.

• Index the tray to the next stack. If the tray is complete and has not been flagged, index the tray to the pellet insertion station. If the tray has been flagged, move the tray to the storage area for manual rework.

These requirements all need to be met in order to have successful completion and implementation of this system. There are many different methods that can be used to achieve the end result that meet all of these requirements, therefore an analysis of the opportunities, assumptions, and constraints is performed.

2.3.1 Opportunities

Certain opportunities are available during the design of this system in order to achieve the desired functionality. These opportunities result from the development of past technology to a point where it can be used in an innovative fashion to complete the tasks in this project. For the automation of the system, these opportunities include:
• An automated indexing system. Trays will move to the measurement system, then shift accordingly to allow measurement of the stacks. This allows the measurement system to remain stationary.

• The design and deployment of a hopper system to hold trays that are awaiting final pellet placement and measurement.

• The use of a robot to perform the pick-and-place of the pellets.

• The design of an end effector for the pick-and-place system to perform the operation accurately and expediently.

For the measurement aspect of this project, different technologies can be examined for use, including:

• Laser measurement technology to determine overall stack length and diameter. This can be done by using a differential interferometer or a laser micrometer.

• Gauge measurement by placing the gauge on the end effector of the pick-and-place system.

• Optical measurement using existing technologies, or through developing a new technology that is customizable to this project.

Additionally, SLAPS can be removed from use, and in their place the number of different sizes of end pellets can be increased from three to five. By adding one size larger and one size smaller, the system will be able to account for the loss of SLAPS and be able to accommodate the majority of stacks.

2.3.2 Assumptions

When designing this system, there are a few assumptions that can be made regarding the layout prior to the stacks arriving at the end pellet station.
• Pellet quality will be checked before being loaded into the system.

• The system will not require SLAPS. If the stack is not acceptable, it will be removed for manual inspection.

• The hoppers where the end pellets and stacks are located will be loaded manually.

With these assumptions, the project specifications can be narrowed down to focus on the automation and measurement of the end pellet process.

### 2.3.3 Constraints

There are certain constraints when designing this system due to the nature of the industry this system will be used in. With the presence of uranium in the plant, any robots that are used on the system and any electrical components will need to be properly protected against any uranium dust that may get inside the components. Another constraint of this project will be the accuracy of the measurement technology chosen. With different methods and equipment chosen, the resolution and system accuracy varies, so choosing a system that meets the required tolerances of the stacks, and can perform the measurements at a high rate of speed is important. Finding the balance between the two requirements is something that will be examined throughout the course of this design.

### 2.4 Physical Requirements

Along with the functional requirements of the system, there are also several physical aspects that need to be examined. They are as follows:

• Reduce the overall footprint of the station.

• Properly guard all equipment to prevent injury.
• Eliminate the effect of the equipment on surrounding environment (noise, etc.).
• Eliminate vibrations of the station so that accurate measurements can be taken.

These are important aspects of the system because they will allow for a smooth transition from the current mode of operation to the automated method without requiring a major redesign of other current practices within the work area.

2.4.1 Opportunities

Opportunities for the physical aspects of this project include reducing the overall size of the station, reducing the number of stations needed to produce the output, and eliminating the affect of the equipment on its surroundings, which includes vibrations and other interference. There are many ways to achieve these physical requirements, such as:

• Reduce the number of moving parts to minimize vibrations.

• Properly mount and shield the pick-and-place system so it does not cause vibrations and is not affected by uranium dust.

• Properly mount and shield the measurement equipment.

• Reduce the cycle time for the operation so that the number of stations can be reduced from two to one while increasing the overall productivity of the system.

Another major factor that affects the opportunities for physical design of the system is safety. The system will be guarded appropriately as per the guidelines from the Robotics Industry Association (RIA)\(^1\) and the Canadian Standards Association (CSA), specifically standards Z432: Safeguarding of Machinery [18] and Z434: Industrial Robots and Robot Systems - General Safety Requirements [19].

\(^1\)http://www.robotics.org
2.4.2 Assumptions

Within the plant, an assumption can be made that there will be enough space to house this station. It can also be assumed that before the system is to be operated, it will pass all safety standards as set out by the RIA, CSA, and nuclear regulatory bodies. In the event that something is not up to code, the system will be immediately shut down and the problem will be resolved. For this project, it will also be assumed that the appropriate power and air supplies will be available at the work cell in order to run the automated system effectively. In the event that power and/or air pressure is not present due to a failure, the system will not be operational until the power and/or air pressure is restored.

2.4.3 Constraints

This project is constrained by the safety measures that must be met in order to use automation in this industry. Also, the amount of floor space available within the plant will constrain the overall size of the station. Currently, there are two stations performing this operation. With the goal of reducing the number of stations to one, it would be preferred if this one station was smaller than the two current stations combined.

2.5 Additional Requirements

In addition to the functional and physical requirements mentioned above, Cameco has set out some additional requirements for this system. The main requirement is that the system must be able to be placed into the existing line, which has a mix of manual and automated processes. This means that all equipment must be appropriately guarded in accordance with the CSA standards Z423 and Z434 as previously mentioned. Cost was also a concern to the Cameco group, and a budget for the system was set.
In order to keep the project on budget existing technologies were used as much as possible.

It was also requested that any components that were standard off-the-shelf be from the same manufacturers that are currently used by Cameco, where possible. This would include using FANUC robotics, Allen-Bradley controllers, and Norpak Conveyors where available. If Cameco’s current suppliers could not meet the demands of this project, then external suppliers would be consulted.

2.6 Discussion of the Requirements

The design of the automated pellet stacking station will require a system that reduces the current amount of floor space taken by this operation, increase the output of the station on a per shift basis, and accurately measure the length of the stacks before and after end pellet placement to ensure the high level of quality that is associated with Cameco is being met. Through the entire project, safety will be a main concern and all equipment will be guarded as per the guidelines proposed by the RIA and CSA, as well as shielded from any potential harmful materials in the plant, such as uranium dust. It is proposed that any equipment used be from the current suppliers used by Cameco unless a specific product is not available. In this case, research will be conducted to determine the best course of action and company to approach regarding this equipment.

The additional requirements are a direct result from meetings with the Cameco design team and every attempt will be made to satisfy these requirements.

2.7 Summary of the Requirements

From the previous sections, the following list of requirements is developed:
• R1: Index the tray so that it is in the proper position for measuring the first stack. There are 16 stacks in total that need to be measured per tray.

• R2: Accurately measure the stack length.

• R3: Determine if the current stack is acceptable.

• R4: If at least one stack on the tray is unacceptable, flag the tray.

• R5: If the stack is acceptable, determine the proper combination of end pellets from the available selection.

• R6: Pick the proper end pellets and place them on the ends of the stacks.

• R7: Measure the final stack length of each stack to ensure it is within tolerance.

• R8: Record the tracing data for the pellets that were chosen for each stack.

• R9: Index the tray to the next stack. If the tray is complete, index the tray to the pellet insertion station.

• R10: Reduce the overall footprint of the station.

• R11: Properly guard all equipment to prevent injury.

• R12: Eliminate the effect of the equipment on surrounding environment (noise, etc.).

• R13: Eliminate vibrations of the station so that accurate measurements can be taken.

• R14: The system must be able to be placed into the existing line.

• R15: Minimize the cost of the system.

• R16: Try to keep consistency with the suppliers currently used by Cameco.
These requirements will be used in the development of specifications and it will be ensured that all of these requirements will be met in this system.

### 2.8 Functional Decomposition

The overall goal of this project is to develop an automated stacking system to place end pellets on stacks of uranium pellets used in the manufacturing of fuel bundles. With this goal in mind, several subsystems can be developed by analyzing the customer requirements and decomposing the functions required in the system. In this section, the project is broken into its basic functions for each subsystem in order to develop concepts that will be feasible and meet the customer requirements. Each subsystem must interact with the others in the overall system to achieve an optimal design. The automated pellet stacking station is decomposed into the following subsystems:

1. Measurement Subsystem
2. Pellet Placement Subsystem
3. Work Tray Subsystem
4. End Pellet Handling Subsystem
5. Material Tracking Subsystem
6. Control Subsystem

Each of these subsystems can be broken down further into the functions required for each subsystem to operate properly and efficiently. The relationship of these subsystems, as well as the decomposition of the subsystems into their primitive functions, is shown in Figure 2.1 and discussed in depth in the following sections.

The flows of energy, material, and information are also analyzed in order to understand the effects of each function on this system. For this, the end goal of placing end pellets
on each stack of the tray was considered, and Figure 2.2 shows the flow of material, energy, and information through this process.

2.8.1 Measurement Subsystem

The measurement subsystem will be used to determine the length of the stack prior to end pellet placement, as well as to confirm the final stack length. In this subsystem, there is a degree of accuracy that must be maintained in order to ensure the quality of the stacks. The measurement system will take measurements before and after end pellet placement, as required by the customer. The initial measurement is used to determine which end pellets are required to meet the stack dimensions, while the second measurement ensures the pellets that were placed are correct and the stack meets the overall dimensional requirements. An additional part to this system is the stack compression device. This device is used prior to each measurement in order to...
ensure there are no gaps in the stack. Any gaps that are present in the stack will return false measurements in the system, which may lead to problems with the fuel bundle. This system is the cornerstone of the automated pellet stacking system. The success of this system depends on the effectiveness of the compression system and the accuracy of the measurement of the stacks to ensure the proper pellets are placed on the stacks.

### 2.8.2 Pellet Placement Subsystem

The pellet placement subsystem will require the use of a mechanism to place the appropriate end pellets at the end of each stack. The mechanism to be designed must be able to hold the size and shape of the different end pellets without causing any damage. The functions of the pellet placement subsystem include picking up the required pellet from a designated place, transferring it to the end of the current stack, and placing it on the tray. This is a subsystem that may pose a bottleneck in the
process, which will affect the overall productivity of the pellet stacking system.

2.8.3 Work Tray Subsystem

The work tray subsystem is required to maneuver the trays to which end pellets are added, herein referred to as work trays, throughout the system. Within this subsystem, designs are required for a work tray indexing system, a method to sort the trays in the event that a stack cannot be completed with the end pellets available, and a storage device for the trays both before and after the stacking process. The work tray indexing system is used to accurately position the work tray in the required spot for measuring the stacks. For storage of the trays, Cameco currently has a design for a hopper that is manually loaded and will place trays on a conveyor to be brought into the system. This design will be looked at during the analysis of this subsystem, and modifications may be suggested in order to integrate this design into the work tray subsystem.

2.8.4 End Pellet Handling Subsystem

This subsystem has three components that branch from it: handling the trays of end pellets, placement of the end pellets in an area where the pellet placement subsystem can access them, and removal of the empty end pellet trays once all the pellets have been used. The end pellet trays are initially stored in some area of the system, and as they are needed, would be called into the system. The end pellet tray handling portion of this subsystem is required to bring these trays from their storage location to an area where the end pellet placement portion of this system can operate. The end pellet placement portion of this system will take the end pellets and maneuver them to an area where they can be placed on the work trays. Once the end pellet tray is empty, the tray is to be extracted from the system and sent back to a loading station.
2.8.5 Material Tracking Subsystem

This subsystem is required by the customer in order to trace what lots of uranium have gone into which stacks. If there is a problem discovered with a certain lot after the pellets have been placed, this system will be able to determine which fuel bundles include the affected uranium, thus enabling the ability to recall the bundles. This subsystem is not just present in the automated pellet stacking system, but would be implemented throughout the automated line. The information on each tray is required to be stored in a central location where it can be accessed by quality control supervisors as well as engineers and technicians when required. The basic functions of this system include the ability to read the information from the end pellet trays, store it in a central location, and write information to the work tray database when a specific lot of uranium is added to the work tray.

2.8.6 Control Subsystem

The control subsystem is the brain of the system. This unit will govern the overall operation of the preceding subsystems to ensure that they work together to achieve the proper functioning of the automated pellet stacking system. The functions for this subsystem include the control of the measurement subsystem, pellet placement subsystem, work tray subsystem, end pellet handling subsystem, material tracking subsystem, and all of the functions that each of these subsystems require.

2.9 Development of the Specifications

From each of the subsystems presented, the functional and physical specifications can be developed to further analyze the concepts and perform Quality Functional Deployment (QFD) [20] of the system. These specifications must be developed to meet all of the customer requirements.
Table 2.1: Required cycle time based on the desired system outputs

<table>
<thead>
<tr>
<th>Stacks per shift</th>
<th>Cycle Time</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s/tray</td>
<td>s/stack</td>
</tr>
<tr>
<td>5,120</td>
<td>81.0</td>
<td>5.1</td>
</tr>
<tr>
<td>6,000</td>
<td>69.1</td>
<td>4.3</td>
</tr>
<tr>
<td>7,000</td>
<td>59.2</td>
<td>3.7</td>
</tr>
<tr>
<td>8,000</td>
<td>51.8</td>
<td>3.2</td>
</tr>
<tr>
<td>9,000</td>
<td>46.1</td>
<td>2.9</td>
</tr>
<tr>
<td>10,000</td>
<td>41.5</td>
<td>2.6</td>
</tr>
<tr>
<td>10,240</td>
<td>40.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.9.1 Functional Specifications

The functional specifications are used to provide the customer requirements with metrics relating to the function of the system as a whole, as well as the individual subsystems.

2.9.1.1 Automated Pellet Stacking System

Each of the subsystems presented in Section 2.8 make up the automated pellet stacking system for this project. As stated, the current manual system produces 5,120 stacks in an eight hour shift. Table 2.1 shows a breakdown of the required cycle times of the system in order to achieve different outputs of the system. In this table, the cycle time of seconds per tray begins when the tray is removed from storage and has entered the system and ends when the last stack has been completed and the next tray is coming into the system, while the current tray is moved to storage. It is desired that this station produce a 230 bundle equivalent of stacks per day, which is 8,510 stacks per day. The breakdown in Table 2.1 shows the cycle times per eight hour shift with a 10% downtime. The plant currently runs three eight hour shifts per day, so if 8,510 stacks must be done over the three shifts, then the cycle time per stack would be 9.1 seconds per stack. To achieve the same output in one shift, the required cycle time is 3 seconds per stack, and in two shifts, the cycle time required is 6.1 seconds.
2.9.1.2 Measurement Subsystem

The measurement subsystem is required to take fast and accurate measurements that can be used to determine the end pellets required to complete the stack, and also to ensure the final stack length is within the required tolerances. Due to the tight tolerances on the overall stack length, the resolution of the measurement subsystem should be at least 0.001 mm, which is sufficiently smaller than the tolerance on the stacks. The subsystem is also required to interface with the control subsystem in order to pass the measurement information to the other subsystems. The measurement portion of this subsystem should be able to obtain an accurate measurement reading for the stack length at a rate of at least 50 measurements per second in order to meet the required cycle times.

The other part of the measurement subsystem is the compression mechanism that will ensure that there are no gaps in the stack during measurement. In order for this compression mechanism to move an entire stack of pellets, it requires a minimum of 5 N of force provided from one end of the stack. This force must be applied to the pellet in such a way that it will not damage the pellets or jar the pellets out of the groove on the work tray.

2.9.1.3 Pellet Placement Subsystem

The pellet placement subsystem is required to pick the pellets from a designated holding area and place them on the appropriate end of the stack. It must ensure that each end of the stack receives exactly one end pellet, and that the pellets are not damaged in any way. The system designed for the pellet placement must be able to carry at least 2 kg of payload and maintain a cycle time 0.5 s from the picking point of the end pellets to the end of each stack, totaling 1 s of operation per stack.
2.9.1.4 Work Tray Subsystem

The main function of the work tray subsystem is to transport the trays from storage, through the system, and sort the completed trays as to whether they were completed or not. Any trays that have stacks which could not be solved by any combination of end pellets provided would be moved to a separate storage area where it can be manually reworked. In the indexing area of this subsystem, the distance between the centres of the stacks on a tray is 39 mm. To ensure accuracy of the end pellet placement, the stacks should be indexed precisely. Each work tray, when fully loaded weighs 10 kg, and the speed at which it moves through the system will depend on the desired output of the system, as shown in Table 2.1. When the trays are complete, they will come out of the system, be sorted, and stored until the next step in the manufacturing process. Once the tray has had all the end pellets placed, the next tray can begin to proceed through the subsystem. This is another area that will help to reduce the cycle time by queuing the work trays.

2.9.1.5 End Pellet Handling Subsystem

For this subsystem, the main functional requirement is that it brings the end pellets into a position where they can be handled by the pellet placement subsystem. This has two components within it: the handling of the trays; both bringing them into the system and removing the empty trays, and the handling of the end pellets; ensuring they are placed within the reach of the pellet placement subsystem.

2.9.1.6 Material Tracking Subsystem

The purpose of a material tracking subsystem is to track what batches of uranium go onto which tray. This is important for any recalls that may occur. There is no function of this subsystem that will affect the functional operation of the overall system; however, this is still a vital part of the overall manufacturing process. This
system must read and write data to the trays and log all communication on a central server. This can be done as a multi-tasked step and will not affect the overall cycle time of each tray.

2.9.1.7 Control Subsystem

The control subsystem is a vital part to ensure proper operation of the overall system. This program handles all aspects of the system, including executing measurements, calculating the pellets required, and controlling the pellet placement subsystem, the end pellet handling mechanisms, the work tray subsystem, and the material tracking subsystem. All these aspects are controlled here and are required to work in tandem to complete each tray in the required time.

2.9.2 Physical Specifications

The physical specifications are used to provide the customer requirements with metrics relating to the physical aspects of the system as a whole, as well as the individual subsystems.

2.9.2.1 Automated Pellet Stacking System

The overall system will replace the two manual stations that currently exist at Cameco. It is desired that this automated system use less space than the two current stations, and that it fit inline with the new automated manufacturing line being prepared, in a 3 m by 5 m area of floor space. The height is only restricted by the ceiling of the factory; however, the guards and safety shielding that must be placed will also affect the overall layout of the system. All of the components introduced must be placed within this system and must not collide with each other during operation.
2.9.2.2 Measurement Subsystem

For the measurement subsystem, it is desired that the measurement device be small enough that it will not impede the area needed to maneuver the pellets and trays through the system. The measurement system needs to be mounted independent of the moving parts of the system in order to eliminate vibrations in the system, and ensure the accuracy of the measurements. The measurement device should be able to operate in standard room temperatures (0-40 °C) and have the ability to measure the length quickly and accurately.

For the compression component of this subsystem, it requires a device that will compress the stacks with a minimum of 5 N of force while not damaging the pellets. It must also work fast enough in order to keep the cycle time low. The cycle time for the compression component should be minimized with a target of 0.5 s to compress one stack.

2.9.2.3 Pellet Placement Subsystem

With the pellet placement subsystem, the physical reach of the mechanism and the payload capabilities are very important. The selected mechanism to place the pellets on the work trays should have a minimum reach of 800 mm in order to reach each side of the work trays from a stationary position, and should support a minimum payload of 2 kg. Due to the nature of the environment this subsystem is in, the pellet placement mechanism, as well as any other components should be properly shielded to protect against uranium dust that can break down gears and motors.

2.9.2.4 Work Tray Subsystem

The work tray subsystem will require a fast but accurate drive, as previously discussed in the functional breakdown. The mechanisms in this subsystem must be able to support the weight of a fully loaded tray, which is 10 kg. While moving the tray
though the system, it must not disturb the layout of the pellets on the tray, which
will create extra work for the compression component during measurement, ultimately
slowing the cycle times. In this subsystem, speed and accuracy need to be balanced
in order to achieve the desired cycle times.

