Developing Modern Graphite Exponential Pile Experiments to Augment Reactor Physics Education

by

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ABSTRACT

Reactor Physics is not always an intuitive subject for students to understand. When nuclear engineering was beginning as a field it was common for students to complete measurements on sub-critical reactors, which could not sustain a fission chain reaction, in order to develop student intuition. The Massachusetts Institute of Technology has one such reactor, a graphite exponential pile, which went unused for decades. In this thesis the MIT Graphite Exponential Pile was returned to experimental operation, and a prototypic student experiment was completed. The material buckling was found by indium foil activations completed with a plutonium-beryllium source in the pile. From the experimental results it was calculated the pile would have to be a cube with sides that are 5.42m long to become a critical reactor. This proof of concept experiment makes it possible for mens et manus based education at MIT for reactor physics.

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Chapter 1

Introduction

Reactor Physics is a difficult subject with many non-intuitive non-linearities. Currently there are no hands-on or experimental components in the reactor physics curriculum at MIT. This has made it difficult for students to develop an intuition for reactor physics. In the early days of nuclear engineering in the '50's and '60's it was commonplace to use hands on experiments to augment reactor physics lectures. At its peak there were hundreds of these university owned reactor physics experiments.

Graphite sub-critical reactors, or graphite exponential piles, have been used for decades to model and understand reactor physics. These sub-critical reactors are nuclear reactors which cannot sustain a fission chain reaction, and cannot produce power. This is because more of the neutrons from the fission of uranium-235 are lost than those neutrons that cause new fissions. The neutrons are lost by either being absorbed by materials other than the uranium-235 fuel or by leaking out of the reactor and not returning. When an external neutron source is placed in the reactor, the source of neutrons and loss of neutrons come into equilibrium such that there is a steady-state condition for the neutron population in the reactor. Usual neutron sources include californium-252, which produces neutrons through spontaneous fission, and plutonium-beryllium (PuBe), where the alphas emitted from plutonium decay induce neutron emission from beryllium-9.

A reactor is usually a heterogeneous assembly of two main components: a fuel, and a moderator. The fuel is composed of a material that is very likely to fission, and release energy and neutrons when it is hit by a neutron of any energy. These are considered fissile materials, and uranium-235 is the most commonly used. However the neutrons produced from fission are at such a high energy they are very likely to escape the reactor before hitting fuel. So a moderator is added to the reactor. This moderator absorbs most of the neutron energy, slowing it down, which makes the probability of the neutron inducing a fission much higher. The moderator must be more likely to cause the neutron to scatter than to be absorbed.

Since these sub-critical reactors require an external neutron source they are extremely safe. They are very low power, and can not undergo power excursions. The only risk during operation is the neutron and gamma radiation, which is at extremely manageable levels. This makes the reactors ideal for teaching and student experiments. Students can predict the neutron flux distribution in a sub-critical reactor and then experimentally verify or disprove their predictions.

MIT has one such sub-critical reactor, the MIT Graphite Exponential Pile (MGEP), which has been at MIT since 1957. The pile is made of a graphite moderator and natural uranium fuel. The natural uranium is only about 0.7% uranium-235.

The MGEP is the largest university-owned graphite pile in the United States. It is made of two parts: a graphite-uranium lattice, and a graphite pedestal. The lattice is comprised of graphite blocks with a 12x12 square array of fuel channels drilled completely through the lattice horizontally. The separation between the channels is 7.25". Ten fuel slugs can be loaded in each channel. This allows for a maximum loading in the pile of 1,440 slugs. However MIT only has access to 1,288 slugs. The graphite-uranium lattice is located on top of a graphite pedestal, which is about 2 feet tall, and made of graphite blocks. The neutron source is placed in source channels in this pedestal. The graphite then removes energy from the neutrons from the source through collisions as the neutrons travel through the pile. This continues until the neutrons are at thermal equilibrium with the graphite. This process is called thermalization.

In this thesis the MGEP was used to improve the reactor physics curricula for the undergraduate reactor physics class, 22.05. The purpose of this thesis was to bring the MGEP back into operation. This included cleaning and inventorying the pile, and assisting in applying for an amended license from the Nuclear Regulatory Commission. An experiment was designed to test the prediction of the neutron flux profile from student models.

Chapter 2

Pile Description

The MIT Graphite Exponential Pile (MGEP) is a sub-critical reactor constructed of graphite and natural uranium. The Pile is comprised of a lattice and a pedestal. The lattice is a cube of graphite with natural uranium lying in horizontal channels in the lattice. The lattice rests on top of the pedestal. The pedestal is comprised of graphite designed to thermalize neutrons from the external neutron source. The Pile is usually shrouded in aluminum sheeting. It was originally designed to hold Cadmium sheets, which have since been re-purposed. Now the aluminum sheeting is primarily used as a part of the security system for the pile's uranium fuel.

2.1 History

The story of the MIT Graphite Exponential Pile (MGEP) began in 1954 with then MIT President, Dr. Killian, deciding to build a nuclear reactor on campus. While investigating research reactors, Manson Benedict met Theos J. Thompson at Los Alamos. Manson Benedict was the institute's first Professor of Nuclear Engineering, and later on became the first Department Head of the Nuclear Engineering Department. In the spring of 1955, Professor Thompson joined the MIT Nuclear Engineering faculty with the goal of creating the MIT Reactor (MITR-I). Construction of MITR-I began in June of 1956 at the site of a cheese storage warehouse previously used by the Kraft-Phenix Cheese Company [1].

While searching for a source for nuclear grade graphite, the team was fortunate enough to discover that Brookhaven National Laboratory (BNL) had 100 short tons of surplus nuclear graphite [2]. MIT was able to purchase this graphite for about 7% of the market price. This much graphite was in excess of the needs of the MITR-I so it was proposed to make a reactor that was similar to Argonne's CP-5 reactor [3]. Thus the idea of making the Graphite Exponential Pile was born.

The design was quickly scaled back from a critical reactor such as CP-5 to a sub-critical reactor with a 13x13 lattice of fuel channels with a 7.25" pitch between channels. This called for 169 fuel channels[4]. It is unclear when the lattice was scaled down to be the 12x12 channel lattice it is today. This was likely caused by an inability to procure enough fuel, as they were never able to procure enough fuel for a full loading of the 12x12 lattice.

The pile was constructed in 1957 in the middle laboratory at what is now the MIT Nuclear Reactor Laboratory (NRL) as part of Richard W. Knapp's undergraduate thesis, under the supervision of Professor Thompson. The construction took a little over a month spanning from March 28 through the end of April. This was made possible by the aid of the students from Professor Thompson's Nuclear Engineering Laboratory class (N41)[5][6]. That following summer another of Professor Thompson's students, William F. Reilly, constructed a standard pile, which contained no uranium, for his master's thesis next to the MGEP. This standard pile was meant to measure the nuclear properties of the graphite and was constructed of the excess graphite not needed for the MITR-I or the MGEP [7].

The Graphite Exponential Pile continued to be used as an experimental facility. Pearson and Sims completed their master's thesis on the Pile in 1959 under the supervision of Professor Thompson[8]. It does not appear that any more theses were conducted on the pile since Pearson and Sims, but it continued to be used for various experiments. By the time Professor Kord Smith entered the MIT department of Nuclear Engineering as a graduate student in 1976 the pile was not common knowledge, as he graduated without ever hearing of its existence. However, student experiments were still being run intermittently on the pile until at least 1991 [9].

In 2016 the Department of Nuclear Science and Engineering "rediscovered" the pile when a curious Professor Michael Short asked about the large aluminum shroud box in the middle lab of the NRL[10]. This led to Professor Smith proposing this thesis topic in order to incorporate a hands-on experiment into the Department's Reactor Physics curriculum.

2.1.1 Fuel Slug Origin

Little is known about the exact origin of these slugs, and therefore their exact composition. In Pearson and Sims there is a one-line mention that the slugs are "standard AEC [Atomic Energy Commission] issue for educational use..."[8]. This lack of details may have been due to cold war secrecy. It is possible that these slugs were initially intended for production of weapons-grade plutonium at either the Hanford or Savannah River sites. The slugs are 1.084" in diameter and 8.41" in length, and made of metallic natural uranium clad in aluminum. They are described in more detail later.

This hypothesis is supported by declassified documents on uranium slug production at the Savannah River Plant. In this process 1" diameter by 8" long natural uranium metallic slugs are used. These slugs are dipped in a series of baths including bronze, tin, and aluminum-silicon. The slugs are then bonded to the aluminum cans and caps are welded on [11]. This method does agree with the physical measurements which have been taken of the slugs.

2.1.2 Graphite Origin

The plan to create a graphite exponential pile began in April 1955, when it was discovered that Brookhaven National Laboratory (BNL) had 100 short tons of surplus nuclear graphite available[3]. This graphite contained multiple batches all of varying purities.

The lowest purity graphite in these batches was AGHT graphite[4]. AGHT and AGOT are both forms of nuclear graphite. AGOT has a lower boron content than AGHT and is the higher quality reactor graphite of the two[12]. AGOT contains about 0.4ppm boron and has a thermal absorption cross-section of 4.07 millibarns [13]. The graphite was then sent from Brookhaven to the National Carbon Company in Columbus, Ohio to be machined to the appropriate size for the pile and the MITR[14]. During machining it was apparent that there would not be enough blocks which were long enough to span the length of the pile with two pieces, so it was decided that blocks which were not foil or fuel stringers would be any length that was manageable[15].

2.2 Pile Geometry

Very detailed documentation of the design of the Graphite Exponential Pile and its components are given in appendix B. An overall photograph of the pile is shown in Figure 2.1. As can be seen in the figure, the pile is made of graphite blocks with cross-sections that are less than four inches to a side. Each layer alternates orientation so the long axis of the blocks are perpendicular to the adjacent layers' long axes. No single block is the same length as the entire pile. The longest blocks go half the length of a side with most blocks being far less than that length. During manufacturing there was not enough stock to make all of the blocks the same length so each layer is pieced together with various lengths of blocks [15]. The pile has a set of covers which cover all of the pile which is above ground. The covers were originally all made of aluminum with cadmium sheets 0.02" thick lining the inside of the cover. This was intended to isolate the pile from the room and remove thermal neutrons before they were reflected by the surrounding walls back into the pile. Cadmium is useful for this purpose since it has a very high thermal absorption cross-section. However, the cadmium has mostly been scavenged for other shielding uses and now there is only cadmium on the top of pile and on the western face.

To generate the drawings in appendix B many sources of information were combined. An initial model was created from Knapp[6], Pearson & Sims[8], and educated guessing. When the graphite documents in appendix D were discovered the pile was measured and matched to the nominal block sizes which were ordered. These drawings are not true as-built documents. Measurements were used to find the number and nominal size of the blocks. The documentation is based on nominal values. The important dimensions are shown in table 2.1.

Table 2.1: Important dimensions of the Pile

Dimension	**Inch**	**cm**
East-west length (X)	90.75±0.28	230.5±0.7
North-south length (Y)	91.00±0.33	231.1±0.84
Height (lattice) (Z)	90.75±0.24	230.5±0.61
Height (pedestal) (Z)	26.25±0.07	66.68±0.18
Height (total) (Z)	117.0±0.31	297.2±0.79
Lattice pitch	7.25±0.03	18.4±0.08

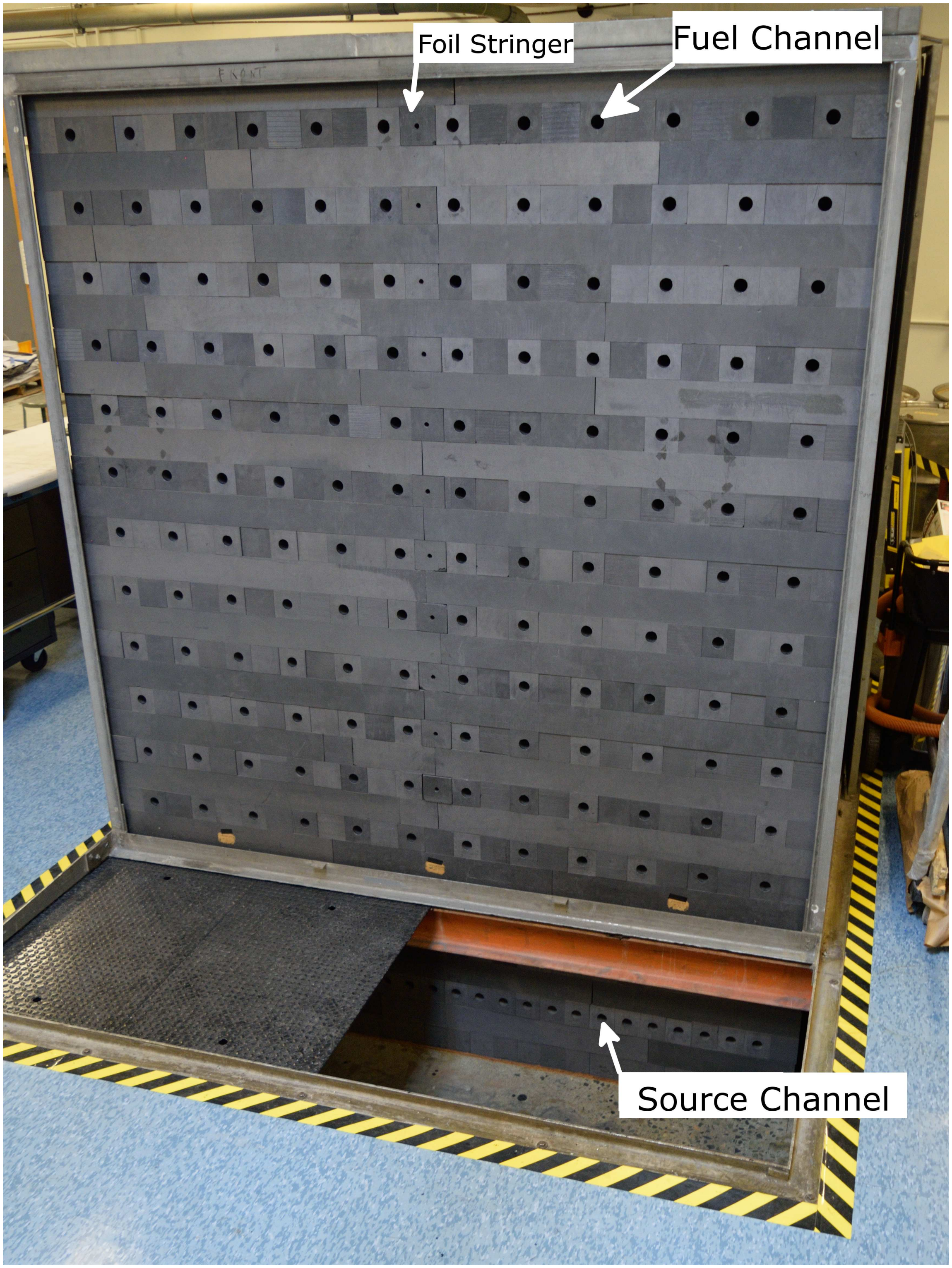

Figure 2.1: The north face of the Graphite Exponential Pile with the covers removed. Half of the floor grates have been removed to show the source channels as well. The fuel channels will normally be filled the uranium fuel slugs. The foil stringers in the center of the pile can be removed and loaded with foils for foil activation analysis. In the pedestal of the pile are many source channels where the neutron source can be inserted.

Figure 2.2: The Graphite Exponential Pile East face. Only one cover is removed from this face. Here both types of neutron measuring blocks can be seen. These blocks are removable and can be moved to create a desired configuration. The extra fuel channels have been re-purposed for use with neutron detector probes.

2.2.1 Measurement Capabilities

The Graphite Exponential Pile has many possible locations for instrumentation, and is highly configurable. The main approaches to measuring the neutron flux is by either foil activation or directly with a neutron detector, such as a BF_3 or a helium-3 probe. As can be seen in Figures 2.1 and 2.2 there are detection blocks which run east to west, north to south, and run through the center of the pile. For foil activations a foil stringer is used which has multiple pockets for positioning foils inside of the pile. For neutron detector probes an extra fuel channel is used. These blocks can be swapped out and moved around for the desired measurement. In appendix B the measurement blocks are shown as they were set up by Pearson and Sims. Note that this was not the configuration which was used for collecting data.

2.2.2 Tolerances

All tolerances are included with appendix B. Here are all of the tolerances to which the pile was machined to, including the source of this information.

- All graphite Blocks
  - Lengths of cross-sectional sides: ±0.010” [14]
  - Long edges feathering: <1/32" deep [14]
  - Maximum chip size: 1/4" deep x 1/2" long [16]
  - Flatness: within 0.010" of flat [16]
  - Perpendicularity: Vary from perpendicular by <0.010" in 4"[16]
- Fuel Stringer
  - Hole Position: $\pm\frac{1"}{8}$ [14]
  - Hole Inner Diameter: $\pm\frac{1"}{16}$ with no steps. [14]
- Foil Stringer
  - Hole Positions, depths, and diameters: $\pm\frac{1"}{16}$[17].
  - Angle of bottom of foil trays: ±2° [18]

2.3 Fuel Properties

The pile contains 1,288 fuel slugs, with each slug being a cylinder about 1 inch in diameter and 8 inches long. The slugs are comprised of metallic natural uranium slugs with an aluminum clad. Unlike modern ceramic fuel the cladding is bonded directly to the uranium metal.