2.9.2.5 End Pellet Handling Subsystem

The tray handling portion of the end pellet handling subsystem must be able to
support the weight of a fully loaded end pellet tray, which is roughly 10 kg. The
mechanisms must be able to accurately move and support this weight during oper-
ation. The system must also be able to transfer the trays from the storage area to
the loading area in a way that will not increase the overall cycle time of the system.
For handling of the actual end pellets, the pellets must be handled with care in order
to avoid damaging them. Any mechanism that is used to handle the pellets requires
clean room protection and should be fast, accurate, and position the pellets within
the reach of the pellet handling subsystem.

2.9.2.6 Material Tracking Subsystem

The main physical requirement is that a reader be present in the system to read
the information from the trays. The reader should be linked to the central server
where the information will be stored. Again, this is not a subsystem specific to the
automated stacking project, but something that will be implemented throughout the
entire line. The readers should be small enough that they will not affect the other
subsystems, and have a minimum transmission range of 0.5 m so the exact positioning
of the readers is not a critical component in the system.
2.9.2.7 Control Subsystem

A physical controller will be required at this station in order to execute the different operations at the appropriate time. This controller should have a sufficient number of input/output (I/O) ports, as well as multiple RS-232 serial communication ports, and an Ethernet communication port to link to the central servers currently in place at Cameco.

2.10 Summary of the Specifications

From the previous section, the following list of specifications is developed:

- S1: Minimize measurement resolution to 10 µm.
- S2: Minimize the cycle time according to Table 2.1.
- S3: Maximize production per eight hour shift to double the current output to 10,240 stacks per day.
- S4: Minimize the overall station size to fit within a 3 m by 5 m area of floor space.
- S5: Maximize the measurement rate to 50 measurements per second.
- S6: Compression component force of 5 N minimum.
- S7: Pellet handling mechanism minimum payload of 2 kg.
- S8: Minimize pellet handling mechanism cycle time to 0.5 s.
- S9: Repeatability of the work tray indexing component within 0.1 mm.
- S10: Work tray indexing component supports a load of 10 kg.
- S11: Pellet placement mechanism reaches a minimum of 800 mm.
- S12: Maximize components that are protectively sealed to 100%.

- S13: Maximize the transmission range of the material tracking device, minimum 0.5 m.

- S14: 100% of the system is safety-proofed and meets all safety standard requirements.

These specifications are required to meet and quantify the customer requirements. Through the use of QFD, specifically the House of Quality, it can be shown that the specifications that have been derived satisfy all of the customer requirements. This is discussed further in the next sections.

### 2.11 Quality Function Deployment

The House of Quality shown in Appendix A is one example of how QFD is used to aid in the design of this system. Each of the specifications that have been developed can be related to the customer requirements in order to ensure that they have all been satisfied. Additionally, the House of Quality will show the effect that varying one specification to its limit will have on the rest of the system specifications. This information is useful in developing compromises within the system in order to ensure the final design will meet all the customer requirements and be the optimal design for this system. In the House of Quality presented, the customer requirements were compared with the specifications. This section will explain the main relationships shown in the House of Quality.
2.11.1 Planning Matrix - Relating the Requirements to the Specifications

The correlation matrix shows the relationships that each customer requirement has with the specifications that have been developed. Within this matrix, there are three levels of relationships that are shown: strong, moderate, and weak. This area of the House of Quality is used to ensure that all of the customer requirements have been met by the specifications. This will ensure customer satisfaction with the final product.

In the House of Quality shown in Appendix A, there are some key relationships in the correlation matrix that are discussed in this section. The first requirement, R1, is that the trays must be indexed to the proper position. This relates strongly to the specifications dealing with cycle time and productivity, as well as the repeatability of the work tray component, the load support of the tray movement subsystems, and the pellet placement mechanism reach. The relationship with the pellet placement mechanism reach is strong since if the work tray is not in the proper position, the placement of the end pellets may be incorrect, resulting in stacks that do not meet the required tolerances.

For the second requirement, R2: Accurately measures the stack length to determine if they are in acceptable range, a strong relationship is shown in relation to the desire to minimize the measurement resolution. With a higher degree of resolution of the measurement system, very small changes in stack length can be determined, and as a result, the tight tolerances on the stacks can be met. For this requirement there are also some moderate relationships which should be noted, specifically the target goals for productivity per shift. If the measurement system does not have the desired degree of accuracy, there may be times when stack lengths are outside the allowed tolerances, which will require rework and ultimately reduce the productivity.

For R3: Determine the proper end pellet combination, a strong relationship is shown in relation to S3: Maximize production per shift, while a moderate relationship is
shown with S1: Minimize measurement resolution. There is also a weak relationship with S2: Minimize cycle time. This relationship is caused by accounting for any errors in the determination of the end pellets. Should the method for determining which end pellets to use not be fast and efficient, there may be stacks with the wrong end pellets, causing the stacks to fail the final measurement test.

For R4: Pick the end pellets from the trays and place them at the ends of the stacks, a strong relationship is noted with several specifications, including S2, S3, S7: Payload of the pellet handling mechanism, S11: Pellet placement mechanism reach, and S14: Meets safety and shielding requirements for automated components. The strong relationship with S7 and S11 is required since in order for the pellet placement mechanism to meet the customer requirements, it must have a payload capable of handling the pellets, and it must have a workspace that can cover the area required to reach the different varieties of end pellets as well as the work trays.

For R5: Record the pellet tracking data to a database, a strong relationship occurs only with S13: Transmission range of the material tracking device.

R6: Take final measurement to ensure stack length is within specified tolerances has the same relationships as R2, when the initial measurements are taken, for the same reasons.

R7: Reduce the overall footprint of the station relates strongly to S4: Minimize overall station footprint within a 3 m x 5 m area, which is roughly half of the space currently used by the two manual stations at Cameco.

R8 requires that all equipment be properly guarded to prevent damage and injuries. This requirement relates strongly not only with S14, but also with S11 and S12: Percentage of components that are properly sealed. S12 is a major concern due to the nature of the environment that this system is installed in. With the quantity of uranium dust in the plant, machines that are not clean room protected are subject to shorter mean time to failure (MTTF) as a result of the uranium dust gumming up
gears and motors required to operate the system.

For R9: Ensure that the pellets are not damaged during the stacking process is a very important requirement to ensure the overall performance of each fuel bundle that is shipped from Cameco. This requirement has a very strong relationship with S6: Compression component force to correct stacks. If the force applied to the pellets is excessive, it may chip or crack the pellets. If a damaged pellet is then placed in a fuel bundle used in a reactor, it can result in a bundle failure.

The final requirement, R10, requires an increase in the current production. For this requirement, a strong relationship is observed with S2, S4, S5, and S8: Pellet handling cycle time. In order to increase the production, a decrease in cycle time of the overall system is required. The pellet handling subsystem is viewed as a bottleneck for this system, therefore reducing the cycle time of the pellet handling mechanism will greatly assist the overall goal of the system.

2.11.2 Correlation Matrix - Discussing how the Technical Specifications Support or Compromise One Another

In the correlation matrix, each specification is pitted against the other specifications to find areas where certain specifications work together to accomplish a common goal, and areas where two specifications are working against one another. In the latter situation, a compromise is required in order to meet the customer requirements, but still have a system that meets the technical specifications. In this matrix, S1 requires a compromise with S2, S3, and S5. This compromise is required since a higher degree of resolution in the measurement system will result in longer processing times, increasing the cycle times, and decreasing productivity. As a result, a resolution should be chosen that is one degree more accurate than required by the system tolerances.

When analyzing S2, it is determined that, with the exception of S1, there is strong synergy with the rest of the specifications. Most of the specifications have been
developed to aid the reduction of cycle time, as that is one of the main requirements of this automated system. The same can be said for S3, as the cycle time directly affects the productivity of the system. A by-product of reducing the cycle time is an increase in productivity.

The overall footprint of the system (S4) requires a compromise with the pellet placement mechanism reach. As the footprint of the overall system is minimized, the reach of the pellet placement mechanism will have to be limited so that it does not extend outside of the rest of the system. A target value of 800 mm was selected for the reach of the mechanism, while the overall footprint of the system is targeted at 3 m x 5 m, meaning the mechanism should fit neatly within the confines of the system.

Another important relationship in the correlation matrix is the relation between the payload of the pellet handling mechanism and the cycle time of the pellet handling mechanism (S7 and S8). A strong compromise is required between these two specifications, since adding weight to the payload is going to slow down the cycle times that the mechanism is capable of achieving. There is also some compromise required with the pellet handling reach. In the final design, the end pellets should be placed as close to the work tray as possible, which would be a suitable compromise for the pellet handling subsystems.

Safety and shielding requirements is a major specification that has synergy with all mechanisms in the system. It is required that 100% of the automated components in this system be properly guarded and shielded, not only to meet the standards, but to prevent injury and damage to the pellets and workers.

### 2.12 Summary

This chapter developed and discussed the requirements and technical specifications for the automated pellet stacking system and related them through QFD. Prior to
developing these specifications, functional decomposition was performed to develop the subsystems and overall functions that are required to have a successful system. Using QFD techniques, a House of Quality was developed to show these relationships, and these relationships were discussed in detail. A majority of the specifications developed work together to accomplish the goals of the system, however there are some that require compromise in order to meet the customer requirements. For each of these specifications, target values were set and these values were compared to the current method of manually stacking the pellets.
Chapter 3

Literature Review

There are currently only two companies that produce the fuel for CANDU reactors in Canada, Cameco Corporation and GE Energy. These two companies work independent of one another, and thus have different manufacturing processes. GE Energy’s production methods are a trade secret and thus are not available for review. There are other places throughout the world producing fuel bundles for other types of reactors. The overall manufacturing process for each of these types of reactors is similar, and the methods these companies use for automated stacking are discussed here. In addition to these production lines, specific technologies are also examined in order to develop solutions for the different subsystems required. These technologies include compression systems, high-speed measurement systems to meet the required accuracies, pellet placement technologies, and material tracking methods.

3.1 Fuel Bundle Production Methods

There are different types of nuclear reactors, including Pressurized Heavy Water Reactors (PHWR), Boiling Water Reactors (BWR), and Pressurized Water Reactors (PWR) to name a few. These reactors all have different fuel bundle structures, but the overall stack assembly is relatively the same. There are a few published methods
in the specific area of stacking fuel pellets, as well as other technologies and methods that can be modified to work in a system to manufacture nuclear fuel.

In US Patent 4,842,808, invented by Rieben et al., a pellet collating system is introduced [1]. The main components of this system include a tray positioning station, and a pellet collating line. This system, shown in Figure 3.1, is designed for fuel rods which have different zones of enrichment. An example of such a rod is shown in Figure 3.2, where the different enrichment zones are marked by the different hatching of the pellets. In this fuel rod design, there is no need for a different diameter for the end pellets, as there is space between the end caps and the end pellets in the stacks. In this design, there is a measurement head that picks up two pellets at a time and records the measurements of these pellets. It does this for each enrichment zone of the stack and sums them together to ensure the overall length of the stack is acceptable. The design has a complicated measurement mechanism that the inventors claim is necessary due to the different enrichment zones in the stacks [1]. In this patent,
the basic manufacturing process for single-enrichment fuel rods is discussed. It states that to fill a typical fuel rod, such as the type used in CANDU reactors, pellets are fed continuously into a fuel rod until the desired depth is achieved. In this model, all pellets would be used at some point to fill a stack. These pellets are presented to the system on supply trays and any supply tray not completely empty for one fuel bundle will be used in the next. A system such as this would require very tight tolerances on the length of individual pellets. This system has application to this project if the entire pellet manufacturing process was being evaluated. Since the objective of this thesis is to design a drop-in automated system for stacking end pellets, this is not a feasible solution.

US Patent 4,762,665 presents a stack forming apparatus that can be used to stack uranium pellets to obtain the proper size lengths to be placed into the zirconium tubes [21]. This invention is used to create the pellet stacks of a predetermined length for nuclear fuel bundles. During the creation of each stack, there are numerous devices that are used to create a precise stack length. This system focuses on achieving the correct stack length by dividing each stack into three sections, and matches the sections accordingly to achieve the desired stack length. In this process, the intermediate pellet size group is used first. While the stack is being assembled, length measurements are taken in order to estimate the final stack length. If the measurements are determining that the stack length will be outside of the required dimensions, then smaller or larger pellets will be chosen and added to the initial section. Small, medium, and large pellets are continually chosen until the stack length is complete. One advantage to a system like this is that each stack will be the correct length at the end of the process. The patent claims to have control over the length of the stack during the entire stack assembly process and can adjust the length early in the assembly to meet the target length. Additionally, this system combines multiple parts of the stack assembly process into one system, which would create extra space
in the plant. One disadvantage to this system is that there are numerous stages of measurement in order to achieve the correct stack length, including the initial sorting of pellets, the initial intermediate stack, as well as every time a pellet is added to the stack. This would require multiple measurement units, or a measurement system that is capable of moving to measure in different areas of the system. Another disadvantage to this system is that the stack is built one pellet at a time, which would make this system the bottleneck of the fuel bundle manufacturing process. A system such as this would actually increase the current cycle time, making this an infeasible solution. US Patent 5,509,039 presents a system used to assist an operator in achieving the length of a pellet stack [22]. This system was created in response to a need to replace an older process of stack measurement, which required a user to control a Cartesian probe to contact the two ends of the stack and then press a foot pedal to record the length measurement into a database. The method presented in this patent removes the foot pedal and implements a force feedback system into the Cartesian measurement system. When the probe contacts the stack, force is applied to ensure that there are no gaps in the stack. When the force on the probe reaches a set point, the measurement is taken. The maximum force point is set at a position to ensure that it will be reached when the stacks are entirely compressed.

One major advantage to this system is that any gaps in the stacks are eliminated prior to measurement, which is important for taking accurate stack measurements. A disadvantage of this design is that the user is still required to manipulate the head of the Cartesian device to get it in a position for measurement. This system could be further modified by automating the Cartesian head. Another disadvantage to the measurement head is that it requires contact with the stack to take a measurement. That adds additional time to the overall cycle time, which would make it difficult to reach the cycle times required by Cameco.

Sharma et. al. [23] describe in detail the problem of using robots to intelligently
stack uranium oxide pellets. The main problem outlined in [23], which is also a main problem for the design in this work is that the tolerance for the stack length is tighter than the sum of the tolerances for the individual pellets which go into a stack. The paper presents three intelligent machine stacking techniques. The first involves a robot taking each pellet from an input tray and placing it on a laser micrometer platform to determine the pellet length. If the pellet is within a predetermined length it is put into a stack, and the stack length and pellet count are updated accordingly. The robot would repeat this action until the number of pellets is in the range of 26 to 31 (which is the desired number of pellets for their bundles), and the length of the stack is within 480.03±1.15 mm. In this method, once the end of the stack is approached, and the pellet that comes in will cause the stack length to be too long, it can be placed in the next stack on the tray, or be placed on the current stack, if the overshoot length is less than 8 mm. The system will then swap out pellets from the first stack until the tolerances are met.

The second method presented in [23] involves placing up to 23 unmeasured pellets on a tray, and taking the measurement on these stacks. From here, the number of pellets and the lengths of each pellet required are computed. A set of pellets is measured similar to the process described in method one, and if they are required, will be placed on the required stack. Preliminary test results shown in [23] suggest that this is not a good method to complete stacks as the probability of getting the correct sized pellets is around 1 in 55.

The third method presented in [23] tries to imitate the operator action except for the calculations and swapping operations. In this method, the robot places the pellets in the first stack on a tray until there are 23 pellets in the first stack. After 23 pellets have been placed, the system estimates the number of pellets required to complete the stack. In this method, they have pellets that vary in length from 15.27 mm to 18.57 mm. The authors discovered that even after 23 pellets have been placed, there
are certain ranges where no pellets will solve the stack. The authors determined that by reducing the number of pellets initially placed to 21, they encountered zero dead bands with their inventory of pellets.

Method three presents a major modification to the overall manufacturing of the pellet stacks. With the system being designed for this project, the customer requested that this be a drop in solution that would not require a major modification to the manufacturing process. In place of measuring each pellet to obtain the lengths as was suggested in [23], it would be ideal if the tolerances on the individual pellets were tightened and inspection was performed prior to the stacking stage to ensure the pellet length tolerances have been met. This would help reduce the cycle time and the bottleneck at the stacking station.

### 3.2 Measurement Technologies

A key requirement of the system will be some method to accurately measure the stack length. There are two types of measurement technologies that could potentially be used: contact and non-contact measurement systems. Contact measurement systems require some sort of physical contact with the object being measured, such as a transducer. Non-contact measurement systems use sound or light reflecting off of the surface being measured to obtain measurement readings. This section examines these two technologies and devices that could be used to measure the stack lengths. The measurements need to be made quickly in order to meet the cycle time requirements for this project. The measurements also need to be accurate, and the measurement device requires a resolution of at least 0.001 mm, which is sufficiently accurate for the tolerance required on the overall stack length.

There are many methods that can be used to measure the length that is required for this project. As part of the research, not only were products researched, but also the
methods that are used to perform these measurements. These methods are presented below.

### 3.2.1 Contact Measurement Devices

Contact measurement devices are defined as those that require physical contact with the work piece in order to determine measurements. There are a few different technologies that use contact to obtain measurements including coordinate measurement machines (CMM) and transducers.

#### 3.2.1.1 Coordinate Measurement Machines

A CMM is a device used to measure the geometric characteristics of an object. These machines can generally be operated either in a manual or automatic mode. They generally have three perpendicular moving axes, with a probe attached to the third axes used to define the measurement points. These probes can be mechanical (contact) or optical (non-contact). Contact CMMs will be the focus in this section.

To obtain measurements, the probe is located at the position on the object being measured, and positional information from all three axes is obtained by the controller. By contacting multiple points on an object, a general size and shape can be determined, as well as specific measurements such as length, height, and width of the object.

These devices are used in manufacturing and assembly processes to test parts for accuracy. The controller for the CMM can check part dimensions against the required dimensions and ensure quality of these parts. The following are two different CMMs that could be used in this project.

**Tarus TBCMM-1275 Bridge CMM Machine**

The Tarus Company has developed a line of CMMs including the bridge model shown in Figure 3.3. This model encloses a work envelope of 3,600 mm x 2,032 mm x 1,524 mm and has a scale resolution of 0.5 microns. The maximum travel speed of the probe
is 25.4 m/minute [2].

The accuracy this machine is within the required specifications. However, with the contact required between the probe and the part, the time to measure the stacks in this project will be high, thus decreasing the overall output of the system. Another disadvantage to this system is that the overall footprint of the machine is much larger than the current manual stations. To add this machine as well as all the other required parts to the system would not meet the space requirements set out by the customer.

**Metris LK V-GO High-Accuracy Gantry CMM**

Gantry CMM machines are used ideally for measurements where inline inspection or special accessibility is needed for very large, long, or heavy parts and assemblies. The Metris LK V-GO High-Accuracy gantry CMM has an accuracy of 3.5 microns with a probe travel speed of 22 m/minute. The gantry CMM can be see in Figure 3.4. The measurement style of this system works similar to the bridge CMM described above in that the probe requires contact with the ends of each stack and measures the distance. Distance is measured by a computer after the x, y, and z coordinates of the recorded points is analyzed [3].

The gantry CMMs have the accuracy that is desired for this project, however the speed at which it can perform the measurements as well as the space it will take up makes these machines less likely to be useful in the environment which the operation
is performed. The overall footprint needed for a CMM machine when compared to a non-contact solution is viewed as a negative.