The slugs' length, diameter, and mass were all measured. For the first 140 slugs all three measurements were taken. After this point it was determined that the standard deviation was low enough on the dimensional measurements that it wasn't necessary to measure the dimensions for all the slugs. The mass was taken for 1,286 slugs. Two slugs were not measured due to clerical errors. The entire set of data is presented in appendix F. A summary of these data is presented in table 2.2. The design of a typical fuel slug is shown in figure 2.3.

The natural enrichment of the uranium was verified using gamma spectroscopy with a Canberra GL0515R-DET low-energy high-purity germanium detector. The enrichment was calculated using the Canberra U/Pu inspector software package. This did not consider attenuation in the aluminum cladding. There is too much uncertainty due to this attenuation to quote an exact enrichment level, but it can be said with some certainty this uranium was not enriched past natural levels.

Table 2.2: Summary of slug measurements made.

Property	**Units**	**mean**	**Std. Dev.**	**Maximum**	**Minimum**
Mass	grams	2006	7	2026	1960
Length	inches	8.41	0.01	8.452	8.387
Diameter	inches	1.084	0.001	1.088	1.081

From these data in table 2.2 it is then possible to calculate the volume fraction of the slug which is uranium, if it is assumed that only the uranium and aluminum clad make up a significant portion of the slug volume. The total density would then be given by equation 2.1.

$$\rho_t = \frac{V_U}{V_t}\rho_U + \left(1 - \frac{V_U}{V_t}\right)\rho_{Al} \tag{2.1}$$

In this equation ρ is density, V is volume, and subscript t is the total value. For convenience I will define the uranium volume fraction to be $X = V_U/V_t$. The solution for X from equation 2.1 is presented in equation 2.2.

$$X = \frac{\rho_t - \rho_{Al}}{\rho_U - \rho_{Al}} \tag{2.2}$$

Pearson and Sims reported a number density for the metallic uranium, and not a density so the density was found with equation 2.3.

$$\rho = n\frac{M}{N_A} \tag{2.3}$$

Here n is the number density, N_A is Avagadro's number, and M is the molar mass. The data for solving these equations are presented in table 2.3.

Calculation of the volumes was done assuming all regions were perfect right circular cylinders. It is suggested by the Savannah River document[11] that the metallic uranium slug is 1.00" in diameter. If it is assumed that this is true, then the uranium slug has a length of 8.07". This means the end caps of aluminum have a thickness, T, of 0.17".

Table 2.3: Various values necessary to calculate the mass of uranium in a fuel slug, and various properties calculated thereof.

Variable	**Value**
n_U	$4.7325 \times 10^{22} cm^{-3}$[8]
ρ_{Al}	$2.7\frac{g}{cm^3}$ [19]
N_A	$6.022\,141\,5 \times 10^{23}$[20]
M_U	237.98[21]
ρ_U	$18.702\frac{g}{cm^3}$
ρ_t	$15.77\frac{g}{cm^3}$
X	0.8169
V_U	$103.9 cm^3$
$mass_U$	1.94 kg
T	0.17"

2.4 Graphite Properties

The purity of the graphite was tested by neutron activation analysis. For the neutron activation analysis (NAA) four samples were taken from the same graphite block. This

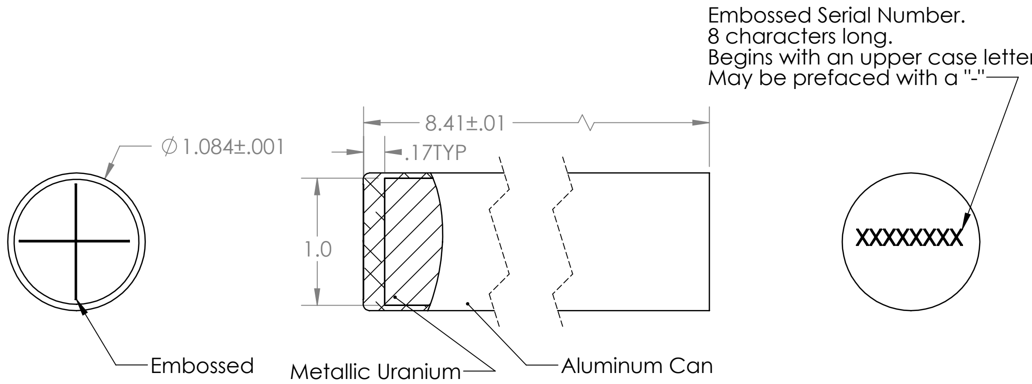

Figure 2.3: The design of the Uranium fuel slugs used in the MGEP. The values shown are nominal and are not universal.

Table 2.4: Density of the Graphite Pile's graphite as measured by different theses.

Source	**Density**
Knapp[6]	$1.69g/cm^3$
Reilly[7]	$1.662g/cm^3$

graphite was from the surplus graphite for the pile which was in storage. The analysis was completed by the NRL. It should be noted that NAA relies on a (n, γ) reaction, however boron-10 undergoes a (n, α) reaction, so boron is not detectable by NAA. The data from this analysis are presented in appendix C.

The density of the graphite was calculated two separate ways by Knapp and Reilly. Knapp took a small sample of the graphite from the MGEP, machined it into a cube, and weighed and measured the cube to calculate the density[6]. Reilly weighed every bar while assembling the standard pile, and calculated the average graphite density using the calculated volume of each bar[7]. These data are presented in table 2.4. Due to its more accurate and precise nature, Reilly's datum was used.

Chapter 3

Background

3.1 Foil Activation for Flux Measurement

One way to measure neutron flux in an exponential pile is by foil activation, in which a foil is activated with neutron radiation, and the radioactivity is then measured to obtain the neutron fluence at that point. Indium is a favorable material for this application for many reasons. Indium has a large thermal absorption cross-section, which forms a radioactive isotope. This isotope has about a one hour half-life which is ideal for taking activity measurements. The capture reaction for indium-115, which is the most abundant naturally ocuring indium isotope[21], is shown in equation 3.1. In these competing reactions both the ground-state and metastable state of indium-116 are possible products of the reaction. The metastable state is at an excited energy state with respect to the ground state.

$$^{115}In + {}^{1}_{0}n \rightarrow \begin{cases} \gamma_1 + {}^{116m}In \\ \gamma_2 + {}^{116}In \end{cases} \tag{3.1}$$

However ^{116}In has a half-life of 2.18 seconds, whereas ^{116m}In has a half-life of 54.29 minutes[22]. In any reasonable experiment only the ^{116m}In will be detectable, due to almost all of the ^{116}In decaying away in the time between the samples being removed from the neutron field and the samples being measured.

3.1.1 Calculating Activity

To be able to measure the flux it is first necessary to measure the activity of the foils after foil activation. The radioactive decay of a substance is governed by differential equation 3.2.

$$\frac{dN}{dt} = -\lambda N \tag{3.2}$$

In this equation N is the number of atoms of the isotope present, and λ is the decay constant for the isotope. This first-order linear ordinary differential equation has a solution of the form in equation 3.3.

$$N(t) = N_0 e^{-\lambda t} \tag{3.3}$$

Where N_0 is the initial activity when the foil is removed from the neutron field at time, $t = 0$. However this solution describes the amount of atoms present and not the activity level. The activity, A, is given by equation 3.4.

$$A = -\frac{dN}{dt} = \lambda N_0 e^{-\lambda t} \tag{3.4}$$

If it is assumed that the detector setup being used has a constant efficiency, η, which includes both the detector and geometric efficiency, then the number of counts detected will be described by equation 3.5.

$$C = \int_{t_1}^{t_2} \eta \lambda N_0 e^{-\lambda t} dt \tag{3.5}$$

In this integral C is the total number of counts detected, and t_1 and t_2 are the times at which the count began and ended. To solve this integral first the constant terms η and N_0 can be removed from the integrand. Next a change of variable is used by defining $u = \lambda t$. This then implies that $du = \lambda dt$. With these changes the integral is then solved in equation 3.6.

$$\begin{aligned} C =& \eta N_0 \int_{\lambda t_1}^{\lambda t_2} e^{-u} du \\ C =& \eta N_0 \left[-e^{-u} \right]_{\lambda t_1}^{\lambda t_2} \\ C =& \eta N_0 \left(e^{-\lambda t_1} - e^{-\lambda t_2} \right) \end{aligned} \tag{3.6}$$

It may be desirable to do multiple counting sessions that are not contiguous in time for a single foil. This would be helpful to get better average statistics for a batch of foils removed simultaneously rather than having very good statistics for the first foil, and poor statistics for the last foil. In this case the totals counts can be more generically written as in equation 3.7.

$$\sum_{n=1}^{N} C_n = \sum_{n=1}^{N} \int_{t_{n,1}}^{t_{n,2}} \eta \lambda N_0 e^{-\lambda t} dt \tag{3.7}$$

Since η and N_0 are constant with respect time it is possible to solve this integral, which is shown in equation 3.8.

$$\sum_{n=1}^{N} C_n = \eta N_0 \sum_{n=1}^{N} \left(e^{-\lambda t_{n,1}} - e^{-\lambda t_{n,2}} \right) \tag{3.8}$$

Now to find the initial activity at the end of the activation it is just necessary to solve equation 3.8 for N_0, which is presented in equation 3.9

$$N_0 = \frac{\sum_{n=1}^{N} C_n}{\eta \sum_{n=1}^{N} \left(e^{-\lambda t_{n,1}} - e^{-\lambda t_{n,2}} \right)} \tag{3.9}$$

3.1.2 Activity Error Propagation

To quantify the error in these measurements, all sources of error and uncertainties must be propagated through to the final activity calculation. The largest source of uncertainty is the radioactive decay of the activated foil due to its entirely stochastic nature. Since it is a truly random process, the process will be Gaussian and have a standard deviation,σ, described by equation 3.10.

$$\sigma_{c,n} = \sqrt{C_n} \tag{3.10}$$

However these counts are not taken in complete isolation and background needs to be subtracted out. The net counts would then be given by equation 3.11.

$$C_{net} = C_n - \frac{C_{bg}t_n}{t_{bg}} \tag{3.11}$$

In this case subscript n is the count taken with the sample and subscript bg is the background count. The standard deviation would be found by summing the standard deviations for the counts in quadrature as shown in equation 3.12.

$$\sigma_{net} = \sqrt{\sigma_{c,n}^2 + \left(\frac{t_n \sigma_{bg}}{t_{bg}}\right)^2} \tag{3.12}$$

For a single counting session the standard deviation for the activity calculated will be described by equation 3.13.

$$\sigma_{N_0} = \frac{\sigma_{net}}{\eta\left(e^{-\lambda t_{n,1}} - e^{-\lambda t_{n,2}}\right)} \tag{3.13}$$

If multiple counting sessions are used the standard deviations would add in quadrature. The total standard deviation is shown in equation 3.14.

$$\sigma_T = \sqrt{\sum_{n=1}^{N} \left(\frac{\sigma_{c,n}}{\eta\left(e^{-\lambda t_{n,1}} - e^{-\lambda t_{n,2}}\right)}\right)^2} \tag{3.14}$$

3.1.3 Calculating Flux from Activity

While activating indium with the neutron capture reaction shown in equation 3.1 there is the competing decay of the daughter products. The concentration of indium-116m, I, is described in differential equation 3.15.

$$\frac{dI}{dt} = \phi \Sigma_c V - \lambda I \tag{3.15}$$

In this case ϕ is the neutron scalar flux measured in neutrons per square centimeter per second. The macroscopic cross-section (Σ_c) is the microscopic capture cross-section for the indium-115 times the indium number density. The microscopic cross section is the effective nucleus cross-sectional area for a neutron capture reaction, and is energy-dependent. However in this setup it is safe to assume all the foils will be exposed to the same neutron energy spectrum, so the energy dependence will be naturally integrated out. With this multiplication the macroscopic cross-section has units of cm^{-1}, and is thus a path length probability. The volume of the foil is represented by V. This differential equation has the solution shown in equation 3.16.

$$I(t) = \frac{\Sigma_c \phi V}{\lambda}\left(1 - e^{-\lambda t}\right) \tag{3.16}$$

This equation then needs to be solved for the flux. It is convenient to replace the volume with $V = m/\rho$, where m is the mass, ρ is the density. This is shown in equation 3.17.

$$\phi = \frac{I_0 \lambda \rho}{\Sigma_c m \left(1 - e^{-\lambda t}\right)} \tag{3.17}$$

It should be noted that the time in this case is the time since the beginning of the foil activation. A more useful form of this equation is finding the relative flux. This allows for finding the flux profile without having to find an accurate capture cross-section. The relative flux between two foils is shown in equation 3.18.

$$\frac{\phi_1}{\phi_2} = \frac{I_1 m_2 \left(1 - e^{-\lambda t_2}\right)}{I_2 m_1 \left(1 - e^{-\lambda t_1}\right)} \tag{3.18}$$

However this is not very helpful as taking the quotient of two random variables could lead to an increase of uncertainty by up to $\sqrt{2}$. A more useful quantity to use would be $\phi\Sigma_c/\rho$, or r, which is the reaction rate per mass, or the specific reaction rate. This will depend solely on the flux as it is safe to assume in this situation the Σ_c and ρ are constant. The specific reaction rate is given in equation 3.19.

$$r = \frac{\phi \Sigma_c}{\rho} = \frac{I_0 \lambda}{m \left(1 - e^{-\lambda t}\right)} \tag{3.19}$$

3.1.4 Flux Error Propagation

When calculating the scalar flux from the foil activation the dominant uncertainty is from the activity level of the foils. This uncertainty is given by equation 3.13. The standard deviation for the flux calculation in equation 3.17 is given by equation 3.20. The standard deviation for the specific reaction rate found in equation 3.19 is given by equation 3.21.

$$\sigma_\phi = \frac{\sigma_{I_0} \lambda \rho}{\Sigma_c m \left(1 - e^{-\lambda t}\right)} \tag{3.20}$$

$$\sigma_r = \frac{\sigma_{I_0} \lambda}{m \left(1 - e^{-\lambda t}\right)} \tag{3.21}$$

If the relative flux is what is of interest in these measurements. The relative flux is a quotient of random variables. The standard deviation for quotients also sum in quadrature[23]. Thus the standard deviation for the relative flux would be given by equation 3.22.

$$\sigma_{\frac{\phi_1}{\phi_2}} = \sqrt{\left(\frac{\sigma_{I_1}\lambda\rho}{\Sigma_c m\left(1 - e^{-\lambda t_1}\right)}\right)^2 + \left(\frac{\sigma_{I_2}\lambda\rho}{\Sigma_c m\left(1 - e^{-\lambda t_2}\right)}\right)^2} \tag{3.22}$$

3.2 Solution to the One-Energy Diffusion Equation in Pile

The derivation of the neutron diffusion theory from the neutron transport equation is beyond the scope of this thesis, and may be found in most reactor physics textbooks. The important thing to note is that diffusion theory is based on the assumption that the angular flux at a point can be represented by a linear function with Ω. This assumption holds in only certain parts of the graphite pile when measurements are taken far enough away from the heterogeneities that the pile can be treated as being homogeneous. The one group diffusion equation is given in equation 3.23.

$$-\nabla \cdot D\nabla\phi(x, y, z) + \Sigma_a\phi(x, y, z) = \nu\Sigma_f\phi(x, y, z) \tag{3.23}$$

In this equation D is the diffusion constant, which is a material property, ν is the average number of neutrons produced per fission, Σ_f is the macroscopic fission cross-section, and Σ_a is the absorption cross-section. In the graphite pile it can be assumed that the diffusion constant does not vary. A new term the, material buckling, can be defined by equation 3.24. This term is related to the behavior of a reactor which has same material properties as the pile, but is infinitely large. So this buckling is related to how a reactor would behave if there was no neutron leakage.

$$B_m^2 \equiv \frac{\nu\Sigma_f - \Sigma_a}{D} \tag{3.24}$$

Equation 3.23 then becomes equation 3.25.

$$\nabla^2\phi(x, y, z) + B_m^2\phi(x, y, z) = 0 \tag{3.25}$$

To solve this differential equation it is helpful to use a separation of variables to redefine ϕ with equation 3.26.

$$\phi(x, y, z) = \Phi(x)\psi(y)\theta(z) \tag{3.26}$$

Expanding the Laplacian operator on the change of variable used in equation 3.26 is shown in equation 3.27.

$$\nabla^2\phi = \frac{\partial^2\Phi}{\partial x^2}\psi\theta + \frac{\partial^2\psi}{\partial x^2}\Phi\theta + \frac{\partial^2\theta}{\partial x^2}\Phi\psi \tag{3.27}$$

Equation 3.25 can then be divided by ϕ, which is shown in equation 3.28.

$$\frac{1}{\Phi}\frac{\partial^2\Phi}{\partial x^2} + \frac{1}{\psi}\frac{\partial^2\psi}{\partial x^2} + \frac{1}{\theta}\frac{\partial^2\theta}{\partial x^2} + B_m^2 = 0 \tag{3.28}$$

If only the x-axis is examined in a 1-D situation (y and z are constant) all of the other components of the flux, and the material buckling can be clumped into a constant term, F^2, and the whole equation multiplied by Φ.

$$\frac{\partial^2 \Phi}{\partial x^2} = -F^2 \Phi \tag{3.29}$$

This differential equation is satisfied by the functions sin, cos, sinh, and cosh. Since this is a second order ordinary differential equation a complete solution needs to be the sum of two functions. So the solution will either be Acos+Bsin or Acosh+Bsinh. Similar arguments can be made for all dimensions, and it becomes clear that the solution in all dimensions must be a combination of these functions. To find an exact solution boundary conditions must be imposed. First for all of space the flux must be finite and non-negative. Next it is assumed that the flux is negligible at an extrapolated distance from the pile on all faces except next to the source, and can be said to be zero. For such a large pile the extrapolation distance would be much less than the overall dimensions of the pile, and the extrapolation length is neglected. Thus the second boundary condition is that at the faces the flux is zero. The geometry for this problem is defined as shown in figure 3.1, with the origin located in the bottom z-plane of the lattice and centered in x and y. Thus the boundary condition for the x direction can be written as shown in equation 3.30.

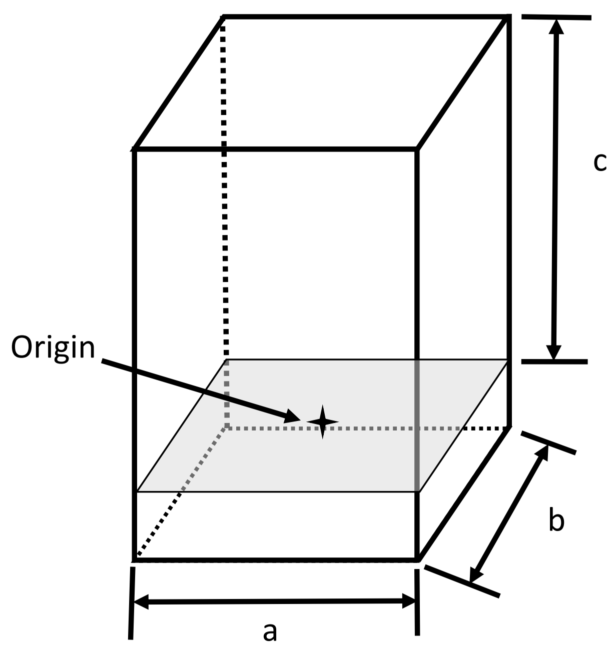

Figure 3.1: The geometry used for the diffusion model. the origin is centered in x and y and located on the plane of the bottom of the lattice. X is aligned with a and Y with b.

3.2.1 Solution in X and Y

$$\Phi\left(\frac{a}{2}\right) = \Phi\left(\frac{-a}{2}\right) = 0 \tag{3.30}$$

It is not possible for cosh and sinh to meet these conditions. Thus it must be a summation of sines and cosines of the form below.

$$\Phi(x) = Acos(Fx) + Bsin(Fx) \tag{3.31}$$

For cosines to be the solution the following condition must be true.

$$\frac{F_{cos}a}{2} = \frac{(2n+1)\pi}{2} \tag{3.32}$$

Where n is an integer. Similarly for sines to be the solution the following condition must hold.

$$\frac{F_{sin}a}{2} = \frac{2n\pi}{2} \tag{3.33}$$

Thus for cosines the angular frequency, F, is given by:

$$F_{cos} = \frac{(2n+1)\pi}{a} \tag{3.34}$$

For sines the angular frequency is given by:

$$F_{sin} = \frac{2n\pi}{a} \tag{3.35}$$

This could also be rewritten as using only cosines for odd values of n, and only sines for even values of n. Thus the flux in the x-direction is given by equation 3.36. It can be easily seen that this would also apply to the y-direction, will be some combination of harmonic sines and cosines.

$$\Phi(x) = \sum_{n=1}^{\infty} \begin{cases} A_n cos\left(\frac{n\pi x}{a}\right) & n \in \mathbb{Z}_{odd} \\ A_n sin\left(\frac{n\pi x}{a}\right) & n \in \mathbb{Z}_{even} \end{cases} \tag{3.36}$$

$$\psi(y) = \sum_{m=1}^{\infty} \begin{cases} A_m cos\left(\frac{m\pi y}{b}\right) & m \in \mathbb{Z}_{odd} \\ A_m sin\left(\frac{m\pi y}{b}\right) & m \in \mathbb{Z}_{even} \end{cases} \tag{3.37}$$

3.2.2 Solution in Z

In the z-direction the top face has a zero-flux boundary condition, and the bottom face is constrained by the neutron source as an initial condition. This asymmetry could never be created with periodic sines and cosines, so the solution in z must be composed of cosh and sinh functions. So theta must take the following form.

$$\theta(z) = Ccosh(\gamma z) + Dsinh(\gamma z) \tag{3.38}$$

If the zero-flux boundary condition is applied the following condition is found.

$$\theta(c) = 0 = Ccosh(\gamma c) + Dsinh(\gamma c) \tag{3.39}$$

$$D = -C\frac{cosh(\gamma c)}{sinh(\gamma c)} \tag{3.40}$$

Substituting these conditions back into equation 3.38 yields the following which may be manipulated.

$$\theta(z) = Ccosh(\gamma z) - C\frac{cosh(\gamma c)}{sinh(\gamma c)}sinh(\gamma z) \tag{3.41}$$

$$\theta = C\frac{sinh(\gamma c)}{sinh(\gamma c)}cosh(\gamma z) - C\frac{cosh(\gamma c)}{sinh(\gamma c)}sinh(\gamma z) \tag{3.42}$$

$$\theta = \frac{C}{sinh(\gamma c)}\left[sinh(\gamma c)cosh(\gamma z) - cosh(\gamma c)sinh(\gamma z)\right] \tag{3.43}$$

Now to simplify this expression a difference of arguments identity of sinh comes in handy.

$$sinh(x-y) = sinh(x)cosh(y) - cosh(x)sinh(y) \tag{3.44}$$

This identity can be used to simplify equation 3.43. In addition the term $sinh(\gamma c)$ will be constant and can be combined into the constant, C.

$$\theta(z) = Csinh[\gamma(c-z)] \tag{3.45}$$

3.2.3 Combined Solution

All positive values for γ will satisfy the finite flux condition, but the ones which will be able to exist in this problem will be constrained by the boundary conditions. These discrete solutions will be noted as γ_k. All solutions must be able to solve the beginning equation, 3.28. The x,y,z and solutions will be combined from equations 3.36, 3.37 & 3.45, and substituted into equation 3.28.

$$0 = B_m^2 + \begin{cases} \frac{-A_n\left(\frac{n\pi}{a}\right)^2 cos\left(\frac{n\pi x}{a}\right)}{A_n cos\left(\frac{n\pi x}{a}\right)} + \frac{-A_m\left(\frac{m\pi}{b}\right)^2 cos\left(\frac{m\pi y}{b}\right)}{A_m cos\left(\frac{m\pi y}{b}\right)} + \frac{C_k\gamma_k^2 sinh[\gamma_k(c-z)]}{c_k sinh[\gamma_k(c-z)]} & m \in \mathbb{Z}_{odd}, n \in \mathbb{Z}_{odd} \\ \frac{-A_n\left(\frac{n\pi}{a}\right)^2 sin\left(\frac{n\pi x}{a}\right)}{A_n sin\left(\frac{n\pi x}{a}\right)} + \frac{-A_m\left(\frac{m\pi}{b}\right)^2 sin\left(\frac{m\pi y}{b}\right)}{A_m sin\left(\frac{m\pi y}{b}\right)} + \frac{C_k\gamma_k^2 sinh[\gamma_k(c-z)]}{c_k sinh[\gamma_k(c-z)]} & m \in \mathbb{Z}_{even}, n \in \mathbb{Z}_{even} \\ \ldots & \ldots \end{cases} \tag{3.46}$$

These equations were not extended to all possible permutations of m& n even, odd parity, as it can be seen that in all cases the majority of the equation cancels leaving a simple relationship.

$$0 = B_m^2 - \left(\frac{n\pi}{a}\right)^2 - \left(\frac{m\pi}{b}\right)^2 + \gamma_k^2 \tag{3.47}$$

Since B_m^2 is constrained by the material properties and is constant there are only two possible values for γ_k for any combination of m& n . One is positive and the other negative. Since γ_k must be positive to give positive flux values only the positive value of γ_k is possible. Since there is only one value of γ_k for every combination of m& n it is conventional to denote γ_k as: $\gamma_{n,m}$. Any harmonic mode could be used to solve for the material buckling, however the fundamental mode (m=n=1) will be dominant and the easiest mode to measure as shown in equation 3.48.

$$B_m^2 = \left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2 - \gamma_{1,1}^2 \tag{3.48}$$

Finally combining the solutions found in equations 3.36, 3.37 & 3.45 yields the flux distribution at any point in the pile as shown in equation 3.49.

$$\phi(x,y,z) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\begin{cases} A_{m,n} sinh[\gamma_{m,n}(c-z)] cos\left(\frac{n\pi x}{a}\right) cos\left(\frac{m\pi y}{b}\right) & n_{odd}, m_{odd} \\ A_{m,n} sinh[\gamma_{m,n}(c-z)] sin\left(\frac{n\pi x}{a}\right) sin\left(\frac{m\pi y}{b}\right) & n_{even}, m_{even} \\ A_{m,n} sinh[\gamma_{m,n}(c-z)] cos\left(\frac{n\pi x}{a}\right) sin\left(\frac{m\pi y}{b}\right) & n_{odd}, m_{even} \\ A_{m,n} sinh[\gamma_{m,n}(c-z)] sin\left(\frac{n\pi x}{a}\right) cos\left(\frac{m\pi y}{b}\right) & n_{even}, m_{odd} \end{cases} \tag{3.49}$$

3.3 Finding Critical Reactor Size

When a reactor becomes critical (k=1) the neutron flux distribution becomes independent of the external neutron sources. The boundary conditions imposed on Z will no longer hold when the reactor becomes critical, and $\theta(z)$ will become a series of sines and cosines. When critical equation equation 3.48 will change to be as follows.

$$B_m^2 = \left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2 + \left(\frac{\pi}{c}\right)^2 \tag{3.50}$$

Commonly the geometric buckling B_g^2 is used. This is defined as shown below.

$$B_g^2 = \left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2 + \left(\frac{\pi}{c}\right)^2 \tag{3.51}$$

Thus for a reactor to be critical the following condition must be true:

$$B_g = B_m \tag{3.52}$$

If it is assumed that a critical reactor would be made from a large cube, with side s, with the same material properties as the pile the critical geometry is given by the following relationship.

$$B_m^2 = 3\left(\frac{\pi}{s}\right)^2 \tag{3.53}$$

Thus the critical reactor size would be found by equation 3.54.

$$s = \frac{\sqrt{3}\pi}{B_m} \tag{3.54}$$

Chapter 4

Methodologies

In order to measure the material buckling of the Graphite Exponential Pile, indium foils were activated in the loaded pile with an external neutron source. All the fuel was loaded and foils were positioned to allow measurement of the radial and axial flux distribution of the pile.

4.1 Fuel Loading

The fuel was loaded in order to maximize the fuel loading nearest to the source. Layers 1-10 were loaded to capacity. Layer 11 did not have enough fuel for a full loading so it was loaded in order to be symmetric about the central plane. The central 8 channels were filled to capacity. The next channels out were filled with four slugs each. The slugs were then centered in their channels north to south. This was accomplished by placing a locking collar on an aluminum rod at the calculated depth. The slugs were pushed from the north face until the collar came into contact with the pile. For channels with 10 slugs the slugs were pushed to be $3\frac{1"}{2} \pm \frac{1"}{8}$ from the north face. For channels with 4 slugs they were pushed to be $28\frac{3"}{4} \pm \frac{1"}{8}$ from the north face. This loading pattern is shown in Figure 4.1.

4.2 Stringer Configuration

As stated before, the pile can be configured for whatever measurements are desired. For this activation it was desired to establish radial and axial flux distributions. All measurements were taken using the east-to-west stringers. A complete radial profile with 14 positions was established at layer 5. Seven positions running from east to the center were taken at layer 1. An axial profile was taken near the center for layers 1-10. The foil stringers were moved to accommodate this. The fuel channel blocks were moved to fill in the voids. The channel of the lower layers were filled with graphite rods to remove the void from the center of these channels. The foil stringers were centered in the channels. Nominally the stringers would extend 1/2" past the eastern face of the pile. Table 4.1 shows the configuration which was used.

	A	B	C	D	E	F	G	H	I	J	K	L
12	0	0	0	0	0	0	0	0	0	0	0	0
11	0	4	10	10	10	10	10	10	10	10	4	0
10	10	10	10	10	10	10	10	10	10	10	10	10
9	10	10	10	10	10	10	10	10	10	10	10	10
8	10	10	10	10	10	10	10	10	10	10	10	10
7	10	10	10	10	10	10	10	10	10	10	10	10
6	10	10	10	10	10	10	10	10	10	10	10	10
5	10	10	10	10	10	10	10	10	10	10	10	10
4	10	10	10	10	10	10	10	10	10	10	10	10
3	10	10	10	10	10	10	10	10	10	10	10	10
2	10	10	10	10	10	10	10	10	10	10	10	10
1	10	10	10	10	10	10	10	10	10	10	10	10

Figure 4.1: The fuel loading pattern for the foil activation as seen from the north face. The number indicates the number of slugs loaded into a channel. All of the slugs were centered in each channel.

Table 4.1: Loading pattern of the foil and fuel channel stringers for the foil activation. F stands for a foil stringer. O symbolizes a fuel channel with a void, and G is a fuel channel with the channel filled with a graphite rod. The offset was measured by how far the stringers extended past the east face. Measurements are ±1/8".

Layer	East	West	Offset
11	O	O	—
10	F	O	3/8"
9	F	G	3/8"
8	F	G	1/2"
7	F	G	5/8"
6	F	G	5/8"
5	F	F	1/2"
4	F	G	1/2"
3	F	G	3/8"
2	F	G	3/8"
1	F	G	1/2"

4.3 Foil Positions

Indium foil activation was used for measuring the neutron flux levels. Indium foils were prepared by punching out foils. The foils were punched from 0.010 thick indium foil using a 0.95" punch. The measured properties of these foils are presented in table A.1. All the foils were marked with an identifier with a fine-tipped marker, which dented the foils. For some of the foils the letter identifiers were ambiguous, such as: F,H,I,N and Z. To reduce this confusion the letters on these foils were underlined to show the proper orientation of the foil. Foil D was easily confused with O so the symbol Δ was added.

The foils were positioned to allow for finding the radial and axial neutron distributions. The radial distributions were measured on layers 1 and 5. On layer 5 a full profile from east to west was measured with 14 positions in total. On layer 1 a half profile was measured from the east face to the center with 7 foil positions. For the axial profile, layers 1-10 were measured. The foils were placed in position 7 which is the closest position to the center from the east face. Table A.2 lists the positions for all the foils.

4.4 Source

For this foil activation, MIT's 1 Curie Pu-Be, M-52, source was used[24]. It produced approximately 1.73×10^6 neutrons per second at the time of the experiment. The source was inserted into the source channel, which is just to the west of the center, or the 14^{th} channel from the east. The source was inserted 44.5" into the channel as measured from the north face to the top of the source.

The source was inserted to the correct location by taking a tape measure and pushing the source to the correct distance. The neutron source has a steel cable attached to it's attachment point. This was attached by a screw closure carabiner to a string. The string was ended with a figure-8 knot and a safety knot. These were used due to their demonstrated ability to withstand large loads and to not easily untie. The source was inserted on May 4, 2018 at 12:05 PM EDT.

4.5 Foil Counting

The counting of the foils' activity was done in such a way to maximize the amount of decays detected. This was accomplished in many ways. First, "online retrieval" was used where foils were removed while the source was still in the pile, allowing small batches to be counted each time. For a batch, each foil was counted for a short duration and the foils cycled through these counting cycles multiple times. This prevented the first foil getting very good statistics and the last one the worst statistics. The counting was completed with a Protean Instruments Corporation WPC 9550 automated gas flow proportional counter, which is designed for detecting α and β particles from a large set of samples automatically and has an efficiency of 42.64%.

The foils were counted in four batches of 7-8 foils. For each foil stringer a time for removal of the stringer was determined 30 seconds before. When that time was reached ($\pm 1s$) on the author's watch, the stringer was removed from the pile expeditiously. The foils were then transported to the detector and loaded onto sample trays and the automated counted process initiated. This process usually took less than 5 minutes. Each foil in the batch was counted for 2 minutes, and the entire batch went through 4 cycles of this counting cycle. To improve the statistics on the axial traverse, which had the lowest neutron fluxes, 5 cycles were used. The counting data are presented in table A.3.

Chapter 5

Results

In order to determine the material buckling of the MIT Graphite Exponential Pile, when fully loaded with fuel the neutron flux was found using indium foil activation. The indium foils were used to find the radial flux distribution in the east-west (X) axis, and the axial flux distribution. The radial distribution was found on layers 1 and 5. The axial distribution was found on layers 1-10.

The foils were then counted in a way to decrease the uncertainty in the measurements. These counts were then used to calculate an uncorrected specific reaction rate ($\eta\phi\Sigma_c/\rho$) using equation 3.19. This is a very good corollary for neutron flux since in this experiment η, the detector efficiency, Σ_c, the macroscopic capture cross-section, and ρ the indium density are constant. All of the data were entered into a Office Open XML (Excel) spreadsheet. This sheet was then parsed and analyzed using a script written in Python3. This script is included in appendix E. All of the raw data collected is presented in appendix A. The radial data are presented in Figure 5.1, and the axial data are presented in Figure 5.2.