### 3.2.1.2 Transducers

Transducers could be used to take the stack measurements. To use this technology, shown in Figure 3.5, the transducer would push up against one end of the stack, while the other end is against a fixed wall. Using the positional knowledge of the fixed wall, and the current reading from the transducer, a displacement can be determined, and through simple math the length of the stack can be determined.

Transducers provide a smaller contact measurement solution than the CMMs presented above, however there are still some issues that are of concern, especially in this high through-put system. The first issue is the mean time to failure with these transducers. Since they are moving and contacting so many stacks per shift, the con-
tacts on the transducers will wear out faster than a non-contact system, which will require more maintenance and down time for the system. The second issue that will arise is the cycle time for measurements. Since contact with the stacks is required, the time it will take to obtain the measurement may put the overall cycle time over the required time limit for the system.

### 3.2.2 Non-Contact Measurement Devices

Non-contact measurement devices are those that do not require physical contact with a part to take a measurement. There are a few different technologies examined here that may provide a solution for this design including light measurement, triangulation, and doppler.

#### 3.2.2.1 3D Light Measurement

DLI is a company that specializes in 3-dimensional light metrology. They have many different products that use digital light projection to quickly digitize real world objects quickly with high accuracy and precision. The projects work by scanning the object and forming point clouds. The data can be acquired in just a few seconds and used for a vast number of activities including quality inspection, surface metrology, and reverse engineering [24].

This method works very well for fast measurements since there is no contact with the parts required. There are aspects of this system that make it appealing for use in this project, including the accuracy at which the points can be recorded. For an area of 1,000 mm x 750 mm x 100 mm, up to 2,000,000 points can be recorded, giving a resolution of 600 µm. One disadvantage to this system that makes it less likely to be used in this project is that it requires more than six seconds in obtaining the 3D profile of the object. The size of the machines required for this technology is much smaller than the CMM machines mentioned earlier, however, the measurement field
3.2.2.2 Laser Triangulation Measurement

Triangulation is the process of finding the distance to a point using trigonometry and distance measurements. The method is used to achieve accurate measurements in sub-millimetre resolution. This method is best implemented for short range measurements. When dealing with longer measurements, as required for this project, the base unit becomes larger in order to accommodate the angle the laser needs to reflect to give an accurate measurement. The principle of triangulation is shown in Figure 3.6. One issue that will need to be addressed when using this method is the fact that accuracy falls off rapidly with increasing measurement range. Measurement with triangulation sensors is best done off a specular surface, which will give the best reflection of the laser beam. A specular surface is one that is highly polished and reflects light at an angle equal to the angle of the incident light. If the surface diffuses the laser, it will be more difficult to obtain an accurate reading.

Triangulation sensors can be broken down into three subsystems: transmitter, receiver, and electronic processor. The transmitter is the laser beam that is projected upon the object to be measured. The receiver gathers the reflected light off the tar-
get and reports the position of the target to the processor. The processor processes
the data received and returns the distance value of the target from the measurement
unit [25].

The following are a few triangulation sensors that could provide measurement solu-
tions to the automated stacking system.

**LAP Antaris S500 - Triangulation Sensor**

The Antaris line from LAP Laser is a line of displacement sensors using the trian-
gulation principle of measurement. Each sensor can measure displacement, however,
with the right combination of sensors, length and other attributes can be measured. A
photo of the Antaris model is shown in Figure 3.7. The S500 series has a measurement
range of 500 mm, while requiring a stand off distance of 620 mm. The resolution of
this system is 8.3 $\mu$m, which is within acceptable range for the project requirements.

Certain drawbacks were also found while researching this measurement device. This
included a requirement for a flat white surface for measurement. This is a major
problem when designing the system for industrial use where the environment cannot
be guaranteed; especially in the area this system will operate.

In further discussions with LAP, it was determined that these displacement sensors
would not be ideal for measuring length.

**Acuity Laser Measurement Units - Triangulation Measurements**

There are two different series of units from Acuity that were examined for this project;
the AR600 and the AR700. The AR600 from Acuity Laser Measurement makes use
of triangulation in order to achieve a distance measurement. The output of this unit is similar to that of a typical digital measuring tape, except for the accuracy that can be achieved. On a typical digital measuring tape, accuracy can only be recorded up to the millimetre. It is recommended that for any sub-millimetre measurements, the triangulation method be used. With the AR600 model, it is able to operate in a range of temperatures and environments without a noticeable effect on the data. Sample rates can be configured between 200 samples/s for high resolution measurements, and 1,250 samples/s for standard resolution. Figure 3.6 shows a diagram of the laser module with labels that correspond to requirements and specifications of the unit. In this diagram, the span is the distance at which a measurement can be achieved. For the AR600-32 models, which are recommended for the length of stack being measured, the span is 813 mm. The target standoff, which is the optimal measurement point within the span that will yield the most accurate result, is 1,067 mm. The resolution of the measurement is 243.9 microns, which exceeds the required specifications for this project.

One drawback to using this model would be the size of the unit. The measurement unit stands at 632.5 mm tall, which is larger than some of the other units examined. The height of this unit is required in order to allow the triangulation to occur over the distance being measured. In order to measure the length of the stack, two of these units could be used to get measurements from the two ends of the stacks, and by calculating the difference, the length of the stack can be achieved.

The AR700 is the newest model of the laser triangulation units. It uses the same principles as the AR600, only the actual module is smaller in size and has greater accuracy. After examining several different concepts for the system to perform the measurements, it was determined that having measurement sensors at each end of the stack would allow for smaller measurement lengths. This would result in greater accuracy and the ability to use smaller measurement units. The AR700-6 model,
which would be the optimal model for this system layout, has a span of 152.4 mm, and a standoff distance of 254 mm. The resolution of this model is 0.005% of the span, which is 95 microns for the model being discussed.

One advantage this unit has over the AR600-32 is the size. The height of this unit is only 132.1 mm tall, which makes it a much more attractive option for this project. By using two of these units, one on each end, the measurements being taken are smaller than using the AR600-32 from one end, and thus greater accuracy can be achieved.

### 3.2.2.3 Doppler Measurement

Doppler measurement technology works by using a dual-beam laser interferometer to measure the velocity of an object. This velocity is then integrated over time to measure length. The fringe distance, \( d \), which is a function of laser wavelength, \( \lambda \), and the beam length \( \kappa \) can be calculated as:

\[
d = \frac{\lambda}{2 \sin \kappa}
\]  

(3.1)

Velocity is then calculated by taking the fringe distance from Eq. (3.1) and dividing by the time, \( t \). Thus, the equation for velocity in this case is found as:

\[
v = \frac{d}{t}
\]  

(3.2)

The period can be found by taking the inverse of the frequency, and then this can be used to determine the length of the stack [26]:

\[
L = \int_{0}^{T} v dt
\]  

(3.3)

Doppler technology is primarily used for measuring moving parts on a factory line. If a part is not in motion, a measurement cannot be taken, making this method unsuitable for this project.
**Beta LaserMike LaserSpeed 4000**

The LaserSpeed 4000 is a non-contact speed and length gauge from Beta LaserMike. This model uses electro-optics in order to produce highly accurate, non-contact measurements of both length and speed. This specific model has an accuracy of $\pm0.05\%$, which amounts to $\pm0.05$ mm per 100 mm of length measured. The LaserSpeed unit has a measurement frequency of $>20$ kHz. Since it uses Doppler technology to measure the length it requires the stacks to be moving in order to get a length measurement.

Advantages to using the LaserSpeed system include a permanently calibrated unit that is not affected by the environment, low cost, and the fact that the unit takes measurements accurately without contact.

One disadvantage to this unit is the requirement of the object to be in motion in order to obtain a length measurement. Due to the space constraints, as well as the number of measurements that need to be taken per stack, this model will not be the best choice for this design.

3.2.2.4 Differential Interferometer

Differential interferometers (DI) can be designed in one of two ways: a unit with two laser beams that measures the distance between a fixed point and a moving point, or two units taking two measurements and calculating the difference. For this project, the DI method could prove to be very powerful in obtaining a quick and accurate measurement. DI takes the position of two points and calculates the difference in order to determine the length of the object. When designing a DI from two laser units, problems can arise when one module sees the laser beam from another. This will yield errors in data, and will cause problems for the entire system. To avoid this, the modules must be placed a certain distance apart.

The differential interferometer shown in Figure 3.8 is designed to take displacement
measurements of two items and calculate a difference. This is the ideal technology in order to measure the length of a product. The design from Renishaw includes a dual laser beam head that would be mounted to the outside of a work cell. This product is best used for taking measurements within a vacuum area where placement of the measurement head must be outside the vacuum area. This is an extremely accurate measurement device, that has a reported accuracy of < 1 nm over a measurement range of 1 m.

This technology is the most accurate for measuring length of the stacks, however, this device has several drawbacks that would not make it suitable for this project. The accuracy reported for this unit is far greater than what is required, and this accuracy increases the price of the unit. Unit cost for this product is ten times the cost of the AR600 model discussed above. The Renishaw Differential Interferometer is also best used for measurement within a chamber where an operator would not be able to get access to it. With the freedom of placement for this project, as well as the availability of other products to meet the requirements, this unit is not a viable solution for this project.
3.3 Pellet Placement

In this system, there are two times that pellets need to be handled by some sort of mechanism: the end pellets must be unloaded from trays, and the end pellets must be placed on the stacks. For each of these operations, many different existing technologies were examined in order to determine if an off-the-shelf solution was available for pellet placement.

There are a few products currently on the market that could remove the end pellets from their trays. Several different mechanisms were found to be suitable for handling the pellets including cartesian robots, articulated robots, and SCARA robots. There are also existing technologies at Cameco that can be examined and possibly adapted to meet the needs of this system.

To place the end pellets in position at the end of each stack requires a pick-and-place solution that maintains high accuracy throughout the operation. For end pellet placement, different robotic systems were examined and discussed in order to find solutions that could work for this system. These systems included both SCARA robots and articulated robots.

3.3.1 Cartesian Robots

Cartesian robots, like the one shown in Figure 3.9, are generally used for pick-and-place, assembly, and packaging operations. One area where a cartesian robot differs from other robots is in the shape of its work envelope. A cartesian robot works in a rectangular grid envelope and can be built above the work area. This is good when the pick-and-place operation covers a large area. One disadvantage to cartesian robots is the structure required in order to implement them. For an overhead cartesian robot, additional framing and support needs to be built in order to securely attach the robot to the system. This additional framing is not necessary with other types of robots.
Figure 3.9: Example of a cartesian robot [8]

which can be simply mounted to a base connected to the floor.

There are many different models of cartesian robots available, including models by Epson Robots and Adept Technology. Both of these companies offer a similar product, which is customizable based on the customer requirements. For this system, a 3-axis cartesian robot would be required with a maximum reach on one axis of almost 2 m in order to span the minimum distance the trays can be spaced apart. Out of the two companies mentioned, only Adept has the required size of linear module available as a standard product, while Epson would be able to produce the required length as a custom part.

3.3.2 Articulated Robots

The second type of robotic system that was considered for handling the pellets were articulated robots. Typical articulated robots are capable of producing 6-degree-of-freedom (DOF) motion. As was previously stated, one customer requirement was to try to use the same suppliers Cameco uses when available. In this case, Fanuc Robotics was researched to determine if any of their articulated robots would be a possible solution to the pellet handling in this system. One requirement of a robot to handle the end pellets prior to placement was that the robot have a long reach. This is to account for the different sizes of end pellets, and the fact the robot had
to be able to reach all of them. Fanuc presented two possible solutions to this: the M-10iA, and the slightly larger M-20iA, seen in Figure 3.10. Both of these robots are essentially the same, except for the reach and payload capabilities, where the M-20iA exceeds the M-10iA in both areas.

One advantage to using an articulated robot is the size of the work envelope available. With the M-20iA presented above, the maximum reach of the arm is over 2 m, which is important with the need to pick pellets from a large area. One deficiency to using an articulated robot is that the cycle times tend to be slower than a SCARA or parallel robot.

For end pellet placement at the ends of the stacks, the smaller LR Mate 200iC/5L from Fanuc was examined. This 6-axis robot shown in Figure 3.11 was designed by Fanuc to rival the SCARA robots being produced by other robotic companies. The LR Mate robots are manufactured with reaches up to 892 mm for the long-reach model and can handle a 5 kg payload, while achieving cycle times close to the SCARA robots.

### 3.3.3 SCARA Robots

SCARA robots are intended for high-speed pick-and-place operations, where small payloads are acceptable and the distance the parts need to be moved is also small. SCARA robots, like the one in Figure 3.12, are 4-axis robots used when speed and precision are needed. The work envelope for these robots is circular, and generally
quite small. SCARA robots produce 4-DOF Schönflies motion. Schönflies motion consists of three independent translations in the Cartesian space along with one rotation about a fixed axis.

If a SCARA robot was used to unload the pellets from the trays, there are certain design parameters that would be restricted, including the placement of the trays and the unloading point for the pellets. While Fanuc does not build SCARA robots, Epson Robots and Adept Technology are two main suppliers that were examined. Both of these companies produce robots with similar specifications, with the longest reach being around 800 mm, and cycle times less than 0.5 s for a cycle test. The industry standard for these cycle tests is for the robot to move its end-effector vertically on the
Figure 3.13: Cameco cartesian gantry system used for loading/unloading the grinders

$z$ axis 25 mm, translates horizontally in the $x – y$ plane for 300 mm, and down on the $z$ axis 25 mm, and back again. Both of these robots meet the cycle time requirements for this area of the project, however the limited reach is not an attractive feature. One major advantage to using SCARA robots is that they offer the best price to performance for a high speed robot.

3.3.4 Existing Cameco Technologies

Cameco currently has a system that is used to load and unload pellets at the grinding station. This cartesian gantry system, shown in Figure 3.13, is a two-axis system with two fixed-stroke linear modules. The motion of the pick-and-place gripper is the same each time and the trays are indexed to the unloading position. This technology can unload rows of end pellets at a time, and could be modified to meet the requirements of this system. This is an attractive solution since it is an already proven solution.

3.4 Material Tracking

Material tracking is required throughout the manufacturing and assembly process at Cameco in order to track which lots of uranium have gone into which bundles. This is important for quality control, and to ensure that if a recall is ordered for a particular lot of uranium, that all affected bundles can be tracked down and removed from cir-
There are many ways material tracking can be done within a manufacturing environment. The current method at Cameco is to have barcodes on removable plates on each tray. Operators scan the barcodes of the work tray and the barcode for each end pellet size used. This is a highly manual process that would require modifications to continue in the automated process. Another disadvantage to this method is that the system is only able to track what uranium is on each tray. With a more sophisticated system, the database could be able to determine placement right down to the stack. This would be important when multiple lots of uranium end up on one tray.

One technology that is widely used for tracking is radio frequency identification (RFID). RFID uses unique radio frequencies for each tag affixed to a tray. These signals can be read from up to 2.5 m away, and can contain any data programmed to them. This presents a major advantage over the current system since the scanning can be done automatically, and the tag that would be affixed to the tray is small enough that no major redesign of the tray would be required.

One requirement for any technology being attached to the trays is that it be able to withstand high temperatures. The trays take the pellets through a drying cycle that achieves temperatures up to 150°C, and so anything permanently fixed to the tray must be able to withstand this. There are a few companies that produce high temperature RFID tags, as well as some patented designs. All of the designs are similar and can withstand the same range of temperatures, so cost would be a major determining factor in selecting which RFID tags to use, as well as determining whether the companies product can be attached to metal, as this seems to be of concern for some suppliers. The following are a few of the companies that provide high-temperature, metal attachable, RFID tags.
3.4.1 Elecsys Corporation

MBBS, a division of Elecsys Corporation, is a leader in producing and supplying through-metal RFID solutions. Through-metal RFID tags are able to be read through a metal casing they are manufactured with. This metal casing allows the tag to withstand the high temperatures. Mostly used in the medical and industrial sectors, their patented design encases the RFID tag in a metal, which allows it to sustain temperatures up to 240°C [27]. The RFID tags they produce range in size with the smallest advertised size a disc shape of diameter 5.6 mm and thickness 1.7 mm. They will also produce custom RFID tags for any application.

3.4.2 Escort Memory Systems

Escort Memory Systems (EMS) produces a rugged RFID tag that is built to withstand paint ovens that reach temperatures of 200°C. It is able to withstand these temperatures since the actual RFID chip is encapsulated in a thermal resistant material. The range on this chip is up to 1.3 m, however the overall size of the tag is 52 mm by 128 mm, which is too large to attach to the current tray design [28].

3.4.3 Titan Tag

Titan tags are a unique and robust design for on-metal, high temperature applications. Some products in the Titan Tag line can withstand temperatures up to 200°C for up to 6 hours at a time [29], and are small enough that they could be attached to the current tray design. These tags can also be read from 1 to 2.5 metres away, depending on the model that is purchased.
3.5 Summary

A review of existing technologies has been presented in this chapter. These technologies will be examined going forward as concepts are developed to solve the subsystems defined in Chapter 2. Existing technologies will be used as much as possible in order to maximize the number of standard parts used.
Chapter 4

Concept Generation and Evaluation

This chapter presents the concepts that have been developed as possible solutions for the subsystems outlined in Chapter 2. These concepts are discussed and then evaluated using a variety of selection criteria. At the end of the chapter, final concepts are presented for each of the subsystems that make up the automated pellet stacking system.

4.1 Proposed Solutions to the Problem

Through functional decomposition, it has been determined that there are six main subsystems that need to be designed for the automated pellet stacking system:

1. Measurement Subsystem

2. Pellet Placement Subsystem

3. Work Tray Subsystem

4. End Pellet Handling Subsystem
5. Material Tracking Subsystem

6. Control Subsystem

Figure 2.1 in Chapter 2 shows the relationships of each of these subsystems. Within each of these subsystems, a set of concepts is generated to solve the problem. Once the concepts are developed, they are put together in different combinations to determine the best overall system. This iterative design process methodology is a very powerful tool for concept generation and selection.

### 4.1.1 Concepts for Measurement of the Stacks

Within this section of the system, there are two operations that are performed: the compression of the stacks and the measurement on the stacks. Concepts are generated for both of these operations and presented.

#### 4.1.1.1 Concepts for Compressing the Stacks

Before the lengths of each stack can be measured, the system needs to ensure there are no gaps in the stack prior to the measurements. Therefore, a compression system will be developed to compress the stacks so that accurate measurements can be taken. The compression system requires 5 N to fully compress the stack. With this in mind, concepts were developed to remove any gaps in the stacks. Concept 1-1, shown in Figure 4.1, is a compression concept that involves the use of a block designed to fit within the groove of the tray that can be moved with a pneumatic piston. In this concept there is a block on each end of the stack and both are providing the compressing motion. There is an opportunity with this design to use a block with a specular surface that can provide a surface for the measurement. With a block of known width, the length calculation would not be affected. This system would be on a mechanism that adjusts the height of the block so the tray can still be indexed for
A second compression concept, labeled Concept 1-2a is a derivative of the first. The same idea of using a pneumatic block to compress the stack is proposed, however instead of one pneumatic block for each end, one end of the system is fixed against the end of the stack. In this system, one block would be required to push the entire stack against this stationary wall to compress the stack. This stationary wall would be on a mechanism that would raise and lower it as required, as is the case with the compression piston on the other end.

A variation to this concept is to have two fixed blocks at staggered lengths, with two pneumatic pistons at the opposite end. In this concept, labeled Concept 1-2b, the two fixed ends are staggered to account for the placement of the end pellets. The first fixed block would be used for the stacks of 28 pellets, while the second would be for
the completed stacks of 30 pellets. This idea is shown in Figure 4.3. This will allow the system to process multiple stacks at a time, decreasing the overall cycle time of each tray.

Concept 1-3 was developed similar to the first compression concept, except for the blocks. In this concept, the blocks are not grooved to fit on the trays, but instead are flat and sit such that the compression unit does not have to move up and down each time the tray is indexed.

4.1.1.2 Concepts for Measuring the Stacks

There are many methods that can be used for measuring the stack length. A review of the state of the art was shown in Chapter 3. Concept 1-4 involves the use of a coordinate measurement machine (CMM) that will contact the end of each stack with a probe and determine the length. This concept involves the use of a gantry CMM. An advantage to using this system is that the resolution of the CMM can approach 3.5 microns. Another advantage to the gantry CMM machine is the size of the work envelope. The Metris LK V-GO High-Accuracy gantry CMM has a work area of 3,600 mm by 2,032 mm and the probe can travel 22 m/minute [3]. A disadvantage to using a CMM to take the measurements is that the probe must actually touch the part that it is measuring, which would be an issue should the end of the stack not be in the
same spot for each stack on the tray. The system can be programmed for a certain amount of tolerance, but should the stack be outside of the search area of the CMM, an error would occur. The time it takes to travel to each end of the stack would also increase the cycle time to an unacceptable level.

Another concept for a measurement device involves the use of optical and laser measurement systems. These non-contact systems provide near-instantaneous measurements of the stack length, which would help to decrease the cycle time, something the contact measurement units can not do. One method that was explored was using a digital light projection to digitize the stack. The light projection is represented on a computer by a series of points, up to 2,000,000 for an area of 1,000 mm by 750 mm by 100 mm [24]. A major disadvantage to this idea is that for higher degrees of accuracy, more points are required. This can result in data collection taking up to six seconds, which is well outside of the required cycle time per stack.

Within laser measurement technology, there were two other concepts that were explored. The first laser technology explored uses triangulation sensors that bounce a laser off each end of the stack and determines the length mathematically. This method is best used to quickly and accurately obtain sub-millimetre measurements, and is best used for short range measurements. When dealing with longer measurements, the base unit becomes larger in order to accommodate the angle the laser needs to reflect to give an accurate measurement.

Measurement with triangulation sensors is best done off a specular surface, which gives the best reflection of light. A specular surface is one that is highly polished and reflects light at an angle equal to the angle of the incident light. The uranium pellets are a dark colour that absorb some light, which may be a disadvantage to this method.

Multiple triangulation sensors can be arranged to measure an object. Concept 1-5 was developed using two triangulation sensors, one placed at each end of the stack.
These sensors take a measurement from the laser position to the end of the stack, and through the same principles as differential interferometry, calculate the distance of the stack. This concept, shown in Figure 4.4, has the two measurement units that are stationary in the middle of a platform. The work trays in this concept move through the system, and when a stack is in line with the measurement units, a measurement is taken.

Concept 1-6 is similar to the previous one, except that there is only one measurement unit that has two beams, and encased in this unit is a controller which determines the stack length through differential interferometry. For the differential interferometer discussed in Chapter 3, the lower laser will reflect off of the closest end of the stack, while the top laser will reflect of the block at the far end of the stack. This provides a specular surface for measurement for the second laser, and can also serve as a device to compress the stack.

Concept 1-7 was developed based on the triangulation idea, with a single sensor at one end of the stack, and a fixed barrier at the other end, shown in Figure 4.5. With this barrier at a known position, the length of the stack can be determined from the measurement of the one sensor.

Doppler technology can be used to measure the length of a moving part. This has several disadvantages for the measurement of the stacks. The accuracy for Doppler systems is around 0.05 mm per 100 mm of length measured [26]. This means that for
a stack of around 480 mm, the error is almost 0.25 mm, unacceptable according to the specifications that were developed. It also requires that the stacks be moving to acquire a measurement, something that is not desirable with this system.

Using the Doppler technology, Concept 1-8 was developed. Instead of moving the tray, the laser unit is mounted on a gantry system that can translate the length of the tray. In this concept, shown in Figure 4.6, the laser measurement unit can also translate the width of the trays in order to scan each stack on a tray. This method removes the need to move the work tray once it is in place for measurement, however the accuracy of the Doppler system is less compared to the triangulation design.

4.1.2 Concepts for the Work Tray Subsystem

4.1.2.1 Concepts for Indexing the Work Trays

This subsystem requires the work tray to be brought from a storage hopper into the measurement subsystem and accurately index the tray through the system so each
stack can be measured and have the correct end pellets placed. The system must work quickly and accurately to reduce the cycle time to the level the customer has requested. Concept 2-1 has been developed for this subsystem, and uses a conveyor to move the trays. This conveyor would be the same style that brings the work tray from storage into the measurement subsystem, as shown in Figure 4.7. The main advantage to using this conveyor system is that it is already in place and will provide a seamless transfer from storage to this system. The conveyor is capable of handling the weight of the trays and is able to move them at the required rate of speed. With this concept, additional sensors would be required in order to start and stop the conveyor with the tray in the proper position for compression and measurement of the stacks. Sensors can be used to locate each stack on the tray and stop the tray in the appropriate position.

Concept 2-2 involves the design of a specific system to handle the trays through the subsystem. This concept uses custom designed carts that are on a track system, shown in Figure 4.8. These carts, coupled with encoders, can move precise distances on the track, in order to move the exact distance required during the measurement
stage of this process. If two sets of carts are used, it will help to reduce the cycle time by having the ability to bring a new tray into the system while the completed one is being transferred to storage. In Figure 4.8, the vertical flaps on the carts that push the trays through the system would be spring loaded so that the trays can be loaded easily on to the cart.

Concept 2-3 for moving the trays involves the use of Geneva wheels. This system, an example of which is shown in Figure 4.9, would be used to index the trays the precise distance for measurement through the system.

4.1.2.2 Concepts for Sorting and Storing the Work Trays

Should a stack have an initial length such that no combination of end pellets would result in the tolerances being met, the entire tray would need to be flagged and moved to a separate, manual stacking station in order to determine the problem. As a result, concepts have been generated to determine a method of sorting and storing the work
trays. The first concept, noted Concept 2-4, involves the use of a conveyor that can be moved once a tray is loaded. This concept, shown in Figure 4.10, would have a 0.5 m conveyor connected to a pneumatic piston. This piston can move the section of conveyor between two outputs in order to sort the trays. A second output conveyor is set up next to the standard output conveyor, and any trays that are not complete would be moved into this area. A storage hopper would be placed at the end of each of these conveyors. This storage hopper would be loaded from the bottom, and when full, would require an operator to empty them and move the trays to the next station. The storage hopper used for this concept is the design that is currently used at Cameco to store trays in their manufacturing line.

Concept 2-5 was designed and involves a single output conveyor with two storage hoppers placed on the single output conveyor. In this concept, shown in Figure 4.11, the first hopper would load any incomplete trays, while the second hopper would load the completed trays. This configuration was chosen since the hopper at the end would be easier to unload, and incomplete trays would happen at a lesser frequency than completed trays.

Another idea for the sorting portion of this subsystem is to design it so that trays
that are finished and that do not require manual attention follow the path of least resistance. Concept 2-6, shown in Figure 4.12, shows how completed trays would pass straight through the system, while trays that require manual rework will be moved off the main conveyor line into a separate storage system. A conveyor that can raise up to move the tray from one conveyor system to another is proposed for this sorting system. In this system, when a flagged tray is leaving the system, this conveyor will raise and cause the tray to kick on to an alternative conveyor which leads to a manual reworking station.

Another concept (Concept 2-7), is used to sort the flagged trays, and would have a two tiered conveyor with a trap door, shown in Figure 4.13. This figure shows that when a tray is flagged, the bridge portion of the conveyor would lift and the tray
Figure 4.13: Work tray sorting concept with a trap door and two tiered conveyors (Concept 2-7)

Figure 4.14: Work tray sorting concept using a Y-style conveyor (Concept 2-8) [11]

of pellets would follow the lower conveyor which would wind around to a manual reworking station.

Concept 2-8 for sorting the trays involves the use of a Y-style conveyor. This conveyor has a switch that will direct trays to a certain area. This can allow completed trays to proceed to the next station, while the trays that require rework will split off into a storage area. An example of this conveyor is shown in Figure 4.14.

For storing the sorted and completed trays, a system is proposed that would take the trays from the work tray handling subsystem and store them. One concept for this subsystem is to have a vertical accumulator, as shown in Figure 4.15. Another concept would be to use the existing tray hopper that is used at the Cameco plant to store trays of pellets. This tray hopper would need to be modified slightly to interface
4.1.3 Concepts for the Pellet Placement Subsystem

For the pellet placement subsystem, there are many different mechanisms and machines that can be used. Concept 3-1 involves the use of a SCARA (Selective Compliance Assembly Robot Arm) robot, as shown in Figure 4.16. In this concept the robotic arm is placed in an area where it can reach the entire stack in the work tray handling system. This robot will simply pick end pellets as needed from a designated position and place one on each end of the stack. This concept involves the use of a simple gripper that is able to pick one pellet from the storage area at a time. From this concept, Concept 3-2 was developed. By adding a second robot to the system, and placing one at each end of the system, the cycle time of the placement can be cut in half. This idea is shown in Figure 4.17.

As an alternative to using a SCARA robot, Concept 3-3 uses a six axis FANUC robot for the pellet placement subsystem. The LRMate series of robots from FANUC are designed as five and six axes robots for pick-and-place operations. These robots have cycle times that rival some SCARA robots, which allows them to be considered for this subsystem. This concept is shown in Figure 4.1.3. With this robot, different
mounting positions can also be considered, including table mounted, inverse mounted, and wall mounted.

To further reduce the cycle time of the end pellet placement, a custom gripper was conceptualized. This gripper is able to hold one of each size of end pellet at any time and is able to individually place pellets on the stacks as required. Since the gripper will always have one of each type of end pellet in its grasp, it will reduce the cycle time, since the robot does not have to wait to determine which pellet it needs. One major disadvantage to this design is the cost associated with designing a custom gripper of this complexity. Concepts 3-4a and 3-4b were drawn to demonstrate this idea, shown in Figures 4.19(a) and 4.19(b), respectively. Figure 4.19(a) shows a carousel design that uses the z-axis rotation of the robot to spin the gripper so the
Figure 4.17: Pellet placement Concept 3-2 involving two SCARA robot arms

Figure 4.18: Pellet placement Concept 3-3 involving one FANUC LRMate 6-axis robot
Figure 4.19: Custom Gripper designs for pellet placement Concept 3-4, a) Carousel custom gripper design for pellet placement Concept 3-4a, b) Ferris wheel custom gripper design for pellet placement Concept 3-4b

proper pellet is in place for placement. Figure 4.19(b) shows a Ferris wheel design that requires an additional rotational source or linkage to have the proper pellet in place for distribution.

An alternative to a gripper holding five end pellets is a gripper that will hold two pellets (Concept 3-4c). With this concept, shown in Figure 4.20, once the pellet combination for a stack has been determined, the robot will pick up the two pellets needed, and then place them at the appropriate ends of the stack. This will eliminate the time needed to return to the pellet infeed after each placement, which will reduce the overall cycle time for each stack.

4.1.4 Concepts for the End Pellet Handling Subsystem

For handling the end pellets, numerous concepts were developed. These concepts present many different and unique ways of transporting the end pellets from storage to an area where they can be in a position for the pellet placement subsystem to use. Concepts were also developed for retracting the empty trays once all of the end pellets
4.1.4.1 Concepts for the End Pellet Unloading Subsystem

To unload the end pellets, there are two approaches that were examined. The first was to have each of the five trays within reach of the pellet placement subsystem, and the mechanism used there would be used to pick the pellets from the trays and place them on the appropriate stacks. The second was to have a mechanism that would pick up multiple end pellets at a time and place them on an infeed, which would bring the pellets closer to the measurement and pellet placement subsystems.

The first concept developed for the pellet handling subsystem involves the use of a Cartesian robot that would be able to pick up a row of pellets at a time and place them on infeed conveyors. This concept (Concept 4-1) is shown in Figure 4.21. With this Cartesian robot, the trays can be moved to a stationary position on the conveyors, and the robot can reach each row on the tray and pick up the pellets as necessary.

A second concept was developed involving a gantry system that is currently used in other areas of the manufacturing of fuel pellets at the Cameco plant. This concept
(Concept 4-2) is shown in Figure 4.22. In this concept, there are two linear slides with a fixed stroke, and a gripper that is able to pick up one row of pellets at a time and place them on an infeed conveyor. One thing to note about this concept is that the tray must be indexed in order for each row to be picked up. The indexing system developed for the measurement subsystem would be used here since the same motion is required.

A third concept (Concept 4-3) was developed involving a robot arm. The FANUC M-10iA robot has a reach of 1,420 mm and could be used with a custom-designed gripper to pick up a row of pellets at a time, and place them on an infeed conveyor. This robot could be mounted from overhead in order to reach the entire area required, or it could be floor mounted in an area that would also allow it to reach all rows of the trays, as shown in Figure 4.23.

Other ideas were explored using a mechanism to push the stacks off of the trays onto the infeed system, which would eliminate the need for a robot. The space requirements required for a system like this are over and above what is available for this station, and thus these concepts were not feasible solutions.

Concept 4-4 is a simple conveyor system that brings the trays directly from storage into the reach of the pellet placement system. The conveyor system is shown in Figure
Figure 4.22: Individual gantry design for unloading end pellets trays (Concept 4-2)

Figure 4.23: Using a FANUC M-10iA robot to pick-and-place end pellets on the conveyors (Concept 4-3)
4.7, and the trays would be arranged as they are shown in Figure 4.17. By using a simple conveyor system for this design, it eliminates the need to custom design an elaborate system that will drive up the overall cost of this subsystem. However, for this concept to be feasible, a secondary system would be required in order to move the pellets from their initial positions on the tray to a position that is designated for pick-up, inside the workspace of the pellet placement subsystem.

Concept 4-5 is a system design involving the use of a SCARA robot on a linear track, and is shown in Figure 4.24. In this design, the trays would be arranged around the SCARA in the fashion shown, and the linear track would move the SCARA so that it would be able to reach each of the five trays, pick up pellets, and place them on the five infeed tracks as shown.

4.1.4.2 Concepts for the End Pellet Conveyor Subsystem

Concept 4-6 involves the use of five vibrating track conveyors to transfer the pellets. In this concept, shown in Figure 4.24, the five V-shaped tracks are mounted on vibrating blocks that will allow the pellets to move toward the pellet placement subsystem at a maximum rate of 10 metres per minute. With these individual tracks, the footprint
of this subsystem increases since there becomes a need to mount each of the vibrating motors and tracks.

Upon researching these concepts, the idea of using chain-mesh conveyors to transport the pellets in the same manner described in Concept 4-6 was developed. In this idea, the chain conveyors can move the pellets much faster than the vibrating conveyors, and can have the pellets ready for placement faster than the vibrating tracks. One disadvantage to having individual chain conveyors for each pellet size is the footprint required.

As a result, Concept 4-7 was developed to have one chain-mesh conveyor with five tracks for the different end pellets. This conveyor concept, shown in Figure 4.25, has a much smaller footprint than the individual conveyor concept, and can interface neatly with the different loading concepts.

4.1.4.3 Concepts for Disposing of the Empty Trays

The third part of this subsystem is the retraction of empty trays. Retracting the trays back through the initial storage area is one concept that was developed, labeled Concept 4-8. In this design, the empty tray is transported on the same conveyor that brought it into the system, only in reverse. This tray would go through the pellet tray
storage area and into either an empty tray storage system, or to another transport system that would take the empty tray back for reloading.

Concept 4-9 was developed for removing the trays and involves a conveyor underneath the end pellet conveyors. In this concept, shown in Figure 4.26, once the end pellet trays are empty, they are moved onto the middle conveyor that will take them out of the system and away for reloading. This concept is good with the layout of end pellet trays shown in Figure 4.26, where the end pellet trays are centred around the end pellet conveyors. A second layout was conceptualized to have all five end pellet sizes on one side, and as a result, the empty tray conveyor would be beside the end pellet conveyors, as shown in Figure 4.27. In this concept (Concept 4-10), once the tray is empty, it would be driven onto this conveyor, and the conveyor would then transport the empty tray back to storage to wait to be refilled.

Concept 4-11 was developed in the event that Concept 4-3 was chosen as the end pellet handling subsystem. If this is the case, then the robot chosen to lift the pellets could also be used to dispose of the trays. In order to have this work, a second tool would be required and a tool change operation would happen in order to move the trays without damaging them. The amount of time and money required to make this concept a reality makes this an infeasible solution to the tray disposal problem.
4.1.5 Concepts for the Material Tracking Subsystem

To automate the material tracking system, there are a few options that currently exist. One idea is to use radio frequency identification (RFID). RFID tags can be attached to each tray and the information stored. Each time a new lot of uranium is loaded to a tray, it can be written to the central data server quickly and easily. Since the trays do pass through an oven to dry the pellets, the RFID tags chosen would have to be able to withstand the high temperatures used to heat the pellets. Using bar codes and readers is another idea that can be explored, and is currently used by Cameco. The current setup requires the operator to hold the scanner and scan each bar code one at a time for each lot of uranium used. This system would have to be modified to allow for automation.
4.1.6 Concepts for the Control Subsystem

The current method of control for similar systems at Cameco is through a Programmable Logic Controller (PLC). It would be ideal that the controller for this system also follow these guidelines for uniformity. The control subsystem is responsible for the overall operation of the system, to ensure that components are in their proper position, and to ensure that no damage occurs as a result of objects colliding or being out of position. Currently, Cameco makes use of Allen-Bradley CompactLogix PLCs. For uniformity, it would be desirable if the controller for this system also used these models.

4.2 Concept Evaluation and Selection

Once the concepts were developed, they were analyzed as both individual components and combined to form different variations of the entire system. At this stage, any infeasible concepts have been removed, and the remaining concepts were evaluated using the customer requirements as the evaluation criteria. In this section, the evaluation of the concepts for each subsystem are discussed to determine the best suitable concepts. To analyze the concepts, decision matrices were used. These matrices take each of the concepts and compares them with respect to the customer requirements, based on the importance weightings. By scoring the concepts in this way, the concept that is most suitable and meets the customer requirements is chosen.