To find the material buckling it is necessary to find the $\gamma_{1,1}$ value. This was found by performing a least-square non-linear regression on $\theta(z)$. However the data aren't entirely dominated by the first harmonic, and the high-order harmonics are more prominent near the source. To remove these effects the two data points nearest the source were not included in the fit. The axial profile with the regression line is shown in figure 5.3. From this regression it was found that $\gamma_{1,1} = 0.01621cm^{-1}$. This regression had a R^2 value of 0.944. From this data and equation 3.48 it was possible to calculate the geometric buckling. These data are presented in table 5.1.

With knowledge of the material buckling it is now possible to calculate the critical reactor size for this lattice configuration. This is done by setting the material and geometric buckling equal. For a cube the side length,s, for a critical reactor can be found with equation 3.54. It was found that the Graphite Exponential Pile would have to be a cube 5.42m to a side in order to become critical.

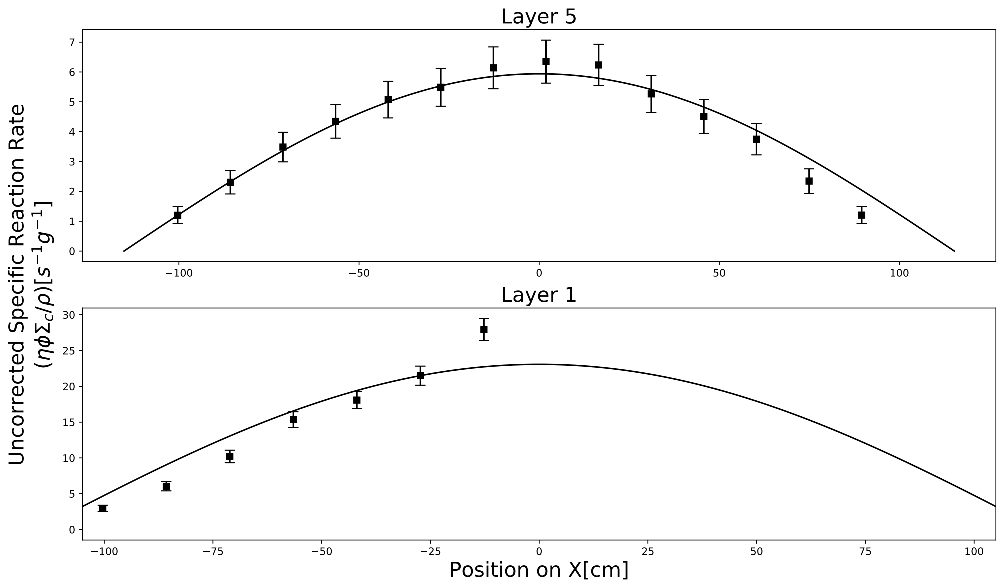

Figure 5.1: The uncorrected specific reaction rate radial profiles for the MIT graphite Exponential pile with a full loading of fuel. The data are uncorrected since the detector efficiency was not included in the calculations, however all measurements used the same detector set-up. On Layer 5 a full profile was found, whereas for layer 1 only a half-profile was measured. Error bars show 1σ. The fundamental cosine mode has been superimposed for convenience.

Table 5.1: The Geometric buckling and other pile properties found experimentally

Parameter	**Value**
$\gamma_{1,1}$	$0.01621\ cm^{-1}$
R^2	0.944
B_m^2	$107.9 \times 10^{-6} cm^{-2}$
B_m	$0.01039\ cm^{-1}$
s	5.24m (206")

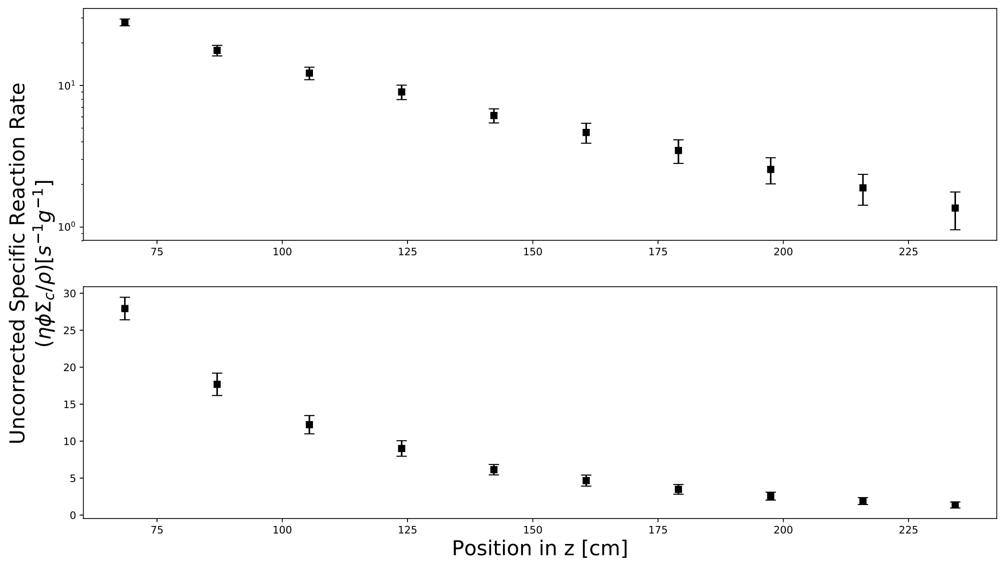

Figure 5.2: The uncorrected specific reaction rate rate axial profile as measured from foil position 7, which is just east of center(x≈-12cm). The detector efficiency was not factored into these calculations, however the same detector setup was used for all measurements. The axial profile was taken for layers 1-10. Error bars show 1σ uncertainties.

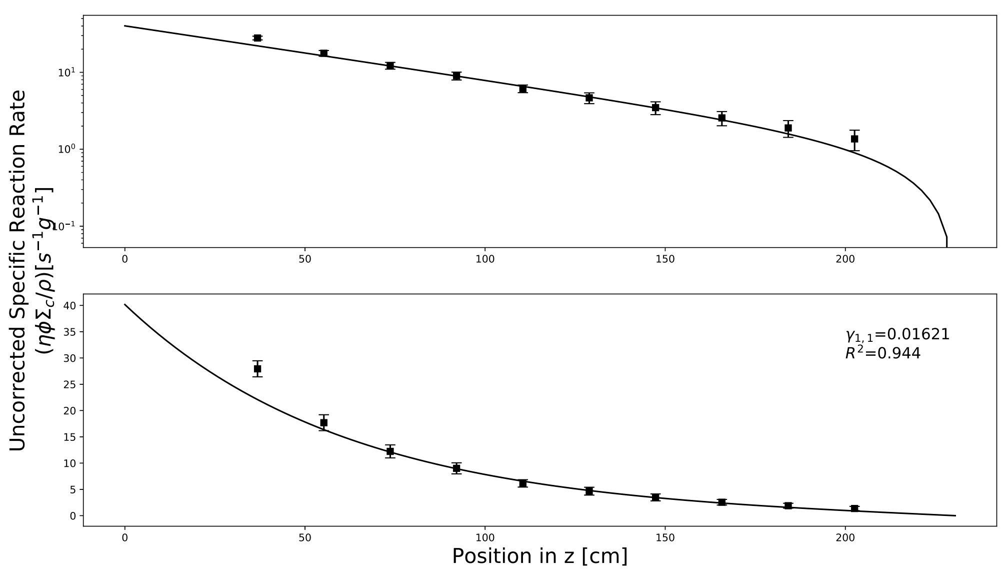

Figure 5.3: The axial reaction rate profile with the $\gamma_{1,1}$ regression super-imposed on the plot. The regression is the least accurate near the source, which is to be expected as the higher modes have not died out at that distance yet. Due to these higher harmonics the first two data points were not included in the regression fit.

Chapter 6

Conclusions

In this thesis the MIT Graphite Exponential Pile was characterized as one demonstration of the many possible uses of the pile for student reactor physics experiments. This was completed safely and in compliance with pertinent regulations; showing this can be safely done by undergraduates. This will start the use of the graphite pile as a class experiment for the MIT reactor physics courses.

It was found that the graphite pile would become critical if it were a cube with a side length of 5.24m. The results agreed well with one-group diffusion theory, and showed that for this system these models are accurate predictors. This confirms one desired use for the pile to help students bring physical meaning to these seemingly arbitrary solutions to diffusion theory. In this one-group model it was shown that it was possible to excite sinusoidal modes due to the source asymmetry.

This thesis is just the beginning of restarting a 60 year old experimental facility. This pile may go a long way towards augmenting reactor physics education, and creating a more mens et manus approach to education. To maximize this impact clear and quantifiable educational metrics should be implemented to clearly and demonstrably measure the effectiveness of this pile as an educational tool. Using the input from these metrics, and other means student experiments should be iteratively improved. Great thought needs to be put into the best way to achieve this, and how best to present these student experiments. One possible approach would be to frame the experiment as an engineering problem. The students would be given a clear set of goals to achieve, and given the tools necessary to achieve them by their own ingenuity.

With modern detectors and computational tools many new student experiments may be done, which were not done in the 50s. With the pile available as a potential neutron source it is possible to generate many short lived isotopes, such as indium-116m, and measure their activities at multiple times in order to calculate the half-lives of these isotopes. It is now possible to create models with dozens of the harmonic modes present. Using these models it would be of interest to complete extremely asymmetric problems with many sinusoidal modes active. These data could then be analyzed by a method similar to a Fourier transform to determine which modes are present. In addition since the asymmetric modes have a faster exponential decay in z it would be of interest to note how different exponential decays can be activated with different source loading patterns. Students may be interested in completing post-irradiation gamma-spectroscopy of a fuel slug to determine which fission products are present.

Finally this pile can still be useful for completing academic research, such as creating a criticality safety benchmark experiment. To work towards these ends many of the uncertainties must be reduced about the pile's material properties. The boron-content of the graphite must be precisely found. It may be useful to complete a precise-sigma pile experiment to benchmark impurity modeling of the graphite. More information about the internal structure and composition of the fuel slugs must be found by destructive or non-destructive means. This especially includes finding the purity of the aluminum clad, and what compounds were used in the slug canning process. Extreme caution should be used in extrapolating information about the canning process as it is possible not all of the slugs were canned the same way.

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Appendices

Appendix A

Experimental Results

A.1 Indium Foil Properties

All foils were punched from two sheets of indium foil using the same 0.95" punch. The thickness was measured near the center of each foil which was punched out with an Anytime Tools 0-1" 0.0001" micrometer, which was zeroed prior to use. The masses were measured using a Sartorius BP 160P analytical balance. The balance was capable of measuring to 0.1mg for mass less than 30g. These data are reported in table A.1.

A.2 Foil Positions in Pile

The foils were placed in the foil stringers that run east to west. Numbering of the layers begins at 1 at the bottom layer. Positions within a layer begin at 1 on the far eastern side and go to 14 on the far western side. All position measurements are relative to the same datum, which is centered north to south, east to west, and is in the bottom plane of the lattice. X is east to west, Y is north to south, and Z is vertical. All times are measured in Eastern Daylight Time synchronized with internet time. Some measurements were based the author's watch's time which was synchronized to within 3 seconds of internet time the morning of the data collection. The source was inserted On May 4, 2018 at 12:05 PM. The foil positions in the pile are reported in table A.2

Table A.1: Indium Foil Properties

Foil	**Diameter (in)**	**Thickness (in)**	**Mass (g)**
A	0.95	0.0097	0.7375
B	0.95	0.0096	0.7511
C	0.95	0.0092	0.7380
D	0.95	0.0096	0.7485
E	0.95	0.0099	0.7492
F	0.95	0.0096	0.7607
G	0.95	0.0095	0.7508
H	0.95	0.0094	0.7373
I	0.95	0.0099	0.7543
J	0.95	0.0100	0.7657
K	0.95	0.0096	0.7397
L	0.95	0.0110	0.7284
M	0.95	0.0110	0.7494
N	0.95	0.0099	0.7621
O	0.95	0.0096	0.7290
P	0.95	0.0099	0.7378
Q	0.95	0.0091	0.6770
R	0.95	0.0092	0.6886
S	0.95	0.0093	0.6953
T	0.95	0.0089	0.6805
U	0.95	0.0091	0.6994
V	0.95	0.0090	0.7111
W	0.95	0.0095	0.7192
X	0.95	0.0089	0.7044
Y	0.95	0.0102	0.7119
Z	0.95	0.0091	0.7213
AA	0.95	0.0093	0.7310
AB	0.95	0.0098	0.7233
AC	0.95	0.0101	0.7206
AD	0.95	0.0094	0.7307
AE	0.95	0.0101	0.7414
AF	0.95	0.0100	0.7367

Table A.2: Indium Foil Positions

Foil	Layer	Position	X [cm]	Y [cm]	Z [cm]	Finish Activation
A	5	1	-100.33	0	110.49	5/7/2018 10:30
B	5	2	-85.725	0	110.49	5/7/2018 10:30
C	5	3	-71.12	0	110.49	5/7/2018 10:30
D	5	4	-56.515	0	110.49	5/7/2018 10:30
E	5	5	-41.91	0	110.49	5/7/2018 10:30
F	5	6	-27.305	0	110.49	5/7/2018 10:30
G	5	7	-12.7	0	110.49	5/7/2018 10:30
H	5	8	1.905	0	110.49	5/7/2018 11:57
I	5	9	16.51	0	110.49	5/7/2018 11:57
J	5	10	31.115	0	110.49	5/7/2018 11:57
K	5	11	45.72	0	110.49	5/7/2018 11:57
L	5	12	60.325	0	110.49	5/7/2018 11:57
M	5	13	74.93	0	110.49	5/7/2018 11:57
N	5	14	89.535	0	110.49	5/7/2018 11:57
O	1	1	-100.33	0	36.83	5/7/2018 15:23
P	1	2	-85.725	0	36.83	5/7/2018 15:23
Q	1	3	-71.12	0	36.83	5/7/2018 15:23
R	1	4	-56.515	0	36.83	5/7/2018 15:23
S	1	5	-41.91	0	36.83	5/7/2018 15:23
T	1	6	-27.305	0	36.83	5/7/2018 15:23
U	1	7	-12.7	0	36.83	5/7/2018 15:23
V	2	7	-12.3825	0	55.245	5/7/2018 13:23
W	3	7	-12.3825	0	73.66	5/7/2018 13:22
X	4	7	-12.7	0	92.075	5/7/2018 13:21
Y	6	7	-13.0175	0	128.905	5/7/2018 13:20
Z	7	7	-13.0175	0	147.32	5/7/2018 13:19
AA	8	7	-12.7	0	165.735	5/7/2018 13:18
AB	9	7	-12.3825	0	184.15	5/7/2018 13:17
AC	10	7	-12.3825	0	202.565	5/7/2018 13:16

A.3 Foil Counting Data

All counts were taken using a Protean Instruments Corporation WPC 9550 automated gas flow proportional counter with an efficiency of:42.6402327% . The counting data are reported in table A.3.

Table A.3: Indium Foil Counts

Foil	Count Start Time	Count End Time	Counts	Background Counts	Background count time (minutes)
A	5/7/2018 10:36	5/7/2018 10:38	115	9	10
A	5/7/2018 10:53	5/7/2018 10:55	76	9	10
A	5/7/2018 11:11	5/7/2018 11:13	72	9	10
A	5/7/2018 11:28	5/7/2018 11:30	48	9	10
AA	5/7/2018 13:30	5/7/2018 13:32	199	9	10
AA	5/7/2018 13:50	5/7/2018 13:52	165	9	10
AA	5/7/2018 14:10	5/7/2018 14:12	130	9	10
AA	5/7/2018 14:30	5/7/2018 14:32	95	9	10
AA	5/7/2018 14:50	5/7/2018 14:52	66	9	10
AB	5/7/2018 13:28	5/7/2018 13:30	146	9	10
AB	5/7/2018 13:48	5/7/2018 13:50	123	9	10
AB	5/7/2018 14:08	5/7/2018 14:10	94	9	10
AB	5/7/2018 14:28	5/7/2018 14:30	76	9	10
AB	5/7/2018 14:48	5/7/2018 14:50	51	9	10
AC	5/7/2018 13:25	5/7/2018 13:28	110	9	10
AC	5/7/2018 13:46	5/7/2018 13:48	80	9	10
AC	5/7/2018 14:06	5/7/2018 14:08	60	9	10
AC	5/7/2018 14:26	5/7/2018 14:28	66	9	10
AC	5/7/2018 14:45	5/7/2018 14:48	45	9	10
B	5/7/2018 10:38	5/7/2018 10:40	221	9	10
B	5/7/2018 10:56	5/7/2018 10:58	151	9	10
B	5/7/2018 11:13	5/7/2018 11:15	120	9	10
B	5/7/2018 11:31	5/7/2018 11:33	94	9	10
C	5/7/2018 10:40	5/7/2018 10:43	302	9	10
C	5/7/2018 10:58	5/7/2018 11:00	228	9	10
C	5/7/2018 11:15	5/7/2018 11:17	168	9	10
C	5/7/2018 11:33	5/7/2018 11:35	145	9	10
D	5/7/2018 10:43	5/7/2018 10:45	348	9	10
D	5/7/2018 11:00	5/7/2018 11:02	279	9	10
D	5/7/2018 11:18	5/7/2018 11:20	221	9	10
D	5/7/2018 11:35	5/7/2018 11:37	181	9	10
E	5/7/2018 10:45	5/7/2018 10:47	415	9	10
E	5/7/2018 11:03	5/7/2018 11:05	308	9	10
E	5/7/2018 11:20	5/7/2018 11:22	243	9	10
E	5/7/2018 11:38	5/7/2018 11:40	204	9	10
F	5/7/2018 10:48	5/7/2018 10:50	466	9	10
F	5/7/2018 11:05	5/7/2018 11:07	333	9	10
F	5/7/2018 11:23	5/7/2018 11:25	247	9	10
F	5/7/2018 11:40	5/7/2018 11:42	200	9	10
G	5/7/2018 10:50	5/7/2018 10:52	443	9	10
G	5/7/2018 11:07	5/7/2018 11:09	358	9	10
G	5/7/2018 11:25	5/7/2018 11:27	294	9	10
G	5/7/2018 11:43	5/7/2018 11:45	236	9	10
H	5/7/2018 12:16	5/7/2018 12:18	467	9	10
H	5/7/2018 12:34	5/7/2018 12:36	391	9	10
H	5/7/2018 12:51	5/7/2018 12:53	299	9	10
H	5/7/2018 13:09	5/7/2018 13:11	258	9	10
I	5/7/2018 12:14	5/7/2018 12:16	439	9	10
I	5/7/2018 12:31	5/7/2018 12:33	411	9	10
I	5/7/2018 12:49	5/7/2018 12:51	305	9	10
I	5/7/2018 13:06	5/7/2018 13:08	261	9	10
J	5/7/2018 12:11	5/7/2018 12:13	403	9	10
J	5/7/2018 12:29	5/7/2018 12:31	363	9	10
J	5/7/2018 12:46	5/7/2018 12:48	276	9	10
J	5/7/2018 13:04	5/7/2018 13:06	210	9	10
K	5/7/2018 12:09	5/7/2018 12:11	351	9	10
K	5/7/2018 12:26	5/7/2018 12:29	307	9	10
K	5/7/2018 12:44	5/7/2018 12:46	236	9	10
K	5/7/2018 13:02	5/7/2018 13:04	176	9	10
L	5/7/2018 12:06	5/7/2018 12:09	299	9	10
L	5/7/2018 12:24	5/7/2018 12:26	222	9	10
L	5/7/2018 12:42	5/7/2018 12:44	211	9	10
L	5/7/2018 12:59	5/7/2018 13:01	168	9	10
M	5/7/2018 12:04	5/7/2018 12:06	183	9	10
M	5/7/2018 12:22	5/7/2018 12:24	152	9	10
M	5/7/2018 12:39	5/7/2018 12:41	153	9	10
M	5/7/2018 12:57	5/7/2018 12:59	113	9	10
N	5/7/2018 12:02	5/7/2018 12:04	116	9	10
N	5/7/2018 12:19	5/7/2018 12:22	71	9	10
N	5/7/2018 12:37	5/7/2018 12:39	71	9	10
N	5/7/2018 12:55	5/7/2018 12:57	69	9	10
O	5/7/2018 15:27	5/7/2018 15:29	284	9	10

Table A.3: Indium Foil Counts

Foil	Count Start Time	Count End Time	Counts	Background Counts	Background count time (minutes)
O	5/7/2018 15:45	5/7/2018 15:47	198	9	10
O	5/7/2018 16:02	5/7/2018 16:04	145	9	10
O	5/7/2018 16:20	5/7/2018 16:22	137	9	10
P	5/7/2018 15:29	5/7/2018 15:32	514	9	10
P	5/7/2018 15:47	5/7/2018 15:49	434	9	10
P	5/7/2018 16:04	5/7/2018 16:07	324	9	10
P	5/7/2018 16:22	5/7/2018 16:24	253	9	10
Q	5/7/2018 15:32	5/7/2018 15:34	747	9	10
Q	5/7/2018 15:49	5/7/2018 15:51	666	9	10
Q	5/7/2018 16:07	5/7/2018 16:09	488	9	10
Q	5/7/2018 16:24	5/7/2018 16:26	396	9	10
R	5/7/2018 15:34	5/7/2018 15:36	1148	9	10
R	5/7/2018 15:52	5/7/2018 15:54	927	9	10
R	5/7/2018 16:09	5/7/2018 16:11	751	9	10
R	5/7/2018 16:27	5/7/2018 16:29	576	9	10
S	5/7/2018 15:37	5/7/2018 15:39	1282	9	10
S	5/7/2018 15:54	5/7/2018 15:56	1127	9	10
S	5/7/2018 16:12	5/7/2018 16:14	866	9	10
S	5/7/2018 16:29	5/7/2018 16:31	648	9	10
T	5/7/2018 15:39	5/7/2018 15:41	1448	9	10
T	5/7/2018 15:56	5/7/2018 15:59	1267	9	10
T	5/7/2018 16:14	5/7/2018 16:16	979	9	10
T	5/7/2018 16:31	5/7/2018 16:34	734	9	10
U	5/7/2018 15:41	5/7/2018 15:43	1924	9	10
U	5/7/2018 15:59	5/7/2018 16:01	1544	9	10
U	5/7/2018 16:16	5/7/2018 16:18	1259	9	10
U	5/7/2018 16:34	5/7/2018 16:36	1012	9	10
V	5/7/2018 13:42	5/7/2018 13:44	1272	9	10
V	5/7/2018 14:02	5/7/2018 14:04	903	9	10
V	5/7/2018 14:22	5/7/2018 14:24	736	9	10
V	5/7/2018 14:42	5/7/2018 14:44	576	9	10
V	5/7/2018 15:02	5/7/2018 15:04	499	9	10
W	5/7/2018 13:40	5/7/2018 13:42	864	9	10
W	5/7/2018 14:00	5/7/2018 14:02	668	9	10
W	5/7/2018 14:20	5/7/2018 14:22	561	9	10
W	5/7/2018 14:40	5/7/2018 14:42	425	9	10
W	5/7/2018 15:00	5/7/2018 15:02	329	9	10
X	5/7/2018 13:37	5/7/2018 13:40	654	9	10
X	5/7/2018 13:57	5/7/2018 14:00	522	9	10
X	5/7/2018 14:17	5/7/2018 14:20	382	9	10
X	5/7/2018 14:37	5/7/2018 14:39	296	9	10
X	5/7/2018 14:57	5/7/2018 14:59	234	9	10
Y	5/7/2018 13:35	5/7/2018 13:37	337	9	10
Y	5/7/2018 13:55	5/7/2018 13:57	280	9	10
Y	5/7/2018 14:15	5/7/2018 14:17	217	9	10
Y	5/7/2018 14:35	5/7/2018 14:37	163	9	10
Y	5/7/2018 14:55	5/7/2018 14:57	120	9	10
Z	5/7/2018 13:33	5/7/2018 13:35	246	9	10
Z	5/7/2018 13:53	5/7/2018 13:55	207	9	10
Z	5/7/2018 14:13	5/7/2018 14:15	159	9	10
Z	5/7/2018 14:33	5/7/2018 14:35	133	9	10
Z	5/7/2018 14:53	5/7/2018 14:55	116	9	10

The data above were entered into an Office Open XML (Excel) spreadsheet, which was then parsed and analyzed by a script written in Python3. The interpreted data of the uncorrected activity, and specific reaction rates are presented in table A.4.

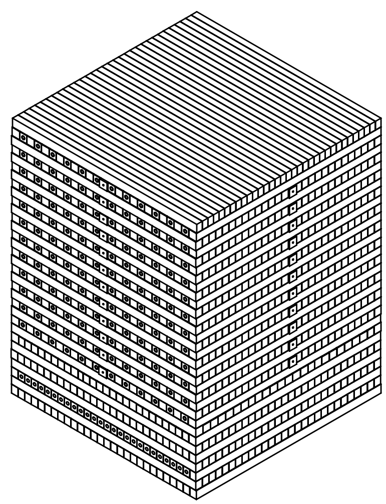
Table A.4: Interpreted Activity Data

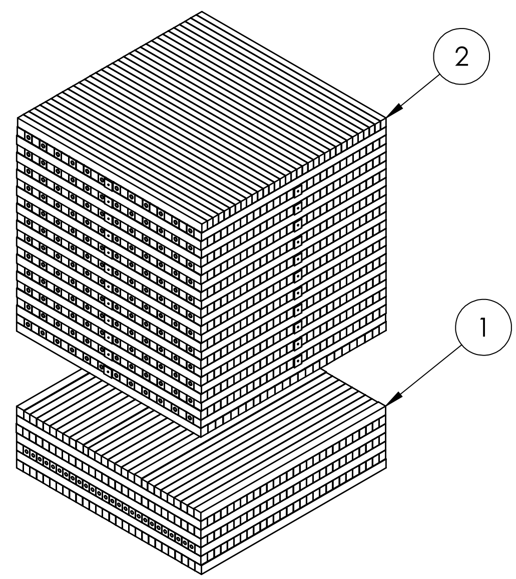
Layer	X position [cm]	Y position [cm]	Z position [cm]	Net Counts	Uncorrected Initial Activity [Bq]	Uncorrected Specific Reaction Rate[$g^{-1}s^{-1}$]	Standard Deviation for reaction rate
1	-100.33	0	68.58	756.3	10114.9	3	0.4
1	-85.725	0	68.58	1517.3	20917	6	0.6
1	-71.12	0	68.58	2289.3	32454.2	10.2	0.9
1	-56.515	0	68.58	3394.3	49692.1	15.4	1.0
1	-41.91	0	68.58	3915.3	59068.7	18.1	1.0
1	-27.305	0	68.58	4420.3	68731.5	21.5	1.0
1	-12.7	0	68.58	5731.3	91830.5	27.9	2.0
2	-12.3825	0	86.995	3976.4	59109	17.7	2.0
3	-12.3825	0	105.41	2837.4	41324.3	12.2	1.0
4	-12.7	0	123.825	2078.4	29806.5	9	1.0
5	-100.33	0	142.24	303.3	4161.3	1.2	0.3
5	-85.725	0	142.24	578.3	8137.9	2.3	0.4
5	-71.12	0	142.24	835.3	12086.8	3.5	0.5
5	-56.515	0	142.24	1021.3	15293.4	4.3	0.6
5	-41.91	0	142.24	1162.3	17869.3	5.1	0.6
5	-27.305	0	142.24	1238.3	19623.4	5.5	0.6
5	-12.7	0	142.24	1323.3	21657.3	6.1	0.7
5	1.905	0	142.24	1407.1	21992.1	6.3	0.7
5	16.51	0	142.24	1408.3	22102.4	6.2	0.7
5	31.115	0	142.24	1244.3	18951.4	5.3	0.6
5	45.72	0	142.24	1062.3	15658.9	4.5	0.6
5	60.325	0	142.24	892.3	12832.6	3.7	0.5
5	74.93	0	142.24	593.3	8258.6	2.3	0.4
5	89.535	0	142.24	319.3	4313.3	1.2	0.3
6	-13.0175	0	160.655	1107.4	15593.8	4.7	0.7
7	-13.0175	0	179.07	851.4	11782.2	3.5	0.7
8	-12.7	0	197.485	645.4	8776.3	2.6	0.5
9	-12.3825	0	215.9	480.4	6433.5	1.9	0.5
10	-12.3825	0	234.315	351.4	4616	1.4	0.4

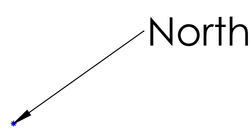
Appendix B

Graphite Pile Engineering Drawings

ITEM NO.	PART NUMBER	DESCRIPTION	Sheet
1	pedastal	The Lower pedastal which features the neutron sources	11
2	lattice	The graphite fuel lattice	4







UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

TITLE:

The full MIT Graphite Exponential Pile

SIZE **A** DWG. NO. OVERVIEW REV

SCALE: 1:50 SHEET 1 OF 18

ITEM NO.	PART NUMBER	Cross-Section	Sheet	QTY.
1	topLayer	3.750x2.750	15	33
2	north_moderating_block	3.750x3.500	15	148
3	fuel_stringer	3.500x3.500	10	299
4	north_foil_block	3.485x3.735	9	24
5	east_moderating_block	3.750x3.250	15	297
6	north_foil_block	3.735x3.485	8	11
7	East_325_35_block	3.500x3.250	15	3
8	E_35_375_block	3.750x3.500	15	22
10	N_325_35_block	3.500x3.250	15	21
11	N_325_375_block	3.750x3.250	15	56
12	right_source_channel	3.750x3.250	15	1
13	source_channel	3.750x3.250	14	26
14	left_source_channel	3.750x3.000	15	1
15	E_325_375_block	3.750x3.250	15	84
16	N_35_25_block	3.500x2.50	15	1
17	N_35_30_block	3.500x3.000	15	2
18	concrete_slab	---------	3	1

Notes For All Blocks:

1. Feathering on Long edge: <1/32" deep
2. Maximum chip size: 1/4" deep X1/2" long
3. Within 0.010" of flat for whole surface
4. Perpendicularity vary by <0.010" in 4"

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±0.010

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

TITLE:

The full MIT Graphite Exponential Pile

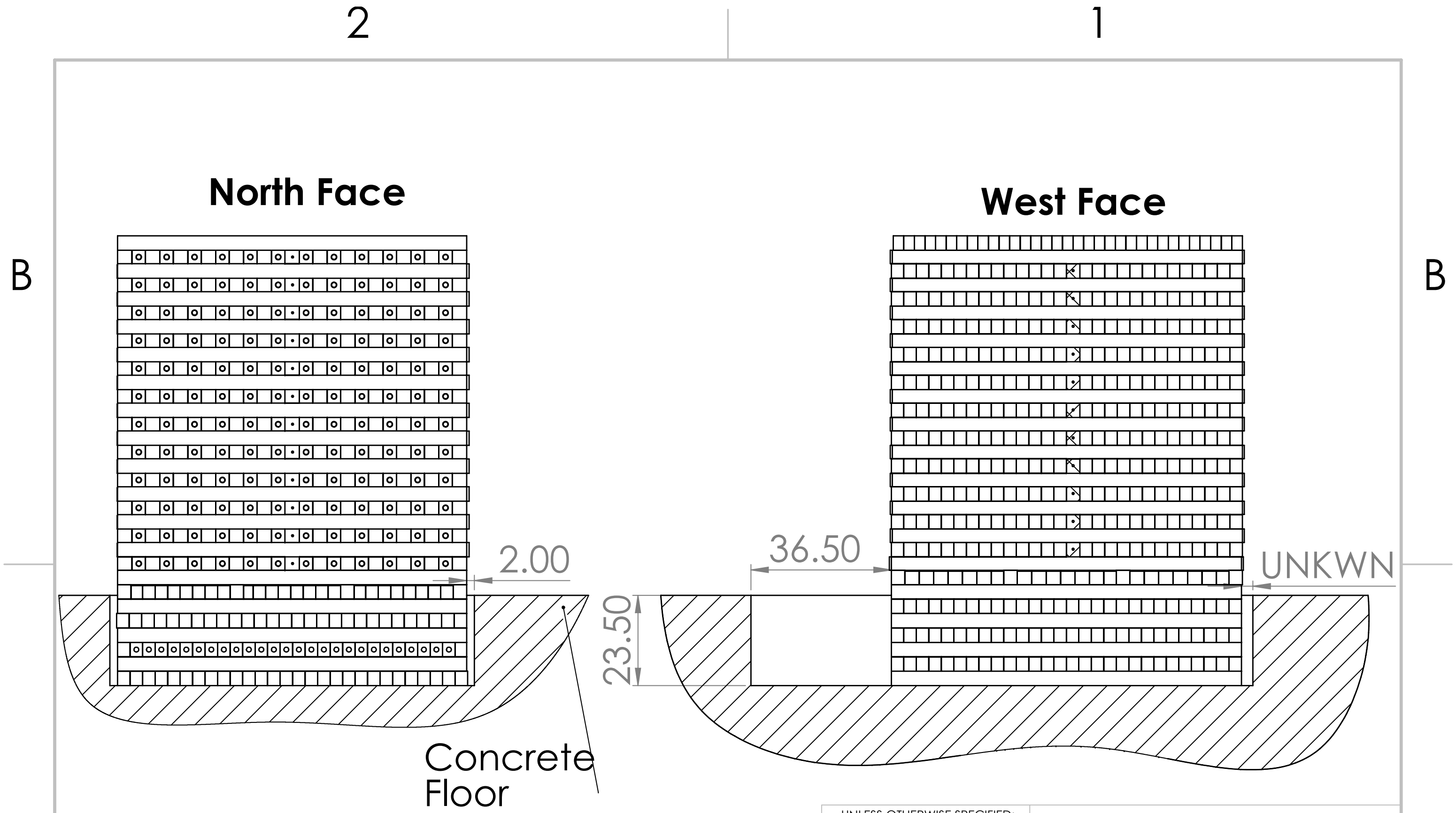
SIZE A

DWG. NO. BILL OF MATERIALS

REV

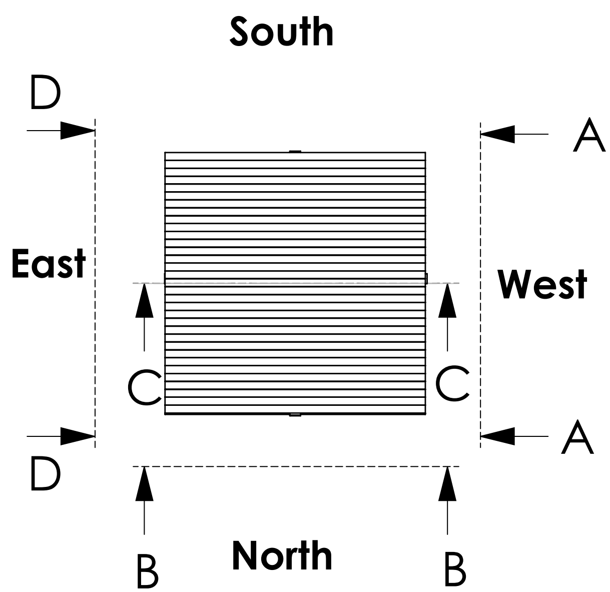
SCALE: 1:25

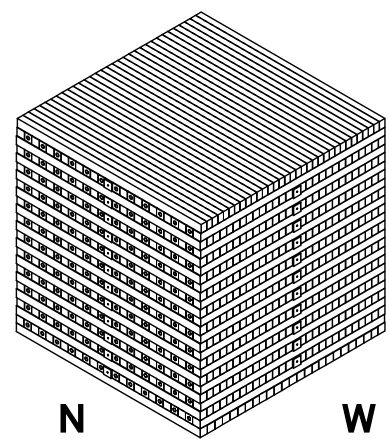
SHEET 2 OF 18



UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.25 THREE PLACE DECIMAL ±	TITLE: The full MIT Graphite Exponential Pile
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL	SIZE A DWG. NO. PILE PLACEMENT REV
FINISH	
DO NOT SCALE DRAWING	SCALE: 1:35 SHEET 3 OF 18