4.2.1 Measurement Subsystem Concept Evaluation

For this evaluation, the measurement system is broken down to discuss both the compression and measurement concepts discussed in Section 4.1.1
4.2.1.1 Compression Subsystem Concept Evaluation

For this evaluation, the measurement subsystem has been broken down further to discuss both the measurement and compression methods. Certain concepts were also developed combining the compression methods and measurement concepts. Table 4.1 shows the decision matrix for the compression components. The concepts for compression presented in Section 4.1 are:

- Concept 1-2: Grooved block with two pneumatic pistons
- Concept 1-2a: Flat block with one pneumatic piston compressing against a fixed wall
- Concept 1-2b: Flat blocks, two staggered pistons and two independent, staggered, fixed walls
- Concept 1-3: Flat blocks with two pneumatic pistons, where the blocks rest above the plane of the tray

For the decision matrix, Concept 1-1 was chosen as the datum concept. When compared to Concept 1-2a, it is shown that the fixed wall concept is not ideal. It does not meet the customer requirements in the same way that the datum concept does, especially in the accuracy of the measurements, and the ability to properly guard all of the components. When the datum was compared with Concept 1-2b, it was shown that having flat blocks instead of grooved blocks would help to index the trays through the system in a fast and precise manner, which would also increase the current production. With the staggering of the compression blocks and fixed blocks, it would also allow for faster and easier end pellet placement. Concept 1-3 had the same attributes as Concept 1-2b except that the end pellets could not be placed as easily. Based on these results, it is determined that Concept 1-2b is the best solution for compressing the stacks.
### Table 4.1: Compression Component Decision Matrix

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Importance</th>
<th>Concept 1-1</th>
<th>Concept 1-2a</th>
<th>Concept 1-2b</th>
<th>Concept 1-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Index trays to proper position</td>
<td>10.0</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>R2: Accurately measure the initial stack length to determine if a stack is within the acceptable range</td>
<td>20.0</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R3: Determine the proper combination of end pellets</td>
<td>8.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R4: Pick the end pellets from the tray and place them at the ends</td>
<td>11.0</td>
<td>-</td>
<td>+</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R5: Record the pellet tracking data to a database</td>
<td>8.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R6: Take final measurement to ensure stack length is within specified tolerances</td>
<td>5.0</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R7: Reduce the overall footprint of the station</td>
<td>8.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R8: Properly guard all equipment to prevent injury/damage</td>
<td>15.0</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R9: Ensure that the pellets are not damaged during the stacking process</td>
<td>10.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R10: Increase the current production</td>
<td>5.0</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Total +’s</th>
<th>0</th>
<th>3</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total -’s</td>
<td>-</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>-3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Net Total</td>
<td>-</td>
<td>-40</td>
<td>26</td>
<td>15</td>
</tr>
</tbody>
</table>

### 4.2.1.2 Measurement Subsystem Concept Evaluation

The measurement concepts can now be evaluated to determine the best method to accurately measure the stacks. As previously determined, the measurement concepts are:

- **Concept 1-4**: Coordinate Measurement Machine (CMM)
- **Concept 1-5**: Two triangulation sensors
- **Concept 1-6**: Differential measurement concept
- **Concept 1-7**: One triangulation sensor and a fixed point
- **Concept 1-8**: Doppler measurement

Table 4.2 shows the decision matrix for the measurement concepts. For this evaluation, the datum concept was Concept 1-5. When comparing the use of a CMM to the datum, it was shown that while this method will produce accurate measurements, the overall size of the system would need to be expanded to accommodate this system.
Table 4.2: Measurement Subsystem Decision Matrix

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Importance</th>
<th>Concept 1-4</th>
<th>Concept 1-5</th>
<th>Concept 1-6</th>
<th>Concept 1-7</th>
<th>Concept 1-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Index trays to proper position</td>
<td>10.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R2: Accurately measure the initial stack length to determine if a stack is within the acceptable range</td>
<td>20.0</td>
<td>S</td>
<td>Datum</td>
<td>-</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>R3: Determine the proper combination of end pellets</td>
<td>8.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R4: Pick the end pellets from the tray and place them at the ends</td>
<td>11.0</td>
<td>S</td>
<td>S</td>
<td>+</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>R5: Record the pellet tracking data to a database</td>
<td>8.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R6: Take final measurement to ensure stack length is within specified tolerances</td>
<td>5.0</td>
<td>S</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>R7: Reduce the overall footprint of the station</td>
<td>8.0</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>R8: Properly guard all equipment to prevent injury/damage</td>
<td>15.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>R9: Ensure that the pellets are not damaged during the stacking process</td>
<td>10.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R10: Increase the current production</td>
<td>5.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
</tbody>
</table>

Total +’s: 1, Total -’s: 4, Net Total: -28

Also, since the CMM must make contact with each end of the stack, the cycle times will be increased resulting in less production.

The differential measurement concept (Concept 1-6), which uses one laser head with two lasers has one distinct disadvantage over the datum concept. The accuracy of the measurement decreases over large distances, so measuring from one end of the stack to the other would produce greater error in the measurement than the datum concept.

Concept 1-7 presents the idea of using a fixed point of reference for one end of the stack, while measuring the displacement of the other end with a triangulation sensor.

In this concept, two measurement systems could be set up side by side, one to perform the initial measurement and one to perform the final. In this layout, the productivity could be increased, and the area where the pellets are being placed would be clear of any mechanisms.
Concept 1-8 uses Doppler technology to measure the length of the stacks. This Doppler unit is mounted on a gantry device that scans each stack to give a measurement. The main issue surrounding this technology is the accuracy of the Doppler system. It does not meet the tolerance requirements of this system in order to ensure an accurate stack length for the fuel bundles.

From Table 4.2, it is shown that Concept 1-7 would be the best measurement concept for this subsystem. In addition to being the best suited to meet the main customer requirements, this concept is also the most cost-effective solution to accurately measure the stacks. As discussed above, by using two triangulation sensors in a configuration shown in Figure 4.3, productivity can be increased and the area in which the pellets are being placed is clear of any measurement or compression equipment.

4.2.2 Work Tray Subsystem Concept Evaluation

For the work tray subsystem, the concepts presented are required to transport the work tray from a storage location into the measurement subsystem and out to a storage area. A second part of this subsystem requires the trays to be sorted based on whether or not they require reworking.

4.2.2.1 Work Tray Indexing Concept Evaluation

The concepts for this component of the work tray subsystem are:

- Concept 2-1: Conveyor system
- Concept 2-2: Cart system
- Concept 2-3: Geneva wheels

For the decision matrix shown in Table 4.3, Concept 2-2 was chosen as the datum. In this concept, carts which run on tracks guide the work trays through the measurement system. This system, although accurate, requires additional equipment and custom
Table 4.3: Work Tray Indexing Decision Matrix

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Importance</th>
<th>Concept 2-1</th>
<th>Concept 2-2</th>
<th>Concept 2-3</th>
<th>Datum</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Index trays to proper position</td>
<td>10.0</td>
<td>S</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>R2: Accurately measure the initial stack length to determine if a stack is within the acceptable range</td>
<td>20.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R3: Determine the proper combination of end pellets</td>
<td>8.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R4: Pick the end pellets from the tray and place them at the ends</td>
<td>11.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R5: Record the pellet tracking data to a database</td>
<td>8.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R6: Take final measurement to ensure stack length is within specified tolerances</td>
<td>5.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R7: Reduce the overall footprint of the station</td>
<td>8.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R8: Properly guard all equipment to prevent injury/damage</td>
<td>15.0</td>
<td>+</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>R9: Ensure that the pellets are not damaged during the stacking process</td>
<td>10.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R10: Increase the current production</td>
<td>5.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Total +’s</td>
<td>1</td>
<td>-</td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Total -’s</td>
<td>0</td>
<td>-</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>-</td>
<td></td>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>Net Total</td>
<td>15</td>
<td>-</td>
<td></td>
<td></td>
<td>-5</td>
</tr>
</tbody>
</table>

designs in order to be manufactured. When compared to the conveyor concept, shown in Concept 2-1, the cost associated with standard conveyors is much less than custom work, and with the conveyors there are less moving components. The Geneva wheels in Concept 2-3 will provide a more accurate indexing, since they guarantee the same motion for each revolution, however again there are more moving components. As a result, using conveyors is the ideal solution to the work tray transportation.

### 4.2.2.2 Work Tray Sorting and Storing Concept Evaluation

To sort the trays, the following concepts were developed:

- **Concept 2-4**: Linear transfer conveyor with two output conveyors
- **Concept 2-5**: Single conveyor with two storage hoppers
- **Concept 2-6**: Raised conveyor
- **Concept 2-7**: Trap-door conveyor
- **Concept 2-8**: Y-style conveyor
### Table 4.4: Sorting and Storing Decision Matrix

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Importance</th>
<th>Concept 2-4</th>
<th>Concept 2-5</th>
<th>Concept 2-6</th>
<th>Concept 2-7</th>
<th>Concept 2-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Index trays to proper position</td>
<td>10.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R2: Accurately measure the initial stack length to determine if a stack is within the acceptable range</td>
<td>20.0</td>
<td>S</td>
<td>Datum</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R3: Determine the proper combination of end pellets</td>
<td>8.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R4: Pick the end pellets from the tray and place them at the ends</td>
<td>11.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R5: Record the pellet tracking data to a database</td>
<td>8.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R6: Take final measurement to ensure stack length is within specified tolerances</td>
<td>5.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R7: Reduce the overall footprint of the station</td>
<td>8.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>R8: Properly guard all equipment to prevent injury/damage</td>
<td>15.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>R9: Ensure that the pellets are not damaged during the stacking process</td>
<td>10.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>R10: Increase the current production</td>
<td>5.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>S</td>
</tr>
</tbody>
</table>

| Total +'s | 0 | 0 | 0 | 0 | 0 | 0 |
| Total -'s | 3 | 3 | 3 | 3 | 3 | 3 |
| Total | -3 | -3 | -3 | -3 | -3 | -3 |
| Net Total | -28 | -28 | -28 | -28 | -28 | -28 |

The single conveyor with two output hoppers was chosen as the datum for the decision matrix shown in Table 4.4, and when compared to the other concepts, it is shown that the datum would perform better in the areas where the sorting and storing of trays was concerned. With the single output conveyor, the overall footprint of the system was dramatically reduced, as was the need for additional guards and safety measures that would have to be put in place with moving parts and conveyors. From this analysis, it was determined that the single output conveyor with two output hoppers was the best design for the sorting and storing of the trays once they have gone through the measurement and pellet placement subsystems.

#### 4.2.3 Pellet Placement Subsystem Concept Evaluation

For the pellet placement subsystem, three concepts were found to be feasible solutions to the problem:

- Concept 3-1: One SCARA robot to place pellets on both ends
Table 4.5: Pellet Placement Subsystem Decision Matrix

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Importance</th>
<th>Concept 3-1</th>
<th>Concept 3-2</th>
<th>Concept 3-3</th>
<th>Concept 3-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Index trays to proper position</td>
<td>10.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R2: Accurately measure the initial stack length to determine if a stack is within the acceptable range</td>
<td>20.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R3: Determine the proper combination of end pellets</td>
<td>8.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R4: Pick the end pellets from the tray and place them at the ends</td>
<td>11.0</td>
<td>S</td>
<td>+</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R5: Record the pellet tracking data to a database</td>
<td>8.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R6: Take final measurement to ensure stack length is within specified tolerances</td>
<td>5.0</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R7: Reduce the overall footprint of the station</td>
<td>8.0</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R8: Properly guard all equipment to prevent injury/damage</td>
<td>15.0</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>R9: Ensure that the pellets are not damaged during the stacking process</td>
<td>10.0</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>R10: Increase the current production</td>
<td>5.0</td>
<td>+</td>
<td>S</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Total +'s</th>
<th>Total -'s</th>
<th>Total</th>
<th>Net Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datum</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-18</td>
</tr>
</tbody>
</table>

- Concept 3-2: Two SCARA robots, one at each end
- Concept 3-3: One FANUC 6-Axis LRMate robot
- Concept 3-4: Design of a custom gripper

When compared using the decision matrix in Table 4.5, it is shown that the design of a custom gripper would be a concept to consider. However, the cost of developing such a gripper to hold all five types of end pellets at one time would put this project over budget. By working with Concept 3-2 and adding an additional SCARA robot and set of end pellets at the other end of the stack, the cycle time is decreased, but the overall footprint of the station is increased, as is the number of safety concerns by adding a second robot in such a confined space. It is shown in the decision matrix that the increase in overall station size has a larger penalty associated with it compared to the need for an improved cycle time, resulting in one robot being the ideal design for this subsystem.
When the SCARA concept in 3-1 is compared to the FANUC 6-axis robot, it is shown that the production rate would be roughly the same for either robot. The LRMate robot from FANUC is designed for high-speed pick-and-place applications such as this, and has cycle times that are comparable with the SCARA robots. In addition to the cycle times, the reach of the 6-axis robot is larger than the SCARA, making the placement of the robot more flexible so that it can reach both ends of the work tray and the end pellet infeed area. In addition, Cameco already uses FANUC robots in other operations.

After this analysis, it has been determined that the FANUC LRMate robot is the best choice for the pellet placement subsystem.

4.2.4 End Pellet Handling Subsystem Concept Evaluation

There are three main subsystems that make up the end pellet handling subsystem. These are the end pellet unloading, the end pellet conveyor, and the disposal of empty trays.

4.2.4.1 End Pellet Unloading Concept Evaluation

For the end pellet unloading, the concepts developed are:

- Concept 4-1: Cartesian robot to pick up rows of pellets at a time
- Concept 4-2: Individual gantry system for each size of end pellet
- Concept 4-3: FANUC M-10iA robot with a custom gripper
- Concept 4-4: Trays arranged around a single SCARA robot
- Concept 4-5: SCARA robot on a linear track

From Table 4.6, it is shown that the datum concept that incorporates individual gantry systems for each end pellet size is the superior concept. This concept, although having
Table 4.6: End Pellet Unloading Decision Matrix

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Concept 4-1</th>
<th>Concept 4-2</th>
<th>Concept 4-3</th>
<th>Concept 4-4</th>
<th>Concept 4-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Index trays to proper position</td>
<td>10.0</td>
<td>S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2: Accurately measure the initial stack length to determine if a stack is</td>
<td>20.0</td>
<td>S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>within the acceptable range</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Datum</td>
<td></td>
<td>S</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R3: Determine the proper combination of end pellets</td>
<td>8.0</td>
<td>S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4: Pick the end pellets from the tray and place them at the ends</td>
<td>11.0</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R5: Record the pellet tracking data to a database</td>
<td>8.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R6: Take final measurement to ensure stack length is within specified tolerances</td>
<td>5.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R7: Reduce the overall footprint of the station</td>
<td>8.0</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>R8: Properly guard all equipment to prevent injury/damage</td>
<td>15.0</td>
<td>-</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R9: Ensure that the pellets are not damaged during the stacking process</td>
<td>10.0</td>
<td>S</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R10: Increase the current production</td>
<td>5.0</td>
<td>-</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Total +'s</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total -'s</td>
<td>-3</td>
<td>-</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>-2</td>
<td>-</td>
<td>-2</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Net Total</td>
<td>-24</td>
<td>-</td>
<td>-23</td>
<td>-8</td>
<td>-8</td>
</tr>
</tbody>
</table>

a slightly larger footprint than the rest, will increase productivity by decoupling the five end pellet types and their placement. The amount of movement required to pick up a row of pellets is also decreased in this design, and fixed stroke actuators are used to minimize the amount of control required, making the repeatability of the pellet placement much better than other systems.

4.2.4.2 End Pellet Conveyor Concept Evaluation

For the pellet conveyor concepts, the three concepts that were developed were:

- Concept 4-6a - Individual vibrating conveyors
- Concept 4-6b - Individual chain-mesh conveyors
- Concept 4-7 - One chain-mesh conveyor with five lanes for the end pellets

Table 4.7 shows that the single chain-mesh conveyor is the ideal solution for this subsystem. With the single chain-mesh conveyor, the amount of space required is
Table 4.7: End Pellet Conveyor System Decision Matrix

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Importance</th>
<th>Concept 4-6a</th>
<th>Concept 4-6b</th>
<th>Concept 4-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Index trays to proper position</td>
<td>10.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R2: Accurately measure the initial stack length to determine if a stack is within the acceptable range</td>
<td>20.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R3: Determine the proper combination of end pellets</td>
<td>8.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R4: Pick the end pellets from the tray and place them at the ends</td>
<td>11.0</td>
<td>S</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>R5: Record the pellet tracking data to a database</td>
<td>8.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R6: Take final measurement to ensure stack length is within specified tolerances</td>
<td>5.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R7: Reduce the overall footprint of the station</td>
<td>8.0</td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>R8: Properly guard all equipment to prevent injury/damage</td>
<td>15.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R9: Ensure that the pellets are not damaged during the stacking process</td>
<td>10.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R10: Increase the current production</td>
<td>5.0</td>
<td>-</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Total +'s</td>
<td>1</td>
<td>-</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Total '-'s</td>
<td>1</td>
<td>-</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>-</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Net Total</td>
<td>3</td>
<td>-</td>
<td></td>
<td>19</td>
</tr>
</tbody>
</table>

much less when compared to the individual conveyors. Also, the single conveyor concept can bring the end pellets much closer to the work tray, thus making the pick-and-placement of the end pellets much easier.

### 4.2.4.3 Empty Tray Disposal Concept Evaluation

For disposing the empty trays, the concepts that were developed were:

- Concept 4-8: Retract trays through initial storage hopper
- Concept 4-9: Central conveyor underneath the end pellet conveyors
- Concept 4-10: Conveyor at the end of the end pellet placement subsystems
- Concept 4-11: Using the FANUC M-10iA to remove the trays

It was previously determined that Concept 4-11 was infeasible due to the cost and complexity associated with it, as well as the fact that the FANUC M-10iA robot was not chosen as the end pellet placement concept.
Table 4.8: Empty Tray Disposal Decision Matrix

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Importance</th>
<th>Concept 4-8</th>
<th>Concept 4-9</th>
<th>Concept 4-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Index trays to proper position</td>
<td>10.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R2: Accurately measure the initial stack length to determine if a stack is within the acceptable range</td>
<td>20.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R3: Determine the proper combination of end pellets</td>
<td>8.0</td>
<td>S</td>
<td>Datum</td>
<td>S</td>
</tr>
<tr>
<td>R4: Pick the end pellets from the tray and place them at the ends</td>
<td>11.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R5: Record the pellet tracking data to a database</td>
<td>8.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R6: Take final measurement to ensure stack length is within specified tolerances</td>
<td>5.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R7: Reduce the overall footprint of the station</td>
<td>8.0</td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>R8: Properly guard all equipment to prevent injury/damage</td>
<td>15.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R9: Ensure that the pellets are not damaged during the stacking process</td>
<td>10.0</td>
<td>S</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>R10: Increase the current production</td>
<td>5.0</td>
<td>-</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Total +’s</td>
<td>1</td>
<td>-</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Total -’s</td>
<td>1</td>
<td>-</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>-</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Net Total</td>
<td>3</td>
<td>-</td>
<td></td>
<td>8</td>
</tr>
</tbody>
</table>

As shown in the decision matrix in Table 4.8, Concept 4-9 was chosen as the datum concept. It is shown in this matrix that both Concept 4-8 and 4-10 are more viable than the datum in this case, with Concept 4-10 being best suited to dispose of the trays. This is even more true since the individual gantry systems have been selected for unloading the trays.

4.2.5 System Control

The concepts that have been selected for each of the subsystems are combined to provide a comprehensive look at the Automated Pellet Stacking System. Each system will be linked together through a common Programmable Logic Controller (PLC). Radio Frequency Identification (RFID) will be used for material tracking throughout the process. RFID tags will be affixed to each tray that carry pellets and the data for each tray will be stored on a central computer that communicates with the RFID readers.
4.3 Chosen System Design

After completing the analysis and evaluation of the concepts, a final design was chosen for each subsystem, and these subsystems were combined to create the entire pellet stacking system design. The proposed design of the system is shown in Figure 4.28. For the measurement subsystem, two triangulation sensors with two staggered, pneumatic compression pistons are used, while two fixed, staggered walls will provide a base for the compression. In this design, the measurement system will be calibrated so that once the fixed walls are set, the system will determine the lengths of the stack with that point as a zero point. The layout for this system is shown in Figure 4.29. For the work tray subsystem, the conveyor concept is used with an external sensor system to provide the accurate indexing required. These sensors will be designed to index the tray so that each stack is in the same position for measurement and
compression. This will ensure that the measurements are being taken from the same spot for each stack and that the stacks are in the right position to receive the end pellets. For sorting and storing the work trays, the single output conveyor with multiple hoppers has been selected, and is shown in Figure 4.30.