View	Description	Sheet
B-B	North Lattice Face	5
A-A	West Lattice Face	6
C-C	Center Plane Parellel to North	7
D-D	East Face	7





UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

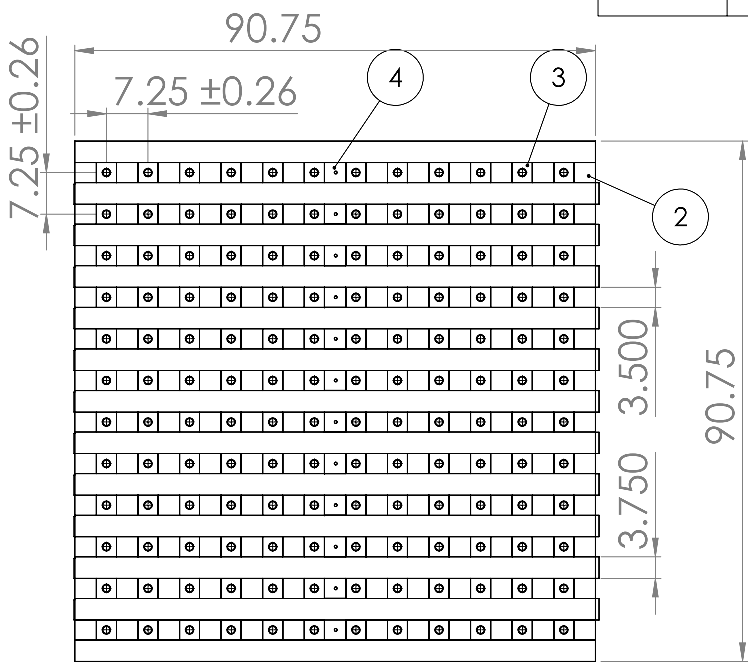
DO NOT SCALE DRAWING

TITLE:
The graphite fuel lattice

SIZE A | DWG. NO. LATTICE OVERVIEW | REV

SCALE: 1:50 | SHEET 4 OF 18

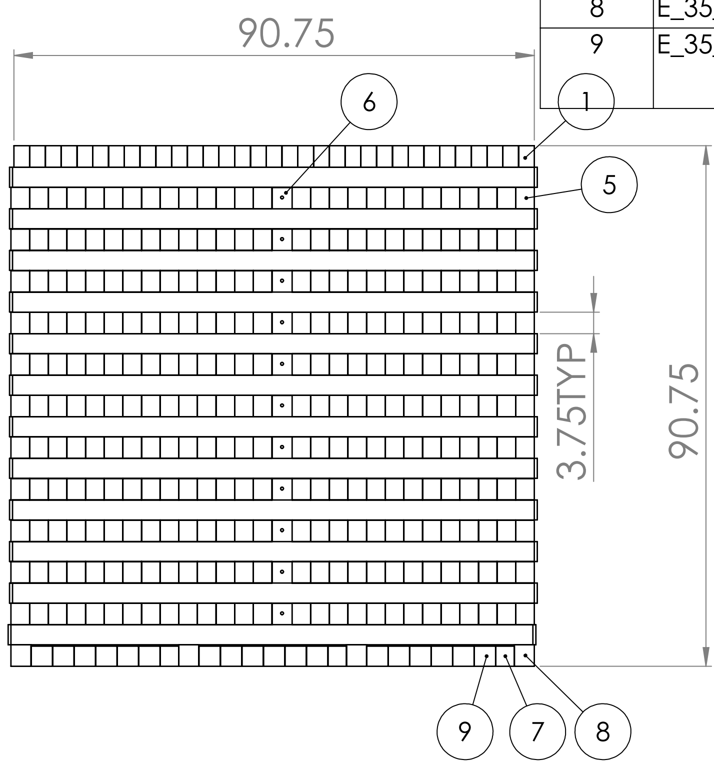
ITEM NO.	PART NUMBER	Cross-Section [1]	Sheet	QTY. [2]
2	north_moderating_block	3.500x3.750	15	12x12
3	fuel_stringer	3.500x3.500	10	12x12
4	north_foil_block	3.485x3.735	9	12x2 [3]



Notes:
1. Vertical Dimension Listed first
2. Vertical quantity listed first
3. Quantity of shuttter slots listed first

UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.24 THREE PLACE DECIMAL ±0.010	TITLE: The graphite fuel lattice
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL	SIZE A DWG. NO. NORTH LATT FACE REV
FINISH	
DO NOT SCALE DRAWING	SCALE: 1:25 SHEET 5 OF 18

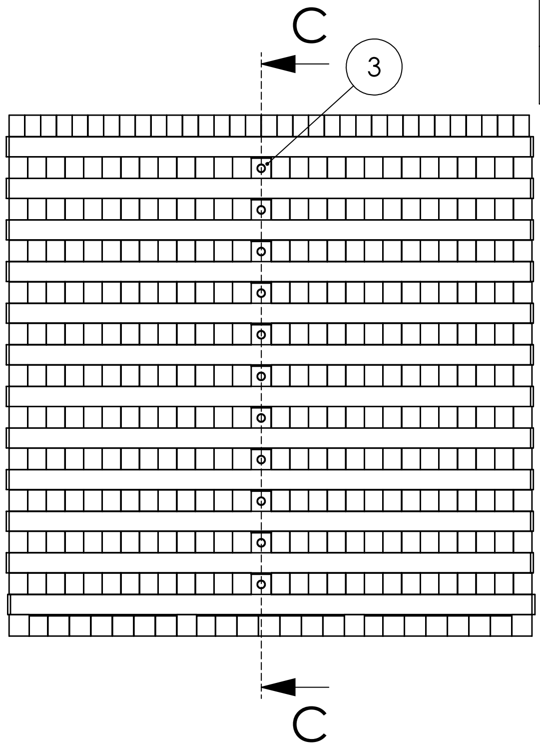
ITEM NO.	PART NUMBER	Cross-Section [1]	Sheet	QTY. [2]
1	topLayer	3.750x2.750	15	33
5	east_moderating_block	3.750x3.250	15	11x27
6	north_foil_block	3.735x3.485	8	11
7	East_325_35_block	3.500x3.250	15	1x3
8	E_35_375_block	3.750x3.500	15	4
9	E_35_375_block	3.500x3.750	15	3x6 [3]



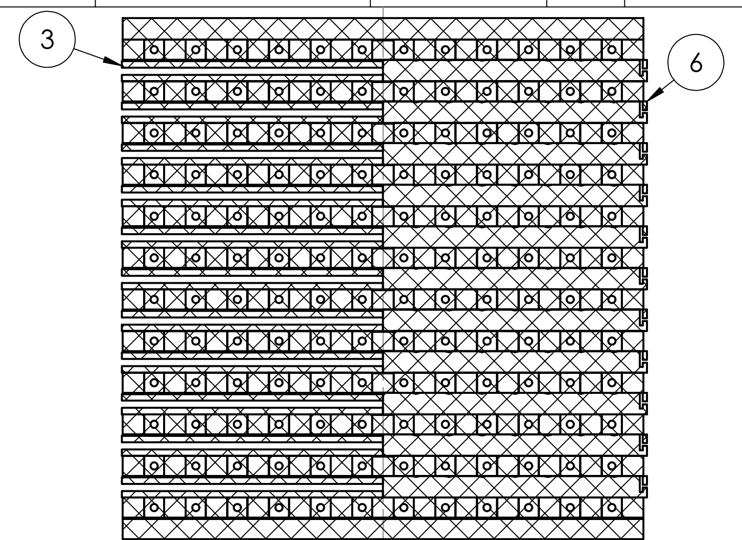
Notes:
1. Vertical Dimension Listed first
2. Vertical quantity listed first
3. Quantity of shuttter slots listed first

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ±0.010 THREE PLACE DECIMAL ±0.330	TITLE: The graphite fuel lattice		
INTERPRET GEOMETRIC TOLERANCING PER:			
MATERIAL	SIZE A	DWG. NO. WEST LATT FACE	REV
FINISH			
DO NOT SCALE DRAWING	SCALE: 1:25		SHEET 6 OF 18

ITEM NO.	PART NUMBER	Cross-Section 1	Sheet	QTY.
3	fuel_stringer	3.500x3.500	10	11
6	north_foil_block	3.735x3.485	8	11



SECTION D-D



SECTION C-C

Notes:
1. Vertical Dimensions are listed first
2. See west lattice, sheet 6 for other dimensions.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±0.010

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

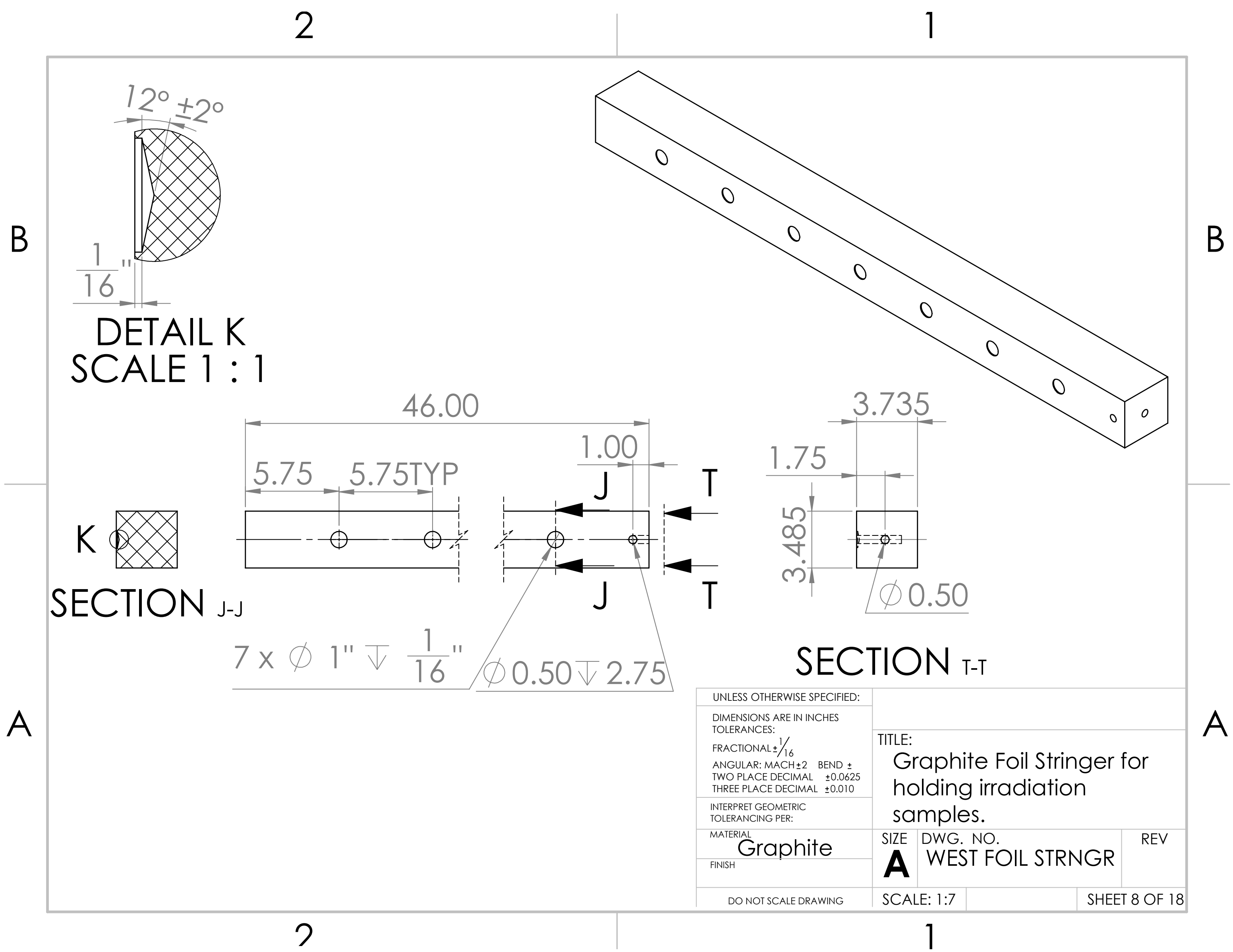
FINISH

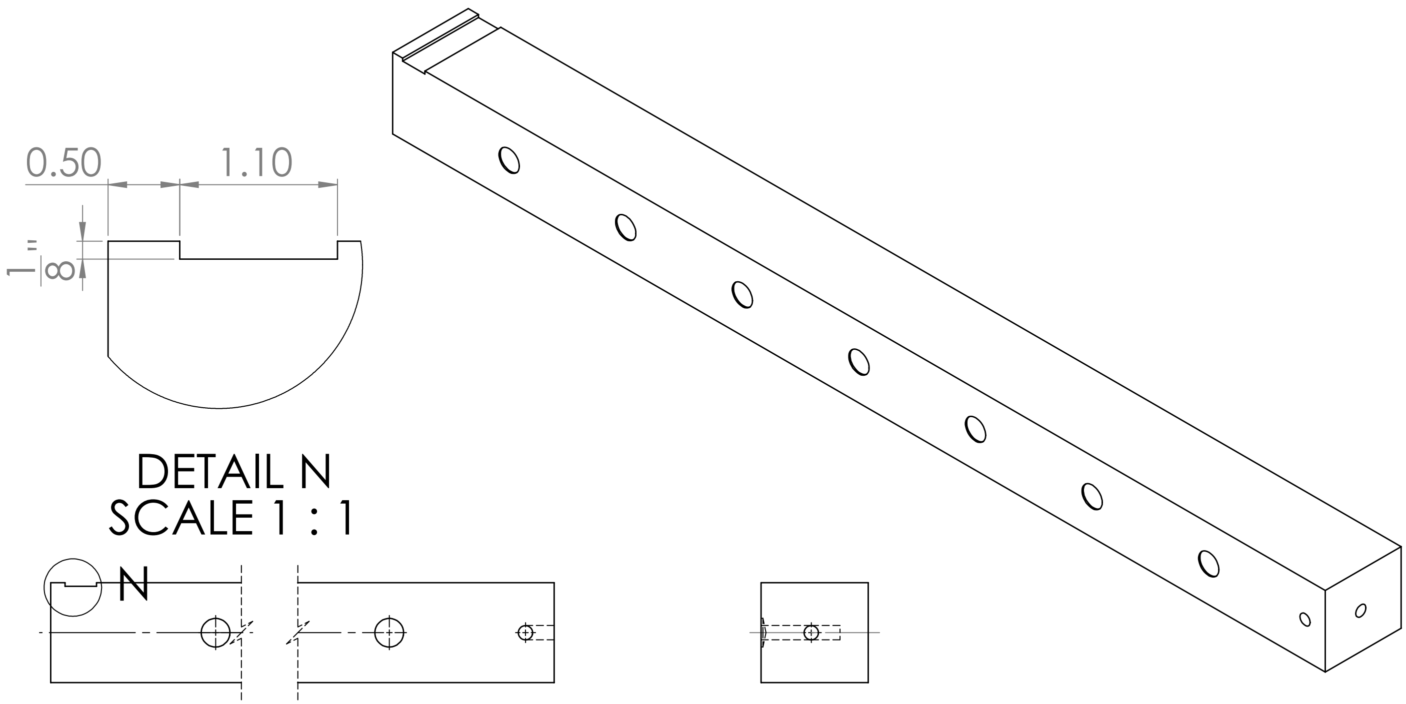
DO NOT SCALE DRAWING

TITLE:
The graphite fuel lattice

SIZE A | DWG. NO. EAST LATT FACE | REV

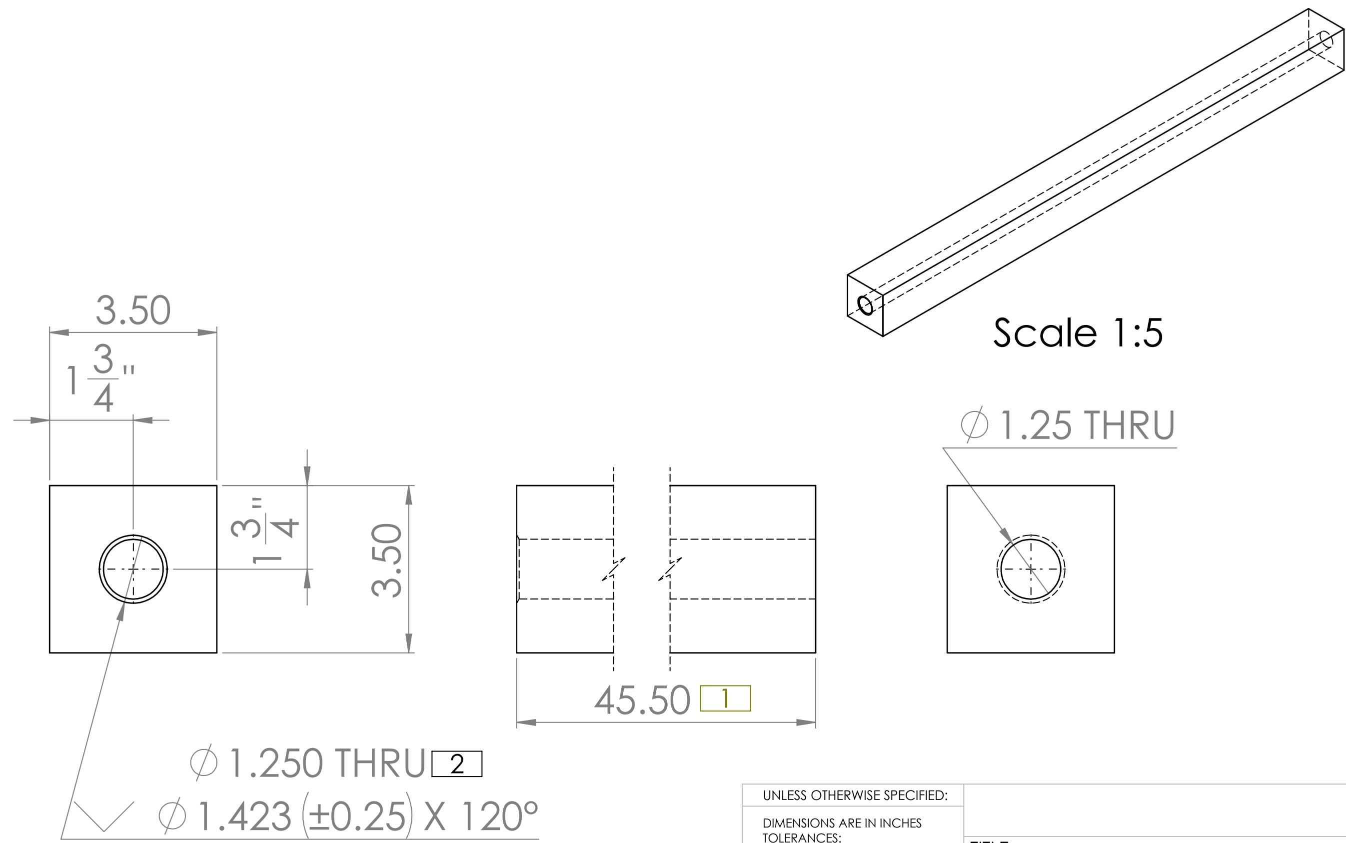
SCALE: 1:25 | SHEET 7 OF 18


12° ±2°
1/16"
DETAIL K
SCALE 1 : 1
46.00
5.75
5.75TYP
1.00
J
T
K
SECTION J-J
7 x ∅ 1" ↧ 1/16"
∅0.50 ↧ 2.75
3.735
1.75
3.485
∅0.50
SECTION T-T
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16
ANGULAR: MACH ±2 BEND ±
TWO PLACE DECIMAL ±0.0625
THREE PLACE DECIMAL ±0.010
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Graphite
FINISH
DO NOT SCALE DRAWING
TITLE:
Graphite Foil Stringer for holding irradiation samples.
SIZE
A
DWG. NO.
WEST FOIL STRNGR
REV
SCALE: 1:7
SHEET 8 OF 18
2
1
B
A



Note:
Unmarked Dimensions are identical to those in
West Foil Stringer, Sheet 8

UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/16 ANGULAR: MACH ±2 BEND ± TWO PLACE DECIMAL ±0.0625 THREE PLACE DECIMAL ±0.010	TITLE: Graphite Moderating block for holding foils for irradiation.
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL Graphite	SIZE A
FINISH	DWG. NO. NORTH FOIL STRGR
	REV
DO NOT SCALE DRAWING	SCALE: 1:5
	SHEET 9 OF 18

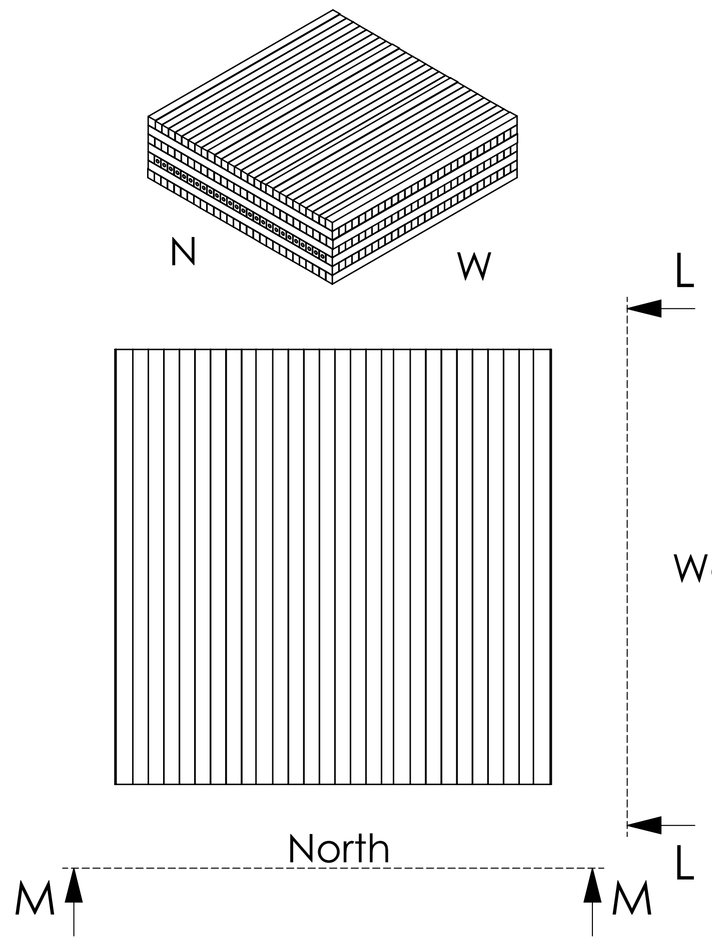


Note:

1. Block length is a Maximum length.
Blocks may be much shorter.
All Channels made of 2+ blocks
2. Hole to have no steps

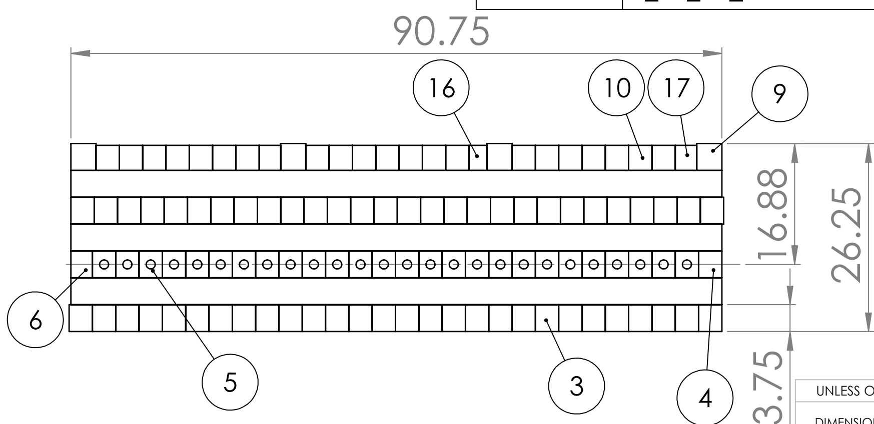
UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/8 ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.010 THREE PLACE DECIMAL ±0.0625	TITLE: Fuel stringer in the lattice. Only goes half the length
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL Graphite	SIZE A — DWG. NO. FUEL STRINGER — REV
FINISH	
DO NOT SCALE DRAWING	SCALE: 1:3 — SHEET 10 OF 18

View	Description	Sheet
L-L	West Face	13
M-M	North Face	12



UNLESS OTHERWISE SPECIFIED:		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	TITLE: The Lower pedastal which features the neutron sources	
INTERPRET GEOMETRIC TOLERANCING PER:		
MATERIAL graphite	SIZE A	DWG. NO. PEDESTAL OVRVW	REV
FINISH		
DO NOT SCALE DRAWING	SCALE: 1:30	SHEET 11 OF 18

ITEM NO.	PART NUMBER	Cross-Section [1]	Sheet	QTY.
2	north_moderating_block	3.750x3.500	15	4
10	N_325_35_block	3.500x3.250	15	3x7 [2]
11	N_325_375_block	3.750x3.250	15	2x28 [3]
12	right_source_channel	3.750x3.250	15	1
13	source_channel	3.750x3.250	14	26
14	left_source_channel	3.750x3.000	15	1
16	N_35_25_block	3.500x2.500	15	1
17	N_35_30_block	3.500x3.000	15	2



Notes:
1. Vertical Dimension is listed first
2. Number of shutter slots listed first
3. number of vertical layers listed first

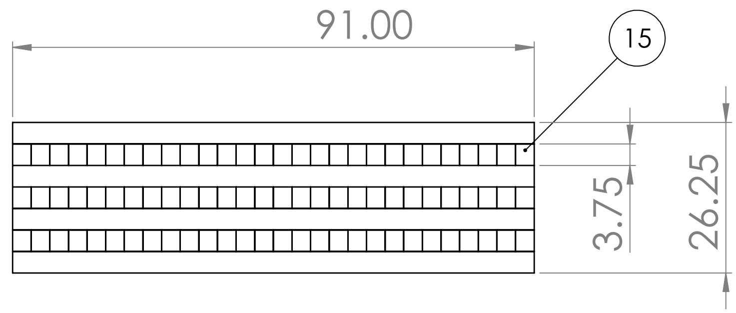
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.28
THREE PLACE DECIMAL ±0.010
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL graphite
FINISH
DO NOT SCALE DRAWING

TITLE:
The Lower pedastal which features the neutron sources

SIZE A
DWG. NO. NORTH PED FACE
REV
SCALE: 1:20
SHEET 12 OF 18

ITEM NO.	PART NUMBER	Cross-Section [1]	Sheet	QTY. [2]
15	E_325_375_block	3.750x3.250	15	3x28

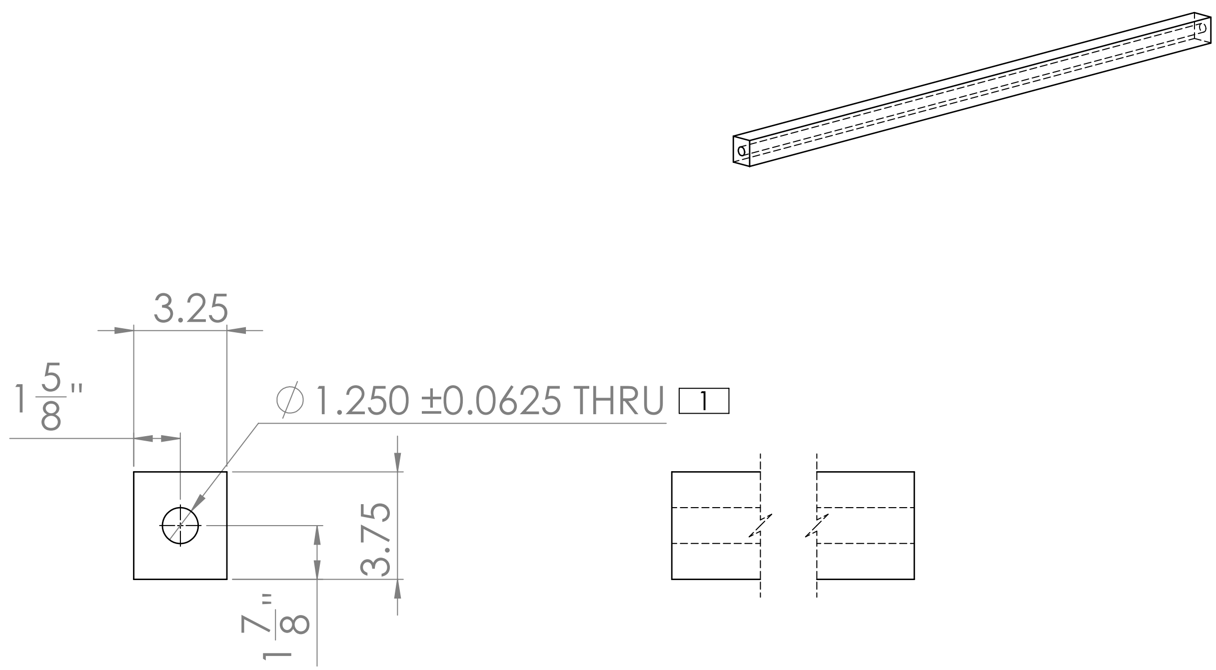
Notes:
1. Vertical Dimension is listed first
2. Number of Layers listed first



UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.28 THREE PLACE DECIMAL ±0.010	TITLE: The Lower pedastal which features the neutron sources
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL graphite	SIZE A DWG. NO. WEST PED FACE REV
FINISH	
DO NOT SCALE DRAWING	SCALE: 1:25 SHEET 13 OF 18

2 1

B B

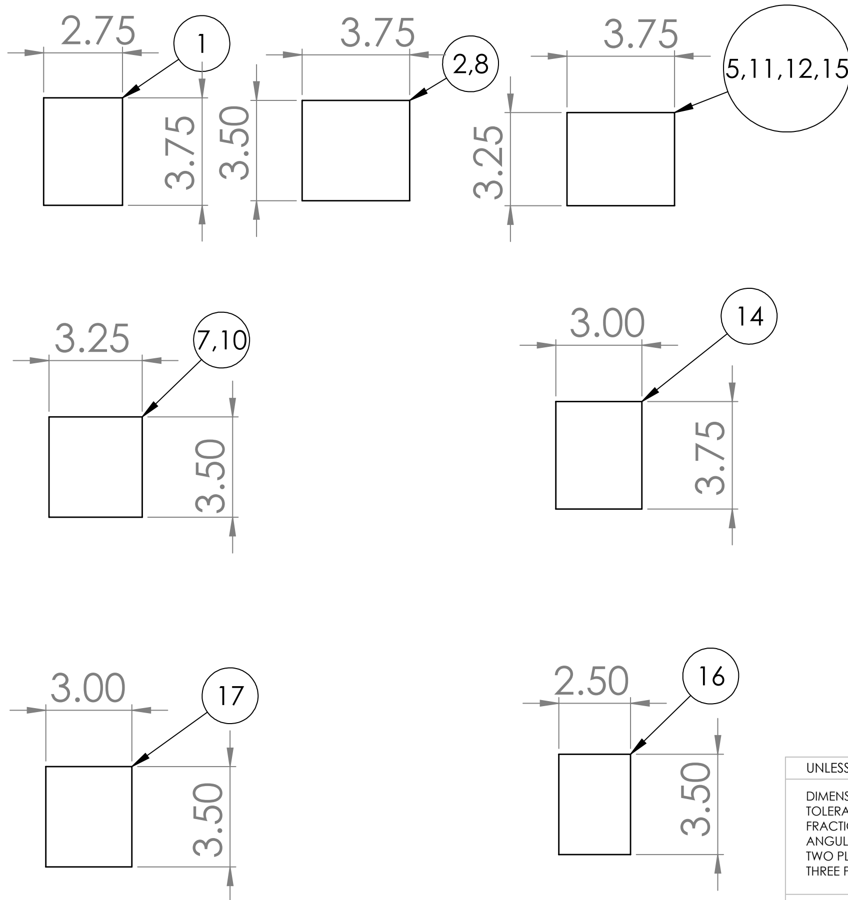


A A

Note:
1. Hole to have no steps

UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/8 ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±0.010	TITLE: Block with channel for holding neutron source
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL graphite	SIZE A · DWG. NO. SOURCE STRNGR · REV
FINISH	
DO NOT SCALE DRAWING	SCALE: 1:5 · SHEET 14 OF 18