For the pellet placement subsystem, the 6-axis LRMate robotic arm from FANUC Robotics is used. This robot is designed specifically to pick-and-place objects at a high rate of speed. The robotic arm used for the pellet placement subsystem can also be inversely mounted to reduce the overall footprint of the system, and to allow the robot to reach all parts of the end pellet conveyors and the work trays. The robot will use a gripper that can pick-up two pellets at a time to reduce cycle times (see Figure 4.20.

For the end pellet handling subsystem, individual gantry systems will be used to place rows of end pellets onto a single conveyor separated into five lanes. For the end pellet handling system, to place the pellets from the trays to the conveyors, a gripper will be designed that can pick-up an entire row of end pellets at one time and place them onto the conveyor. This system is shown in Figure 4.31.
Figure 4.30: Work tray sorting and storing final concept

Figure 4.31: End pellet unloading final concept
The entire system will be framed using T-slotted extruded aluminum and shielded according to the specifications set out by the CSA [18]. In order to allow the end pellets to get close to the work area of the robotic arm, the end pellet conveyors will be set higher than the measurement station.

The entire system will be controlled using an Allen-Bradley PLC using CompactLogix. The robot will have its own controller, but will be interfaced through the PLC. The PLC is equipped with both analog and digital I/O channels, as well as the ability to read in the laser data from the RS232 connections. The PLC will have an operators window and user-friendly interface and be linked to the plant monitoring systems so that the system can be monitored remotely. In addition, the system will record all information concerning which pellets are used in each stack.

4.4 Remarks on the Selected Concept

A proposed final design taking the best concepts from each subsystem has been presented in this chapter. After meeting with the team of engineers at Cameco, it was determined that some modifications were required in order to meet certain criteria for maintenance and quality control. These modifications included eliminating the single end pellet conveyor and having an individual conveyor for each end pellet size. This change was required due to the possibility of wear on the pellets if they are not used for an extended period of time. With the belt constantly running, it could create a flat side to the pellet, which may cause a failure in the bundle once it is put into a reactor.

The second change made was to the layout of the end pellet subsystem. The selected concept had each of the five end pellet placement mechanisms on the same side, with a disposal conveyor on the opposite end. Concerns were raised regarding the ability of maintenance people to reach the end pellet unloading mechanisms in the event of
a failure or required maintenance. As a result, the layout was modified so that the end pellet unloading mechanisms alternate sides, as shown in Figure 4.32. This allows maintenance personnel to access all of the end pellet mechanisms and also load the tray hoppers without interrupting the operation of the system. With this layout, the end pellet disposal conveyor was also removed, and it was suggested by the team at Cameco that the trays be driven back through the storage hopper and into a collection bucket, where they would be picked up by an operator several times a shift.

A modified output system was also discussed due to the amount of throughput for this system. It was suggested that with the reduced cycle time per tray, an output hopper for completed trays would fill quite fast, resulting in a user unloading and moving trays almost constantly throughout a shift. As a result, the output hopper for completed trays was removed and it was decided that Cameco would develop a link between this system and the next stage in the operation. This modified layout is shown in Figure 4.33. Any flagged trays would still be moved into the remaining hopper.

To refine the design of this system further, detailed design methods will be used including an elemental analysis of each component of the system. Material and part selection steps will also be taken in order to ensure that the system complies with the regulations surrounding this industry. The next chapter in this thesis will outline part materials and geometries chosen and will contain engineering analysis for custom designed parts, and the test results from the proof-of-concept prototype.

### 4.5 Summary

This chapter has discussed and evaluated all of the concepts that were generated for each subsystem, and a final concept has been chosen for each area of the system. For the measurement subsystem, two triangulation sensors are used reflecting off two
Figure 4.32: Final end pellet unloading layout
pneumatic pistons which are used for the compression subsystem. For the work tray subsystem, a conveyor is used to index the trays with a sensor tracking the position of the tray to ensure the work tray will be in the proper position for measurement and pellet placement. Pellet placement will be accomplished by a LR Mate 200iC/5L robot from Fanuc Robotics and a gripper that is capable of holding two pellets at a time. The end pellet handling will be done by the custom gantry system that is already in use at Cameco to place and remove pellets at the grinders. These concepts will be further discussed and refined where required in the next chapter.
Chapter 5

Form Design and Analysis

In this chapter the final design is presented and refined based on engineering analysis of the components and feedback received from the team at Cameco. This chapter also discusses the assembly of a proof-of-concept prototype that was built to test the functionality of the system. Results and refinements from testing this prototype will be discussed in Chapter 6.

5.1 Introduction to the System

The final system consists of six subsystems, each of which has multiple components and functions as discussed in Chapters 2 and 4. These subsystems were designed first for function and then the form was built to allow the subsystems to function as required. The functions of each subsystem have been discussed in detail in Chapter 2. This section discusses in detail the form design of these subsystems and provides analysis where necessary to validate the design.

Figure 5.1 shows the layout of the final design. In this model, the end pellets are loaded to the conveyors and moved into the reach of the pellet placement robot. When the pellets reach their pick-up point on the conveyor, a slot sensor is there to stop the conveyor and inform the robot that a pellet is ready for pick-up. This will

104
Figure 5.1: Complete automated pellet stacking system
ensure that the robot is not trying to pick up a pellet that is not there. There is also a cover over the next few pellets on the conveyor so that when the robot picks up the required end pellet, it does not change the orientation of the next pellet.

As the tray is indexed through the system, the required compressions and measurements are controlled by the algorithm which will be presented in this chapter. As end pellets are needed, the robot will pick them up and place them on ends of the stacks. The gripper is designed so that the robot can pick up both end pellets required for a stack before proceeding to place them. This set-up cuts the cycle time down to a level that is acceptable for this system.

When the entire tray has been completed, it will be transferred to an output conveyor so that while it is being transferred to the next stage, the next tray can be transferred to the indexing station. If the tray is flagged because a stack is unsolvable, then it will be loaded into a hopper on the output conveyor to be manually reworked.

The complete set of engineering drawings for the system can be found in [30].

5.2 Measurement Subsystem

The final measurement subsystem concept presented in Chapter 4 was designed to individually compress and measure each of the stacks on the tray. Two measurements are taken; one to determine what combination of end pellets are required to complete the stack, and the other to ensure the end pellets that were chosen have completed the stack to within the specified tolerances. From the functional decomposition, it was determined that a compression subsystem would be needed prior to measurement in order to ensure that there are no gaps in the stacks that would result in incorrect measurements.

The compression pistons chosen for this function are small enough that they can be placed just four stacks apart. This allows for fewer indexes per tray which reduces the
cycle time, but still gives enough room for the pellet placement subsystem to place the pellets without interfering with the other subsystems. During the initial evaluation of the design, it was determined that a third compression unit should be added to ensure the pellets are aligned the same on the trays so that when the tray is indexed to be compressed and measured, the pellets will be clear of the fixed walls. This is an important design feature because if the pellets are not aligned properly on the tray they could be driven into the fixed walls, knocking them out of the stacks and causing a shutdown of the system. The measurement subsystem with this additional compression unit is shown in Figure 5.2.

When a tray enters the work tray subsystem, the initial compression unit aligns the first three stacks before any measurements are taken. This is done because of the spacing constraints of the system. When the fourth stack is being aligned, the first stack is being compressed and measured. That measurement is recorded and from it the required end pellets are determined. This information is sent to the pick-and-place controller. The space between the initial and final measurement systems is four stacks, or 70 mm. This allows enough space for the gripper to place the pellets on the ends of the stacks without colliding with any of the other components in the system. Pellets are placed two indexes after the initial measurement is taken due to space constraints.

To compress a stack, a minimum of 5 N of force is required to be exerted from one end of the stack. This accounts for the force of friction of the uranium pellets against the tray and ensures the complete compression of each stack. Through testing, the optimal operating force for the compression system will be determined so that the stacks are compressed quickly without causing any damage to the pellets.

The blocks that were attached to the pistons to compress the stacks were made from stainless steel. This was required due to the material restrictions with parts that contact the uranium. Only stainless or chrome plated steel can be used to contact
Figure 5.2: Measurement and compression system with third pneumatic unit for aligning the pellets on the trays
It was also determined that the measurement should be taken off of the compression block since the uranium pellets have a concave end profile that would affect the accuracy of the subsystem. It was also determined that the laser beam would reflect better off of the steel block used for compression rather than the dark uranium pellet. With this design decision, the laser measurement units are set up to fire the laser over top of the compression system and hit the top of the compression block. This setup is shown in the close-up in Figure 5.3.
The frame for this subsystem was built from extruded aluminum using standard lengths and fasteners wherever possible. This extruded aluminum was chosen for its modularity, availability, and cost. The stand for the laser measurement units is decoupled from the rest of the system so that any vibrations resulting from the motion of the work tray subsystem or the compression units does not directly impact the measurement units. The fixed walls and compression pistons are mounted to the frame and are fixed in place so that when a tray is in position to be worked on, the pistons, walls, and measurement heads are aligned. The measurement heads are attached to linear adjustment stages that allow for minor adjustments in the laser position in two directions. This adjustment will not alter the distance between the laser and the compression head, which is fixed in order to achieve accurate measurements.

In order to compress a stack and take a measurement, 0.5 seconds is required to switch the solenoid to extend and retract the compression piston and take the measurement. The measurement times do not affect the overall cycle time as the laser head can obtain measurements close to instantaneously upon being triggered. Once the initial measurement has been taken and a length has been determined, the required end pellets need to be determined. Since there are five different sizes of end pellets and two of the same size can be placed on the stack, there are 15 possible combinations of end pellets that can be placed. These lengths can be placed in an array and based on the measurement the control algorithm will determine which combination of end pellets will make the stack within the specifications. The testing that was conducted on this system is discussed in Chapter 6 and any refinements that were made as a result are discussed there.

5.2.1 Measurement Subsystem Proof-of-Concept Prototype

A proof-of-concept prototype was built of the measurement subsystem in order to test the accuracy and repeatability of the laser triangulation sensors, as well as the ability
of the compression system to accurately compress the stacks while not damaging the pellets. The prototype for this subsystem is shown in Figure 5.4. The prototype was set up on a frame constructed from extruded aluminum, which would also be used in the final design of the system.

The conveyor was not used in this prototype, but instead two pieces of extruded aluminum were set up to ensure the tray would be straight and perpendicular to the measurement units.

The fixed walls and compression blocks were constructed from stainless steel.

The pneumatic pistons are keyed to ensure the shaft does not rotate during actuation, which could result in the laser returning inaccurate measurements. The pneumatic valves are 24V, double-acting solenoids that can control both the compression and retracting of the pneumatic pistons. The valve block is shown in Figure 5.5. There are five solenoids on this block; three are used for the compression pistons and the
other two are used to control the gripper in the pellet placement subsystem. All pneumatic products were purchased from Festo.

The spacing of the compression pistons and measurement pistons is the same as the final design presented, however the mounting of certain components is slightly different. In the final design, the measurement units are mounted independently of the rest of the system. This will eliminate vibrations induced from the compression system which could affect the measurements. In the prototype shown in Figure 5.4, the lasers and compression units are all connected to the same frame, as this prototype was used to test the functionality. Even with these two units connected, the system still performs within the required specifications set out by Cameco. The tests that were performed on this subsystem and the results obtained are presented in Chapter 6.

5.3 Pellet Placement Subsystem

The overall goal of this system is to place the proper end pellets on each stack. The consistency, repeatability, and speed of this subsystem are all very important
Figure 5.6: Pellet placement robot with the gripper attached to Joint 6

characteristics to the overall success of this system. It was determined in Chapter 4 that pellet placement would be done by a Fanuc LRMate 200iC/5L robot with a custom gripper. Fanuc robots are the standard used by Cameco. The custom gripper is designed to pick-up and securely hold two end pellets and place one on each end of the stack. This is accomplished by having two grippers attached to Joint 6 (J6) of the robot, as shown in Figure 5.6. These two grippers are connected to a solid plate that is connected directly to J6, and are spaced apart so that each can pick up a pellet without interfering with the other. The control for each gripper is independent so that one gripper can pick-and-place a pellet without affecting the pick-and-place of the other. The grippers are pneumatically actuated.

The main discussion point for this system is the effect the pellet placement operation has on the overall cycle time of the system. A simulation was performed using a Fanuc simulation program that allowed the CAD files of the system to be imported and the robot to be programmed. This was done to ensure that the chosen robot could indeed reach all of the pick-and-place points, and to determine the time it would take to do
the pick-and-place operation. Through this simulation, it was shown that the worst case scenario, which required two extreme sized end pellets spaced the furthest apart in the system, would take the robot 4.1 s to move from its safe position, pick up the two pellets, place them at each end of the stack, and return to its safe point ready for the next pellets. The simulation path is shown in Figure 5.7, while the teach pendant used to program this motion is shown in Figure 5.8.

Through the use of the simulation program, different mounting positions for the robot were experimented with including floor mounting, inverted mounting, and wall mounting positions. Through discussions with Cameco it was deemed that the inverted and wall mounting concepts would require major structures to be built around the system in order to provide enough support for the robot. Since the robot model chosen has a longer reach than most robots for its size, it was determined that mounting the robot on to a platform that would place the robot over top of the output conveyor would be ideal for this system. This layout is shown in Figure 5.9. The platform is made out of steel and welded together to provide a solid base for the robot. It is also fixed
Figure 5.8: Teach Pendant from simulation software, used to program the robot

Figure 5.9: Robot mounted over the workspace
in position to the floor. This is done so that once the robot is installed on the factory floor and the robot’s positions are taught, the robot will not move and thus there will be no need to re-teach the positions if the system gets bumped. The platform, shown in Figure 5.10, is designed to limit the amount of vibrations so that the robot is as steady as possible while operating at high speed, and to maintain the repeatability of the robot. After performing some basic stress analysis on the platform made of solid steel, it was determined that a square, hollow, steel profile could be used for the legs and cross members and still adequately support the robot operating at high speed.

5.3.1 Pellet Placement Subsystem Proof-of-Concept Prototype

A proof-of-concept prototype for the pellet placement subsystem was constructed for testing both the speed of the robot and the ability of the gripper. However, due to circumstances beyond control, the Fanuc robot could not be purchased in time.
As a result, an Epson Pro Six PS3 robot with similar reach capabilities was used. The Epson robot was not comparable in robot speed so an accurate test for cycle time could not be conducted, however the simulation previously discussed gives an estimated cycle time that proves this subsystem is viable.

The gripper design that was previously discussed was constructed and mounted in the Epson robot for testing, shown in Figure 5.11. The prototype setup involved the Epson robot, the gripper, a tray of pellets and two conveyors that were set up the required distance apart. In this prototype, the conveyors were not run, but were just used as supports for the tray. The entire prototype setup is shown in Figure 5.12.

Several tests were done to ensure the grippers would function correctly and could pick-and-place pellets on the tray, hold the pellets securely during robot motion, and would not contact or damage other pellets in neighbouring rows when placing pellets.
5.4 Work Tray Subsystem

For the work tray subsystem, the main components are the conveyor and the sensors. The positioning and sensitivity of these sensors is important for the tray to be indexed accurately, and this will be discussed in Chapter 6.

The conveyor system chosen for the work tray subsystem is a gang-driven conveyor, meaning two belts are driven by a common drive. The two belts have a centre-to-centre distance equal to the distance between the legs on the tray. Gang-driven conveyors are good for this application because the automated tray lift device for loading the output hopper can be placed in between the two belts without impacting any other part of the system. The gang-driven conveyor also allows the two belts to move at the same speed. This will ensure that the tray will not become skewed as a result of two different belt speeds.

The belt on the conveyors is a V-guided belt, shown in Figure 5.13. By having this notch in the belt, it will ensure the belt does not slip to the sides on the pulleys or the main track. The belt has a urethane surface with a polyester core that produces a coefficient of friction with the trays that eliminates slippage of the trays at a normal operating speed. The belt also has a high resistance to chemicals and harmful
materials, making it an attractive option for this subsystem.

The conveyor chosen for this subsystem is a 3200 Series conveyor from the Dorner Conveyor Company. This conveyor can hold up to 180 kg which is much more than a tray of uranium pellets. It is designed to allow for fast belt changes, which will reduce downtime in the event the belt fails or is replaced during preventative maintenance. All bearings are sealed to prevent any uranium dust from entering and breaking down the components.

The indexing sensors that were purchased are manufactured by Banner Engineering, whom Cameco currently purchases sensors from for other systems. The sensors chosen are slot sensors shown in Figure 5.14, which have an emitter and receiver that can easily sense when an edge or hole is present. The sensor has a 300 microsecond response time as well as a sensitivity adjustment in order to fine tune the output [13]. The slot is 30 mm wide and is mounted so that it can detect when a stack is present
by detecting the oblong holes on the trays, as shown in Figure 5.15. The trays are manufactured by a stamping process, so it can be assumed that as long as the trays are manufactured correctly, the holes on the tray will give a suitable point of reference for indexing. The sensor is shown as it was mounted for testing in Figure 5.15. For indexing the trays within the measurement subsystem, two sensors are used and are placed before the first compression system and after the last compression system. Since there are multiple operations that take place in the measurement subsystem, one sensor would not be enough to index a single tray through all of the required operations. Figure 5.16 shows the sensors mounted in the final design. Here it is shown that there are two sensors and the spacing of these sensors corresponds to the spacing of the stacks on the tray. The first index sensor will sense one row before the first compression system, while the second sensor will start to sense the trays two rows after the final measurement. This redundancy allows the tray to always be sensed by at least one of the sensors throughout the entire operation.

5.4.1 Work Tray Subsystem Proof-of-Concept Prototype

A proof-of-concept prototype for the work tray subsystem was also developed. The main purpose for developing this prototype was to verify the accuracy of the indexing method that was developed in Chapter 4. To do this, the indexing sensor was setup
as shown in Figure 5.15 and a tray was placed on the conveyor. The conveyor was run and a program was set up to stop the conveyor each time the sensor had detected a row.

In this prototype, the gang driven conveyor style that was specified for this project could not be implemented in time, so two, individually controlled conveyors were used and set to the same speed. The conveyor could then be run at different speeds to determine the optimal speed that gives the most accurate indexing. This indexing is important to the measurement and pellet placement subsystems so the system can ensure accurate measurements and that the end pellets are being placed on the correct stacks.

During the development of this prototype, there was an issue that arose involving the ability of the trays to be dropped straight on the conveyor. Trays not being straight on the conveyor was found to be a problem for both the accuracy of the measurements and compression subsystems, but also the pellet placement subsystem. If the tray is not straight, the robot could occasionally place an end pellet in the wrong stack. This would create errors for the entire tray. The Cameco team disclosed that they have also had this problem, and had developed a solution for it that could be implemented in this system as well. This solution calls for a pneumatic piston to
push the trays against a fixed partition to straighten the tray. This ensures that the 
trays are straight while running on the conveyor and that all trays are in the same 
position on the conveyor.

It was also determined that by decoupling the input conveyor and the indexing con-
veyor in the measurement subsystem the next work tray could be entered into the 
system sooner, resulting in lower wait times for the overall system.

5.5 End Pellet Handling Subsystem

The end pellet handling subsystem has three different operations that are performed: 
the end pellet unloading, the end pellet conveyor system, and the disposal of empty 
trays.

The end pellet unloading is done by a gantry system that is designed to pick-and-place 
an entire stack of pellets at one time. This fixed-stroke gantry system was designed 
by Cameco to load and unload the pellets at the grinders during the manufacturing 
process. The placement of the pick-and-place mechanism has been modified slightly 
to fit this application, and each unit is staggered slightly so that each unit does not 
require a different, custom stroke mechanism.

The pick-and-place of each row of pellets requires the tray to be indexed each time 
a new row is required. The same sensor setup from the work tray subsystem is used 
to index the trays in the end pellet handling subsystem, however only one sensor is 
needed per tray as the placement of the pick-and-place mechanism allows placement 
of the sensor to be inline with the stack being picked. This system is currently in use 
at Cameco and on their request it will not be built as part of the prototype for testing 
purposes for this system.

The end pellet conveyor system also makes use of existing technologies within the 
manufacturing line at Cameco. Cameco has an existing conveyor design used to
transport the pellets through the grinders. The conveyor for the end pellets was designed to transport the pellets quickly without damaging them while restricting the side-to-side motion of the pellets. This will standardize the pick-up point at the end of the conveyor. A model of one of these conveyors is shown in Figure 5.17. In order to have these conveyors fit within the allotted footprint for this system, each conveyor had to be a different length. This would allow all of the conveyor drives to be placed in the system. With the placement of the end pellet unloading mechanisms being staggered on either side of the end pellet conveyors, the conveyors are designed so the drives are in the open space between the end pellet unloading mechanisms. This can be shown in the overhead view of the system in Figure 5.18

The belt on these conveyors is a stainless steel, balanced weave belt from Ashworth Bros Inc., shown in Figure 5.19. These belts offer an excellent strength to weight ratio, a flat surface, and minimal maintenance. The belts are friction driven and provide a uniform conveying surface with a strong resistance to distortion [14].

A concern was expressed that when the robot picks up the pellet it may re-orient the next pellet in line on the end pellet conveyors. As a result, a cover was designed to be placed over the few pellets directly behind the one being picked up by the robot. This cover will prevent the pellets from flipping up on their ends, which would cause
Figure 5.18: Final end pellet unloading layout

Figure 5.19: Section of the belt used on the end pellet conveyors [14]
Figure 5.20: Cover designed to ensure end pellets do not flip on their ends during pick-up

the system to fail. This cover, shown in Figure 5.20, is an angled block that connects to the guide rails of the end pellet conveyors. There is a channel on this block to allow the pellets to pass through as they progress along the conveyor. The channel is designed so that the end pellet awaiting pick-up is not covered, but the following few pellets are all restricted so that they cannot flip up on their ends as the gripper picks up a pellet.

The sensor that is used to detect the end pellets presence at the end of the conveyor is attached to this block, positioned as shown in Figure 5.21 so that it can sense when a pellet is present. The sensor is positioned in this fashion since the belt width is slightly larger than the slot of the sensor, and any other mounting positions would result in interference between the sensor and either the belt or the gripper as it attempts to pick up the pellets. The block and sensor assembly is shown connected to an end pellet conveyor in Figure 5.22.

The decision to use these existing technologies was made in order to reduce the overall cost of the system, make the system easier to operate and control by Cameco employees, and allow the entire uranium pellet stacking system to be dropped into the
Figure 5.21: Pellet Sensor mounted to the cover

Figure 5.22: Cover and sensor mounted to an end pellet conveyor
existing assembly line. Since all of these technologies are already in use at Cameco, the functionality has been confirmed and Cameco requested that a proof-of-concept prototype for this subsystem not be built at this time.

5.6 Material Tracking

The material tracking concepts that were presented in Chapter 4 have been presented to Cameco for review. Since the material tracking subsystem pertains to the entire manufacturing process, not just the automated stacking station, the final decision on which to implement has been left to Cameco. The automated pellet stacking system has been designed so that integration of a RFID tracking system would be simple and would not require major components of the system to be altered.

5.7 Control Algorithm

The control algorithm is presented by the flowchart in Figure 5.23. The overall goal of the control algorithm is to ensure that all processes and subsystems work together and work in the proper order to ensure successful operation of the system. The final control algorithm will be implemented on an Allen-Bradley PLC to control the entire system. This PLC can be linked into the network at Cameco to be monitored from a remote location.

When starting up, the system will set all counters to zero, and fire the compression pistons and robotic grippers to get the air flowing to the grippers and ensure they are functioning properly. After that, the conveyor is turned on until a tray is sensed by the first indexing sensor. The indexing positions for the following steps that are described are shown in Figure 5.24. In a standard tray, the first and last rows are left empty, and the middle 16 rows contain stacks of pellets. When a new tray is sensed, the index counter is incremented (see Figure 5.24(a)). With the placement
Figure 5.23: Flowchart of the control algorithm for the prototype, specifically for the measurement subsystem, the pellet placement subsystem, and the work tray subsystem
of the sensor, the tray requires two further indexes, making the counter equal three before any other operations happen. Once the index counter is equal to three, the alignment compression begins to operate, shown in Figure 5.24(b). Once the index counter reaches six, the initial compression and measurement is done and the required end pellets for that stack are calculated and stored, shown in Figure 5.24(c). The tray is indexed again and the next stack is compressed, measured, and the end pellets are also determined and stored.

When the index counter reaches eight (shown in Figure 5.24(d)), the robot will begin its actions. It will start by reading the registers to determine the end pellets required for the first stack. It will pick up the two required pellets and place them at the ends of the stack prior to the next index. While the robot is picking and placing the pellets, the initial compression and the initial measurements are taking place for the third stack.

Once the compressions, measurement, and pellet placement have taken place the tray will index and increment the index counter once again. The same sequence described in the previous paragraph takes place again. When the index counter reaches ten (shown in Figure 5.24(e)), the final compression and measurement happens. This operation is in parallel with the other compressions and measurements, as well as the pellet placement. If at any point a stack is unsolvable, the system will not place any pellets on that stack and will flag the tray to be stored for manual rework, and will move on to the next stack on the tray.

As the tray nears completion, the initial index sensor will no longer be able to sense when the tray is present. Therefore, the second index sensor takes over counting after 18 indexes (shown in Figure 5.24(f)).

Once the entire tray has been completed, if the tray was not flagged then it will proceed to the next station in the assembly process. If the tray was flagged then the tray lift assembly at the hopper on the output tray will be triggered when the tray is
Figure 5.24: Sequence of indexes based on the control algorithm
in position to be loaded into the hopper.

While the measurement and pellet placement is happening, the end pellet handling subsystem is also working. Each time a row of end pellets is loaded onto the conveyor, a pellet counter for that size of end pellet is updated. Since the number of end pellets added to the conveyor will be the same each time, the number of end pellets on the conveyor at any time can be tracked. When the number of end pellets on a conveyor drops below a specific value, a new row of end pellets is added. The minimum number would depend on the size of the end pellet. At the pick-up end of each conveyor, there is a sensor to ensure that a pellet is in place to be picked up, as shown in Figure 5.21. If there is no pellet sensed, then the robot will wait before attempting to pick up that specific end pellet. Every time a pellet is taken from a specific conveyor, the pellet counter for that size of end pellet is decremented.

Also in the end pellet handling subsystem, there is the disposal of empty trays. This is accomplished by having a counter that counts the number of rows that have been taken off the tray. Once that counter equals 16, the tray is empty and the conveyor is driven in reverse until the tray is loaded onto the tray disposal cart. A new tray of end pellets is then released from the hopper and moved into position to have the first row picked up.

5.8 Safety Guarding

Safety guarding will also be implemented throughout the entire station. The safety guarding will involve a completely closed-off work envelope where the robot will be operating. There will also be shielding around each of the end pellet handling units so that workers cannot reach inside the envelope of the pick-and-place mechanisms while they are in operation. The whole area surrounding the system will be shielded so that workers cannot walk through the area and accidentally interfere with the operation
of the system. There will also be door on each of the hoppers where the end pellet trays are stored. These doors not only provide safety to the operator, but also help to reduce the external dose of radiation to ALARA.

5.9 Summary

This chapter presented the final design that was determined in Chapter 4, and further developed that design through engineering analysis, form design, and collaboration with the design team at Cameco. A design review took place at Cameco with the design team present and from that review, certain aspects of the design were modified to make the system more suitable to Cameco’s operations. The final design presents a system that is capable of automating the uranium pellet stacking process currently done by manual stations at Cameco. When the system is installed at Cameco, it will require safety guarding in accordance with CSA Standard Z432: Safeguarding of Machinery. This safety guarding will be installed by Cameco at the time of installation. The proof-of-concept prototype that was built for testing was introduced and described, and it was discussed that only certain subsystems of the design were prototyped at the request of Cameco.

In the next chapter, test results are discussed from the proof-of-concept prototype that was constructed for the measurement, pick-and-place, and work tray subsystems. The results of these tests are analyzed and any further modifications to the design as a result of these tests is discussed.
Chapter 6

Test Plan and Results

A proof-of-concept prototype was constructed to prove the functionality of the designs for the measurement, pellet handling, and work tray subsystems. The technologies that were chosen for the end pellet handling subsystem already exist at Cameco and as a result, Cameco requested that a prototype not be built of this subsystem. In addition, the material tracking subsystem is something that will need to be changed throughout the manufacturing process and will be looked at by Cameco as they progress with the integration of this automated system.

6.1 Measurement Subsystem

6.1.1 Measurement Repeatability

The measurement system required certain tests to determine the repeatability of the triangulation sensors. To do this, a controlled stack was placed on a tray. The compression system was moved into place and a series of measurements were taken and recorded. Each laser went through runs of 1,000 cycles to determine the repeatability, and five runs were considered to be one test. The setup for this experiment is shown in Figure 6.1.
It was expected that the laser would give consistent results throughout the entire test and that the compression system was moved into the same position for each stack. To be successful, it was deemed that this test should have a standard deviation of the measurements for each test to be less than 0.05 mm.

In the first test involving the laser used to get the final stack length, a stack was placed on the tray and the pneumatic system was fired. At this point, 1,000 measurements were taken to determine the repeatability of the laser. After the 1,000 measurements were taken, the compression piston was retracted and fired again, and another 1,000 measurements were taken. This was repeated five times to achieve 5,000 total measurements. In one run of 1,000 measurements, the largest standard deviation observed was 0.014 mm, and over the average of all 5,000 measurements, the standard deviation was only 0.019 mm. This is well within the required repeatability for this system.

The raw data collected from this test can be found in Appendix B.

When testing the second laser, it was noted that the results obtained mirrored those of the first test, proving both that the two lasers have the same specifications and measurement capabilities, and that they are within the acceptable range set by Cameco.
6.1.2 Measurement Accuracy

To test the accuracy of the laser measurement units, a rod of known length was constructed and placed on the tray at each of the two measurement points in the system. Measurements were then taken, recorded, and compared to the known length of the rod. This was not only used to determine the accuracy of the measurement units, but also for calibrating the system. Once calibrated, the repeatability is more important.

To calibrate the system, these fixed rods were first measured with a CMM to determine an accurate rod length. The rods were then placed on a tray, and the compression system was fired. The program was then adjusted to account for the position of the fixed wall by taking the obtained measurement and comparing it to the known length of the rod. The mathematical manipulation of the measurements can be altered so that the measurements returned by the control algorithm are the same as the actual lengths of the rod. This calibration check should be done once a shift to ensure that the machine is producing quality measurements. It was expected that once the system is calibrated, it should return accurate measurements for the rods of known length each time the compression system is fired. The test setup is shown in Figure 6.2.

During the first stages of the tests, the overall distance between the laser and the fixed walls was determined. Once this distance was found, the compression pistons were cycled and 1,000 measurements were taken for each cycle. Throughout this test, the repeatability figures that were discussed in the previous section were repeated, and the accuracy to the length of the rod was within the required specifications. There was an average variance between the actual length and the measured length of 0.020 mm over the course of this test. In the first two runs however, the variance was only 0.003 mm. It was determined that this variance occurred as a result of the compression pistons and the lasers being attached to the same frame. This can cause unwanted vibrations in the system which can slightly affect the measurements. The final design presents
Figure 6.2: Measurement accuracy test setup at the (a) measurement end and (b) compression end
a decoupled design for the compression and laser units which will help maintain the constant distance between the fixed walls and the lasers, and give even more accurate results. Even with this vibration, the system is still within the required specifications.

6.1.3 Compression Test

The compression system was tested with different pressures being applied to the stack. As was determined earlier, the required force to move the stack is 5 N. The pressure applied to the stack was varied throughout the test to determine a pressure that would ensure the stack is compressed but not cause any damage to the pellets. This test was also monitored to ensure that no pellets in the stack lifted off the tray as a result of the force applied. Any other movements of the pellets other than in the direction of the applied force would result in incorrect measurements.

In this test, it was expected that the optimal operating pressure would result in the stacks being fully compressed in under 0.5 s and would ensure that when the force was applied to the stack, all pellets would remain on the tray and that there would be no buckling or lifting of any of the pellets in the stack. The buckling was determined by visual inspection during the test.

Several cycles of compressions were performed at different pressures, starting at 15 kPa and decreasing down to 1 kPa. It was noted that at higher pressures there were some pellets in the middle of the stack that would buckle, which would create an inaccurate stack measurement. If there was no buckling in the middle, on some cycles the end of the stack being compressed against the fixed wall would lift off of the tray as a result of the pressure and the distance that the stack was being pushed. This was more prevalent on the final compression after the end pellets had been placed. As the pressure was reduced, the occurrence of this flaw was eliminated. At pressures below 1 kPa, the response time of the compression pistons started to decrease. It was determined that for the steel dummy pellets being examined, that 1 kPa allowed the
stacks to be compressed fully and eliminated any buckling of pellets throughout the stack in the required time of 0.5 s. Due to the restrictions on testing with uranium, further testing on uranium pellets would be needed to determine the correct operating pressure when the system is installed at Cameco.

6.2 Pellet Placement Subsystem

The pellet placement subsystem was tested for three different items: the pick-and-place consistency, the ability of the gripper to securely hold a pellet through high-speed motion, and the ability of the gripper to pick-and-place the pellets without interfering with neighbouring stacks.

6.2.1 Pick-and-Place Consistency

The design of the gripper to pick-and-place the pellets is very important to the success of this system. The gripper should be able to pick and hold the pellets securely and place them accurately at the ends of the stack.

A test was set up in order to test the effectiveness of the gripper fingers. To run this test, the gripper was attached to a six degree-of-freedom (DOF) Epson Pro Six PS3 robotic arm similar to the Fanuc model specified for the actual system. A pellet was then placed on a tray, and a sensor was used to detect when the pellet was on the tray. This sensor was used to check to ensure the pellet had been picked up every time. If the pellet had not been picked up, a counter would increment and at the end of 1,000 cycles, the total number of failures would be displayed. It was expected that there would be no failures during that 1,000 cycles. The test was repeated three times for each gripper for a total of 6,000 cycles.

It was also expected that each time the gripper went to place the pellet back on the tray, the fingers would open and the pellet would be placed within a small area. This
area was denoted by the sensor attached to the tray counting the number of pellet fails. If the gripper did not properly place the pellet, then another counter would increment and be displayed at the end of the run. Figure 6.3 shows the setup that was used for this test.

For the 6,000 cycles that were run, there were no instances of a pellet not being picked up, placed, or dropped at an incorrect time. However, through visual inspection it was noted that on occasion the pellet would not be picked up in the grooves of the gripper fingers, and as a result the pellet would not be securely held. This resulted in the pellet changing orientation slightly at points when it was not picked up directly in the centre of the pellet. To adjust for this, the fingers of the grippers were filed down so that the fingers could get lower on the pellets. This resulted in the pellets being picked up into the grooves of the fingers providing a secure hold on the pellets.

The test discussed above was repeated with these modified fingers and not only were there no failures, it was noted that all pellets were picked up and held in the grooves of the fingers in the proper position. This test was deemed a success and it proved that the gripper fingers that were designed will be able to pick-and-place the pellets.
without dropping them.

6.2.2 Gripper Ability at High-Speed Motion

A second test was performed to test the ability of the grippers to hold the pellets while moving at a high rate of speed. In this test, two sensors were set up at opposite corners of a tray, as shown in Figure 6.4. The robot was programmed to pick up a pellet from one sensor and place it at the location of the other. It then switched grippers and moved the pellet back. This was repeated 1,000 times per test and the test was performed five times to get a good sample of results.

It was expected that the gripper would securely pick up and hold the pellet during the entire motion of the robot. The end result would be zero failures in both the picking and placing of the pellets. Also, the robot should be able to place the pellet within the sensor field for the duration of the test. If the repeatability of the robot results in the pellet being placed outside the sensor field, then the test is considered to have failed.

Throughout the test, it was noted that both grippers were able to securely hold the pellet throughout each cycle, which leads to the conclusion that the gripper design is
satisfactory for the pick-and-place of the uranium pellets in this high-speed operation. The test was operated both with a simple linear motion of the gripper, and also a combination of rotation and linear motion. In both instances there were no failures in any of the 5,000 cycles, resulting in a successful test.

6.2.3 Gripper Pick-and-Place on a Full Tray

A third test was conducted to ensure that the grippers would be able to pick up and place the pellets on a tray when other pellets are present. This is important for the placement of end pellets to ensure that neighbouring stacks will not interfere with the placement of the pellets. The test setup for this test is shown in Figure 6.5. To conduct this test, a completed stack was placed next to a stack awaiting end pellet placement. The gripper then picked up an end pellet and placed it in position on the end of the stack. After placing the pellet, the gripper then picked it back up and placed it again in a motion similar to the first test in this section, ensuring that when the gripper is opened it was not interfering with the completed stack.

It was noted during this test that the original gripper fingers were too wide and made contact with the neighbouring stack. To fix this, the fingers were filed down so that the fingers were narrower. This modification eliminated the contact between the pellet stacks on subsequent runs of the test.

6.3 Work Tray Subsystem

6.3.1 Indexing Accuracy

The work tray subsystem tests included determining the optimal speed the conveyor should travel at in order to index the tray accurately while still reducing the cycle time to the acceptable limits. To perform this test, a setup was made that included the indexing sensors, a conveyor with variable speeds, a controller, and a laser measurement
Figure 6.5: Gripper pick-and-place on a full tray test setup
For each index, a measurement was taken using the laser measurement head and the difference between index distances was calculated. After an entire tray had been indexed, the standard deviation was found. After running this test at different speeds, it was discovered that there was a second order polynomial relationship between the speed of the conveyor and the indexing error. From the test results, the equation for this relationship is:

\[ y = 8.3838x^2 - 4.1507x + 0.5983 \]  

(6.1)

where \( x \) is the conveyor speed and \( y \) is the indexing error.

It is expected that the standard deviation for the indexing of the trays be less than 0.5 mm. This is acceptable so that the compression pistons will not be interfered with by neighbouring stacks, and the end pellets being placed will be placed in the proper stacks.

For the tests, the conveyor was run at different percentages of its speed, and the graph shown in Figure 6.7 shows the standard deviation with respect to those speeds. It was determined through this test that the conveyor could be run between 40% and 45% of its maximum speed before the standard deviation increased above the 0.5 mm that
was specified. Due to circumstances beyond control, this test could not be completed with the specified Dorner 3200 series conveyor, so an alternative conveyor was used. The conveyors used in this test were not gang driven, so when setting the speed of the belts, two separate drives had to be set. This is a source of error in this test. When installing the system at Cameco, this test will require repeating to obtain the optimal belt speed. The raw data from this test is shown in Appendix B.

6.4 Control Algorithm

Different aspects of the control algorithm were tested on different hardware devices to ensure that all of the components would work. The final control algorithm will be implemented on an Allen-Bradley PLC when installed at Cameco, but for testing, it was written in C-language and in a proprietary language, RC+, designed for Epson robots. The measurement and pellet determination algorithm was written in C, while the sensors and conveyors and any other digital input or output devices were connected with the Epson controller and tested using RC+.

Through testing with the measurement subsystem, it was shown that the control algorithm could read in the measurements from the initial stack measurement and
determine whether the stack could be solved or not. If it could be solved, the algorithm then determined which end pellets were required based on the available selection, which was pre-determined. It would then inform the user which end pellets were required. If the stack was bad, it would flag the tray. For the final measurement, the algorithm could take the measurement and ensure that the stack had indeed been solved. If it had not, it would return an error and flag the tray. If it had been solved, it would continue with normal operation.

The sampling of the laser was tuned so that it would only take measurements when triggered from the program. This prevents the laser from running constantly and filling the serial buffer with data that is not relevant to the operation of the system. This test concluded that the designed algorithm would control the operation of the system, and it was determined that the algorithm could be modified to be implemented in any language. The final version of the algorithm will be written in ladder logic which will run on the PLC.

6.5 Summary

In this chapter several tests were discussed that were used to verify certain aspects of the design for the automated pellet stacking system. Tests were performed on the proof-of-concept prototype that was constructed. Only certain aspects of the design were tested at the instruction of Cameco. Tests were not performed on the end pellet handling subsystem since the technologies that were used already exist at Cameco and have been previously verified.

Tests of the measurement system accuracy and repeatability conclude that the system meets the requirements put forth by Cameco, and also give superior results to the current manual stacking method. Each stack can now have an exact length number attached to it through the material tracking system if it is desired by Cameco, as
opposed to the current method which is simply a pass or fail scenario.

The compression system was also tested to determine the best compression pressure that would consistently compress the stacks so that no gaps were present but would not damage the pellets or cause the stacks to lift off the tray. It was concluded in this test that the best pressure to ensure an accurate measurement could be taken is between 0.5 and 1 kPa. Between these pressures the compression pistons act quickly but do not impact the stacks as hard and do not cause the stacks to lift off of the tray while pushing them against the fixed wall.

Tests of the pick-and-place subsystem showed that the custom gripper designed is capable of consistently picking up the pellets and placing them at the desired location without failing to pick up pellets or dropping them before the robot reaches the desired point. A high-speed robot motion test was performed as well and it showed that even at the max speed of the robot, the pellets were still securely held within the fingers of the gripper, resulting in a successful gripper design. The robot motion was also stopped while the gripper was holding pellets, and an attempt to remove the pellet was made manually and was unsuccessful, showing just how firm of grasp the gripper has on the pellets. The pellets were also visually examined and there was no visual evidence of any damage to the pellets resulting from the gripper.

The work tray subsystem was also tested to ensure the accuracy of the indexing with the sensors that were chosen. This test was also done to determine the optimal conveyor speed that will reduce the cycle time but ensure accurate indexing of the work trays. This test concluded that there was a second order polynomial relationship between the conveyor speed and the standard deviation of indexing error, and by running the conveyor between 40% and 45% of its maximum speed, the standard deviation of error for indexing is less than 0.5 mm. The results from this test can also be used when setting the conveyor speeds for the end pellet handling subsystem.

A control algorithm was also tested to show that it was possible to control the subsys-
tems of the prototype. This control algorithm is capable of controlling the conveyor and reading the sensor output and reacting accordingly, whether it is sensing and indexing a tray, or whether a pellet is being sensed as ready for pick up on a chain conveyor. The algorithm also shows that it is capable of taking a measurement from the lasers and computing the remaining stack length and determining a combination of end pellets that are required to meet the final tolerances.

These tests confirm that the designs for the given subsystems are functional and meet the requirements set forth by Cameco. Some of the lessons learned through the tests resulted in design refinements which led to more accurate test results on subsequent runs. Other lessons learned through these tests can be applied to the other subsystems that were not tested, such as indexing trays in other areas of both this system and the overall fuel manufacturing process.

Further development and testing of the subsystems not tested for the purpose of this thesis as well as testing of the complete system will be done by Cameco at the time of installation.
Chapter 7

Conclusions and Recommendations for Future Work

7.1 Conclusions

A novel, automated uranium pellet stacking system has been designed which will be integrated into the existing manufacturing line at Cameco Fuel Manufacturing in Port Hope, ON. Since the entire manufacturing process is not being examined at this time, there are several aspects of the design that are constrained by the existing layout and operations within Cameco. Through a formal engineering design process, the solution presented was developed. Requirements and constraints were developed through meetings with the design team and Cameco, and a list of specifications was developed for review. Concepts were presented in a design review to the Cameco team, and a preliminary final design was decided on. Through engineering analysis and testing, modifications were made to the preliminary concept and ultimately a final design was selected. Prototypes of specific subsystems were then built and tested to confirm the functionality and abilities of the subsystems. Prototypes for certain subsystems were not built since these technologies are currently in use at Cameco,
and Cameco determined testing was not required.

The automated system will replace the current manual method of placing end pellets on stacks of uranium pellets. The manual method involved an operator randomly placing end pellets on the stacks and measuring using a gauge to determine whether the stack was within the specifications or not. If it is not, the user removes an end pellet and tries a different size, based on trial-and-error.

The new system implements an automated solution for stacking the end pellets which increases the output of the system, and removes the random placement of the pellets. This system was broken down into six subsystems: a measurement subsystem, a pellet placement subsystem, a work tray subsystem, an end pellet handling subsystem, a material tracking subsystem, and a control subsystem. Each of these subsystems has many components that were determined through functional decomposition.

When a tray is introduced to the system, each stack is compressed and measured using a laser triangulation sensor. From this measurement, the proper combination of end pellets is determined from a list of known end pellet sizes. These pellets are picked up and placed on the ends of the stack by a robotic arm designed for high-speed pick-and-place operations. The stack is again measured to ensure that the pellets chosen are correct for the stack. This is done for each tray that goes through the system. Should a stack not be solvable, the tray is flagged and, once all stacks have been measured and operated on, it will be removed from the line and manually inspected to determine why it was not complete.

Collaboration with the design team at Cameco took place throughout the design process in order to ensure that their requirements were being met and also to make aware the constraints that were placed on the system. These constraints were discussed in detail in Chapter 2 when the customer requirements were developed.

This system is a step towards the automation of the entire fuel bundle manufacturing process at Cameco. This system will be very important for the workers of Cameco if
the plant begins the production of slightly enriched uranium fuel bundles. This line will be more hazardous to workers, so this system will help to keep worker radiation exposure “as low as reasonably achievable” (ALARA).

A prototype was built for the measurement, pellet placement, and work tray subsystems. The prototype was used to test the design and determine if there were any modifications that were required in order to have successful operation of the system. Through this testing, a few minor modifications were made to make the system operation more stable. These modifications included a modification to the custom gripper design to add grooves to the gripper fingers and make the grooves low enough that a pellet could be picked off a tray. Also added through testing was the conveyor guide that is used to keep the tray straight while indexing through the work tray system as well as the end pellet handling subsystem.

### 7.2 Recommendations for Future Work

The next stage in this work is to implement the system at Cameco. In order to do this, more testing is required for working directly with the uranium pellets. In this thesis, all tests were performed using steel dummy pellets due to restrictions on working with uranium outside of a licensed facility. Testing, especially of the compression system will be required to ensure the pellets are not damaged, and to determine the optimal pressure for compressing the stacks of uranium pellets, as discussed in Chapter 6. The entire system would need to be constructed using what has been learned from the proof-of-concept prototypes and the design analysis presented. The components for the end pellet subsystem would need to be manufactured, assembled, and integrated to validate the design. The Fanuc robot that was specified for this project would need to be purchased and all tray handling conveyors purchased and integrated with the indexing sensors. The control algorithm presented in Chapter 5
will be written in ladder logic for the PLC according to the programming models that Cameco uses. Once this is done, extensive off-line testing will be done to ensure the system functions properly and meets the required output of the system. A material tracking method will also need to be chosen as a plant-wide solution and implemented in all areas of the manufacturing process.

Inline inspection of the pellets will also need to be implemented to replace the inspection the operator at the manual stacking station currently performs. The inline inspection is required to determine if any pellets have flaws, such as inclusions, surface defects, or end squares. End squares results when the ends of the pellets do not sinter properly causing the end of the pellet to not form to the correct specifications. Pellets with flaws cannot be inserted into fuel bundles and therefore need to be removed. An inline inspection system that could be installed after the grinding stage would be able to catch these defects and remove the pellets from production. The pellets can be ground back to powder and go through the manufacturing cycle again.

In addition to inline inspection, an inline measurement that occurs after the grinder is also a possibility for Cameco. In this system, a length measurement of the stacks would be taken as they are placed on the tray coming off of the grinder line. Only stacks that are within a solvable range with the current supply of end pellets will be placed on the tray. This would eliminate trays being partially completed at the automated stacking station and result in increased productivity.

Future work could also involve an analysis of the entire manufacturing process of the pellets. This would include examining the manufacturing tolerances on the pellets to reduce the sum of tolerances of the individual pellets to enable fewer end pellet sizes to be used.

It is possible that if the tolerance on the pellets is made tighter, then the number of end pellet sizes required for this automated system could be reduced to four. This is something that is currently being examined by Cameco and could be implemented
in the future. This would not result in a major re-design of this system. The main alteration is that the fifth end pellet handling unit and conveyor would be removed, decreasing the overall footprint of the system, while reducing the overall cost.

Other future work would include the examination and possible redesign of how the pellets are transferred through the plant. By removing the trays the pellets are currently transported on and having a continuous flow of pellets through the manufacturing line right into the bundles, it would removing many loading and unloading operations involving trays of pellets.
References


Appendix A

House of Quality

The House of Quality shown here was developed in part to show the relationships between the customer requirements and the engineering specifications. This is one part of Quality Function Deployment that was used during the design process of the automated pellet stacking project.
### Customer Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Index trays to proper position</td>
</tr>
<tr>
<td>R2</td>
<td>Accurately measure the stack length to determine if they are within acceptable range</td>
</tr>
<tr>
<td>R3</td>
<td>Determine the proper combination of end pellets</td>
</tr>
<tr>
<td>R4</td>
<td>Pick the red pellets from the tray and place them at the ends</td>
</tr>
<tr>
<td>R5</td>
<td>Record the pellet tracking data to a database</td>
</tr>
<tr>
<td>R6</td>
<td>Take final measurement to ensure stack length is within specified tolerances</td>
</tr>
<tr>
<td>R7</td>
<td>Reduce the overall footprint of the station</td>
</tr>
<tr>
<td>R8</td>
<td>Properly guard all equipment to prevent injury/damage</td>
</tr>
<tr>
<td>R9</td>
<td>Ensure that the pallets are not damaged during the stacking process</td>
</tr>
<tr>
<td>R10</td>
<td>Increase the current production</td>
</tr>
</tbody>
</table>

### Quality Characteristics

- **Demanded Quality** (a.k.a. "Customer Requirements" or "Whats")
- **Weight / Importance**
- **Max Relationship Value in Row**
- **Max Relationship Value in Column**
- **Relative Weight**
- **Direction of Improvement**
  - Minimize (/g378)
  - Maximize (/g376)
  - Target (x)

### House of Quality for the Automated Pellet Stacking Project

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
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<td>R6</td>
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</tr>
<tr>
<td>R10</td>
<td>Increase the current production</td>
</tr>
</tbody>
</table>

### Competitive Analysis

- **Current Design (Manual Station)**
- **New Design (Automated Stacking Station)**

### Specifications

- **Specifications** from MARS Report 2008-001
- **Customer Requirements** from MARS Report 2008-004

### Notes

- This House of Quality is for the system as a whole, with the specifications a result of using functional decomposition.

---

**Title:** Automated Pellet Stacking  
**Author:** Brian Riess, BEng  
**Date:** 02/07/2008  
**Notes:** House of Quality for the Automated Pellet Stacking Project  
Specifications released from MARS Report 2008-004  
This House of Quality is for the system as a whole, with the specifications a result of using functional decomposition.
Appendix B

Test Plan and Results

B.1 Measurement Repeatability Test

Purpose: To determine the repeatability of the measurement and compression system.

Method:

1. Place a stack on a tray at the first measurement point.

2. Compress the stacked with the related compression piston and take a series of 1000 measurements.

3. Record the data.

4. Retract the compression piston.

5. Repeats Steps 2-3.

6. Compare all data obtained for repeatability, both for the different runs and within the individual runs.

Expected Results:

- Standard deviation of $< 0.05$ mm during each test.
<table>
<thead>
<tr>
<th></th>
<th>RUN 1</th>
<th>RUN 2</th>
<th>RUN 3</th>
<th>RUN 4</th>
<th>RUN 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>50.32</td>
<td>50.37</td>
<td>50.36</td>
<td>50.36</td>
<td>50.35</td>
</tr>
<tr>
<td>Max</td>
<td>50.32</td>
<td>50.38</td>
<td>50.36</td>
<td>50.37</td>
<td>50.36</td>
</tr>
<tr>
<td>Min</td>
<td>50.32</td>
<td>50.37</td>
<td>50.35</td>
<td>50.35</td>
<td>50.35</td>
</tr>
</tbody>
</table>

Actual Results:

Standard deviation calculated by:

\[
s = \sqrt{\frac{\sum(X - M)^2}{n - 1}} \tag{B.1}
\]

where \(X\) is the average measurement from run \(X\), \(M\) is the mean measurement, and \(n\) is the number of measurements taken.

Average Standard Deviation: 0.019

**B.2 Measurement Accuracy Test**

Purpose: To determine the accuracy of the measurement and compression system.

Method:

1. Place a rod of known length at the first measurement point.

2. Fire the first compression piston and take a series of 1,000 measurements.

3. Record the data.

4. Retract the compression piston.

5. Repeats Steps 2-4.

6. Compare all data obtained for accuracy based on the known length of the rods, both for the different runs and within the individual runs.

7. Repeat this test with the second measurement unit.

Expected Results:
• Variation of measurements from actual length < 0.05 mm over the entire test.

Actual Results:

<table>
<thead>
<tr>
<th></th>
<th>RUN 1</th>
<th>RUN 2</th>
<th>RUN 3</th>
<th>RUN 4</th>
<th>RUN 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>479.774</td>
<td>479.772</td>
<td>479.744</td>
<td>479.737</td>
<td>479.748</td>
</tr>
<tr>
<td>Max</td>
<td>479.776</td>
<td>479.776</td>
<td>479.755</td>
<td>479.740</td>
<td>479.752</td>
</tr>
<tr>
<td>Min</td>
<td>479.770</td>
<td>479.767</td>
<td>479.743</td>
<td>479.728</td>
<td>479.740</td>
</tr>
<tr>
<td>Avg. Variance from actual length</td>
<td>0.002</td>
<td>0.004</td>
<td>0.028</td>
<td>0.039</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Reasons for Variation: In the test setup, the compression pistons and the lasers are attached to the same frame. This can cause unwanted vibrations in the system which can slightly affect the measurements. The final design presents a decoupled design for the compression and laser units which will help maintain the constant distance between the fixed walls and the lasers, and give even more accurate results. Even with this vibration, the system is still within the required specifications.

**B.3 Pick-and-Place Repeatability Test**

Purpose:

• To ensure the grippers will open and close every time.

• To ensure the pellets would be picked up and securely held each time.

Method:

1. Place a fork sensor on a tray, with the pellet breaking the beam of the sensor.

2. Set up a program to have the robot come down, close the gripper and lift the pellet. If the pellet is still in the sensor, have a counter that increments to indicate a fail to pick. Open the gripper and try again.

3. Place the pellet back on the conveyor. If the sensor does not sense the pellet, increment a fail to place counter.
4. Repeat Steps 2 and 3 for 1,000 cycles.

5. Record the data.

6. Switch grippers and repeat this test.

Expected Results: 100% pick-and-place consistency.

Actual Results:

- 100% pick-and-place consistency
- It was noted that not all pellets were securely held. As a result, grooves were added to the gripper fingers, and when the test was re-run, all pellets were held securely.

**B.4 High-Speed Robot Test**

Purpose:

- To ensure the grippers will hold the pellets securely during high-speed motion.

Method:

1. Place two fork sensors on a tray at opposite corners, with a pellet breaking the beam of one sensor.

2. Set up a program to have the robot come down, close the gripper and lift the pellet. If the pellet is still in the sensor, have a counter that increments to indicate a fail to pick. Open the gripper and try again.

3. Have the robot travel in high speed to the other sensor and place the pellet. Check the sensor status to ensure that the pellet has indeed been placed.

4. Switch grippers and return the pellet to the original location.
5. Repeat Steps 2 to 4 for 1,000 cycles.

6. Record the data.

Expected Results: All pellets will be delivered and securely held.
Actual Results: All pellets were securely held throughout the high-speed motion.

B.5 Indexing Accuracy Test

Purpose:

- To determine the optimal conveyor speed for indexing the trays quickly and accurately.
- To determine the responsiveness of the sensor.

Method:

1. Connect the indexing sensor to the controller and program to index the tray when sensed.

2. Set up a laser measurement unit to measure the distance to the tray after each index.

3. Set the conveyor to low speed, and run the program.

4. Record the distance information, and subtract each measurement from the previous to determine the index distance.

5. Once finished the tray, compute the standard deviation.

6. Repeat Steps 4 and 5, increasing speeds until the sensor begins to miss indexes.

Expected Results:

- Tray will be more accurate at low speeds.
- Optimal index speed with have standard deviation less than 0.5 mm.

Actual Results:

<table>
<thead>
<tr>
<th></th>
<th>RUN 1 20%</th>
<th>RUN 2 30%</th>
<th>RUN 3 35%</th>
<th>RUN 4 40%</th>
<th>RUN 5 45%</th>
<th>RUN 6 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>16.60</td>
<td>16.64</td>
<td>16.34</td>
<td>16.87</td>
<td>15.91</td>
<td>16.30</td>
</tr>
<tr>
<td></td>
<td>16.54</td>
<td>16.62</td>
<td>16.80</td>
<td>16.31</td>
<td>17.03</td>
<td>15.97</td>
</tr>
<tr>
<td></td>
<td>16.56</td>
<td>16.39</td>
<td>16.65</td>
<td>16.56</td>
<td>16.71</td>
<td>17.18</td>
</tr>
<tr>
<td></td>
<td>16.46</td>
<td>16.54</td>
<td>16.52</td>
<td>16.79</td>
<td>16.18</td>
<td>15.98</td>
</tr>
<tr>
<td></td>
<td>16.44</td>
<td>16.51</td>
<td>16.52</td>
<td>16.18</td>
<td>16.66</td>
<td>17.29</td>
</tr>
<tr>
<td></td>
<td>16.31</td>
<td>16.70</td>
<td>16.47</td>
<td>16.72</td>
<td>16.86</td>
<td>15.56</td>
</tr>
<tr>
<td></td>
<td>16.52</td>
<td>16.48</td>
<td>16.65</td>
<td>16.26</td>
<td>16.05</td>
<td>16.78</td>
</tr>
<tr>
<td></td>
<td>16.38</td>
<td>16.71</td>
<td>16.16</td>
<td>16.60</td>
<td>16.32</td>
<td>16.94</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.10</td>
<td>0.11</td>
<td>0.20</td>
<td>0.26</td>
<td>0.41</td>
<td>0.64</td>
</tr>
</tbody>
</table>