2 1



ITEM NO.	PART NUMBER	QTY.
1	topLayer	33
2	north_moderating_block	148
5	east_moderating_block	297
7	source_channel	26
7	East_325_35_block	3
8	E_35_375_block	22
9	E_325_375_block	84
10	N_325_35_block	21
12	right_source_channel	1
12	north_foil_block	24
14	left_source_channel	1
15	N_325_375_block	
16	N_35_25_block	1
17	N_35_30_block	2

Note: Blocks are at most 44.5" long. Most are shorter. Each full side length of pile is composed of 2+ blocks of assorted lengths.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.010
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

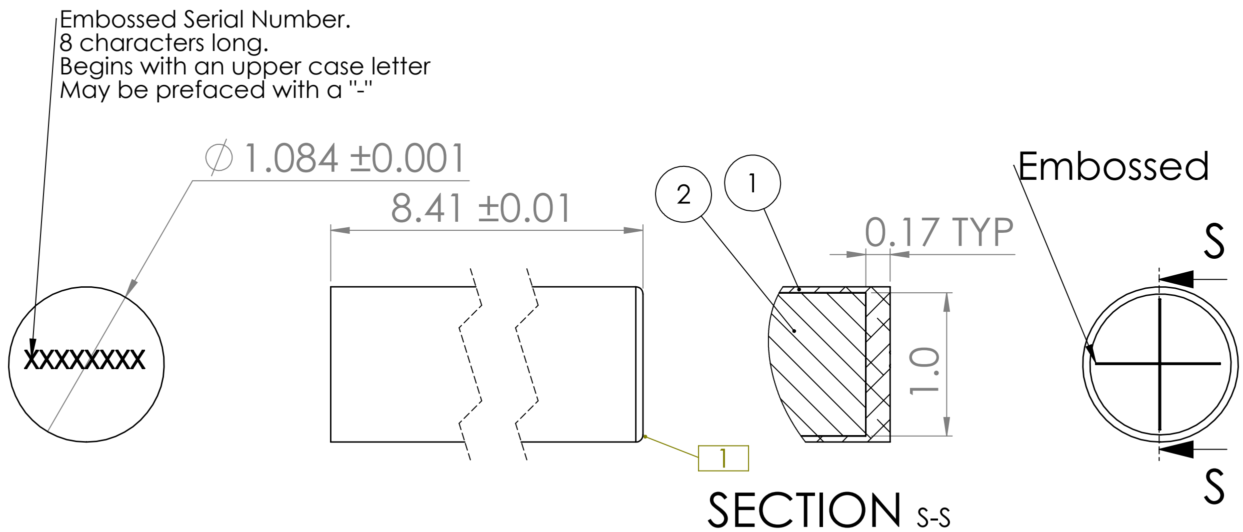
TITLE:

The full MIT Graphite Exponential Pile

SIZE A DWG. NO. MISC BLOCKS REV

SCALE: 1:5 SHEET 15 OF 18

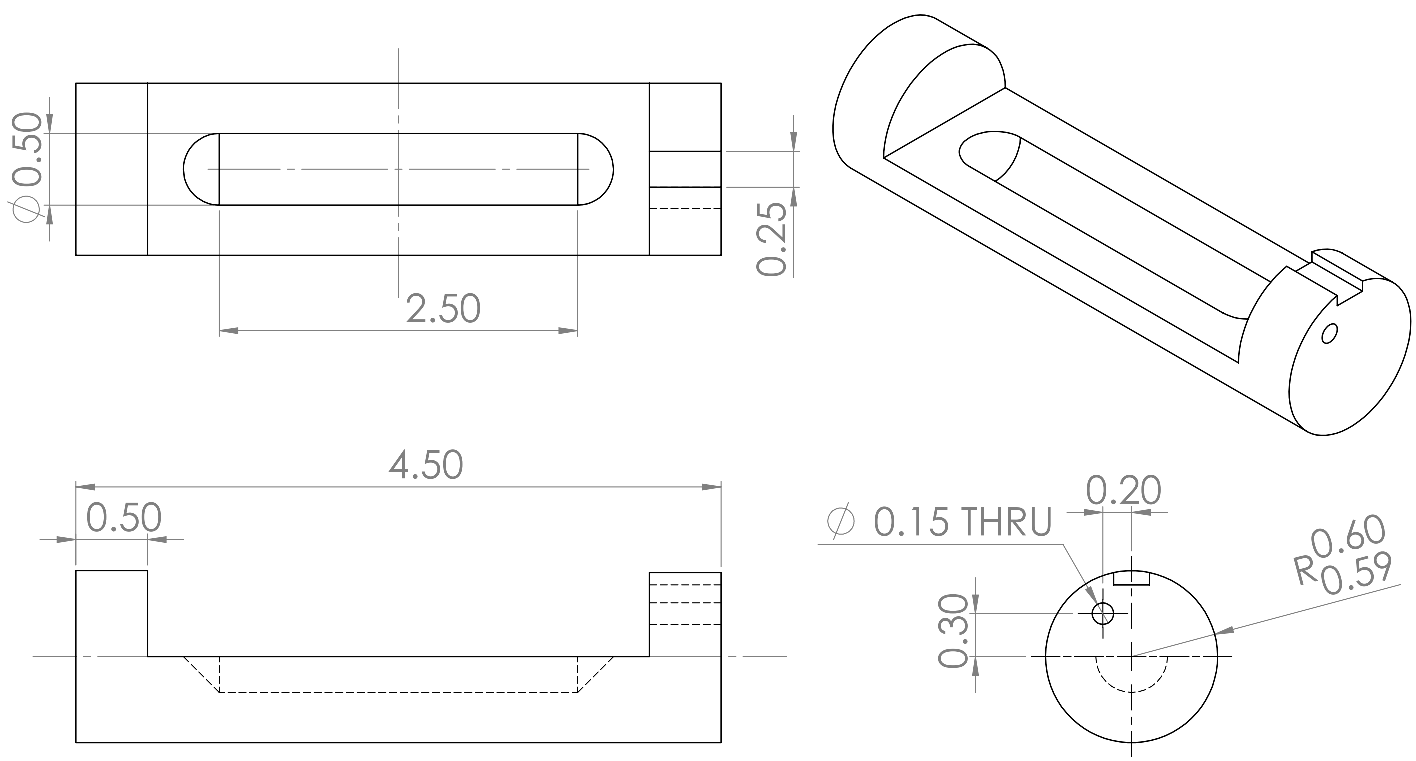
ITEM NO.	Material	Density(g/cc)	Mass(kg)	QTY.
1	Metallic Natural Uranium	18.702	1.94	1
2	Aluminum Clad	2.7	0.066	1



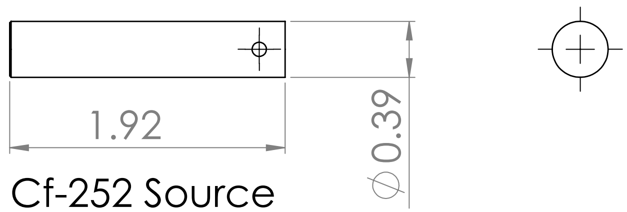
Notes:

1. Radius of Fillet unkown.
2. All internal measurements and mass based on assumptions and calculations. Read section 3.3 for further details.

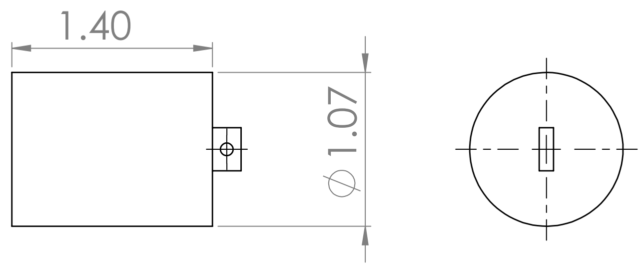
UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	TITLE: Natural Uranium Fuel Slug
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL U & Al	SIZE A · DWG. NO. FUEL SLUG · REV
FINISH	
DO NOT SCALE DRAWING	SCALE: 1:1 · SHEET 16 OF 18



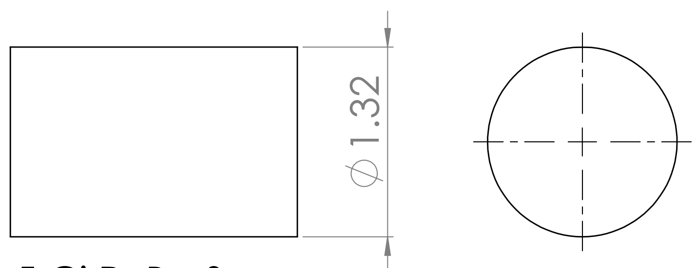
UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	TITLE: Boat for holding Cf neutron source in source channel
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL Aluminum 6061 FINISH	SIZE A / DWG. NO. NTRN SRC BOAT / REV
DO NOT SCALE DRAWING	SCALE: 1:1 / SHEET 17 OF 18



Cf-252 Source



1 Ci PuBe Source



5 Ci PuBe Source

Notes:
To minimize dose very few and innacurate measurements were taken. If a dimension is unmarked it is not known.

UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.1 THREE PLACE DECIMAL ±	TITLE:
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL	SIZE A · DWG. NO. NEUTRON SOURCES · REV
FINISH	
DO NOT SCALE DRAWING	SCALE: 1:1 · SHEET 18 OF 18

Appendix C

Graphite Purity Measurements

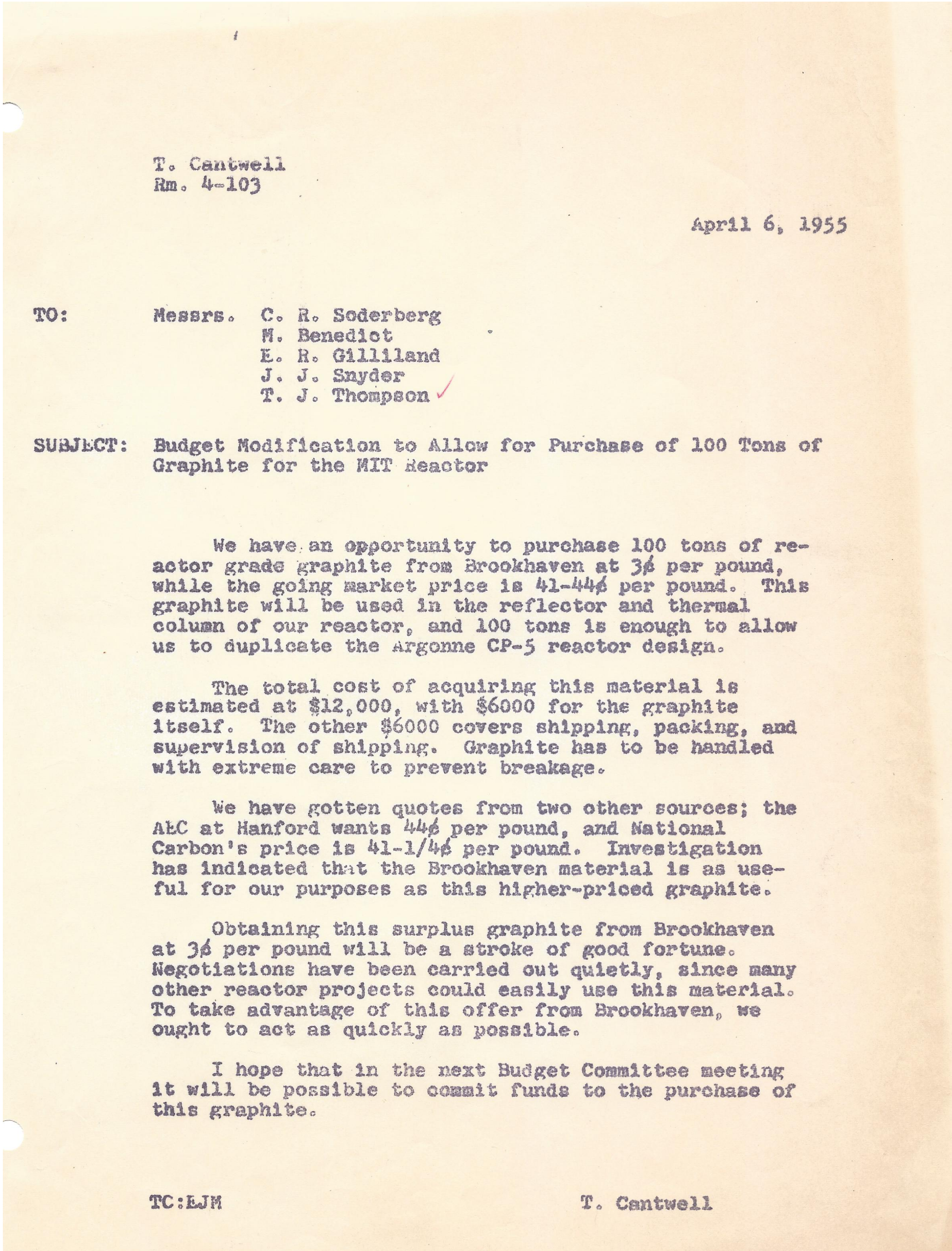
Samples of the graphite were taken and analyzed for their purity. Neutron Activation Analysis (NAA) was performed on one sample. This was completed at the MIT Nuclear Reactor Lab. These data are presented below.

Element	**NAA Impurity by mass (ppm)**	**NAA 1σ uncertainty (ppm)**
Na	0.36	0.01
Mg	<80	
Al	2.7	1.6
Cl	3.3	0.3
K	1.1	0.3
Sc	0.024	0.001
Ti	11	3
V	77	1
Cr	3.5	0.1
Mn	0.019	0.003
Fe	4.4	1.2
Co	<0.012	
Cu	<23	
Zn	<1.03	
As	0.026	0.001
Se	<0.11	
Br	0.046	0.003
Rb	<0.53	
Sr	4.9	0.8
Mo	0.022	0.004
Ag	<0.0105	
Sb	0.0060	0.0005
Cs	0.012	0.005
Ba	3.6	0.6
La	0.062	0.003
Ce	0.11	0.01
Nd	<0.23	
Sm	0.048	0.002
Eu	0.032	0.003
Tb	<0.0075	
Dy	0.008	0.001
Yb	0.014	0.001
Lu	0.001	0.000
Hf	0.013	0.003
Ta	<0.024	
W	0.004	0.001
Au	0.00017	0.00003
Hg	0.17	0.01
Th	0.030	0.004
U	<0.007	

Appendix D

Documents Pertaining to the Procurement of Graphite, and Neutron Sources

D.1 *Budget Modification to Allow for Purchase of 100 tons of Graphite for the MIT Reactor*



T. Cantwell
Rm. 4-103

April 6, 1955

TO: Messrs. C. R. Soderberg
M. Benedict
E. R. Gilliland
J. J. Snyder
T. J. Thompson ✓

SUBJECT: Budget Modification to Allow for Purchase of 100 Tons of Graphite for the MIT Reactor

We have an opportunity to purchase 100 tons of reactor grade graphite from Brookhaven at 3¢ per pound, while the going market price is 41-44¢ per pound. This graphite will be used in the reflector and thermal column of our reactor, and 100 tons is enough to allow us to duplicate the Argonne CP-5 reactor design.

The total cost of acquiring this material is estimated at $12,000, with $6000 for the graphite itself. The other $6000 covers shipping, packing, and supervision of shipping. Graphite has to be handled with extreme care to prevent breakage.

We have gotten quotes from two other sources; the AEC at Hanford wants 44¢ per pound, and National Carbon's price is 41-1/4¢ per pound. Investigation has indicated that the Brookhaven material is as useful for our purposes as this higher-priced graphite.

Obtaining this surplus graphite from Brookhaven at 3¢ per pound will be a stroke of good fortune. Negotiations have been carried out quietly, since many other reactor projects could easily use this material. To take advantage of this offer from Brookhaven, we ought to act as quickly as possible.

I hope that in the next Budget Committee meeting it will be possible to commit funds to the purchase of this graphite.

TC:EJM

T. Cantwell

D.2 *Letter authorizing the sale of 100 tons of graphite to MIT.*

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, L. I., N. Y.
TEL. PATCHOGUE 3-2600

REFER:
XP-11
CHK/amh

April 5, 1955

Mr. T. Cantwell, Project Engineer
Department of Chemical Engineering
Massachusetts Institute of Technology
Cambridge 39, Massachusetts.

Dear Tom:

We have received permission from AEC by their letter dated March 30, 1955 to sell to you approximately one hundred (100) tons of graphite which is excess to the needs of the Laboratory at a cost of .03¢ per pound "as is" and "where is" with M.I.T. assuming all handling and transportation costs.

On the basis of our 'phone conversation today, we will not process any papers until some of your personnel have had the opportunity to visit Brookhaven and select from the items which are excess to our needs, the graphite which would be acceptable to you.

Sincerely yours,

Charles H. Keenan

CHARLES H. KEENAN,
Purchasing Agent.

D.3 *Memo RR-26, Trip to Brookhaven to Inspect Graphite.*

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Memo RR-26
April 25, 1955

TO: Professor M. Benedict
Professor T. H. Pigford

FROM: T. Cantwell & T. J. Thompson

SUBJ: Trip to Brookhaven to Inspect Graphite, April 19, 1955

Thompson and Cantwell inspected the available graphite and marked about 100 tons for MIT. This represents all the available material that is worth using. The material is mostly of unknown quality, but at worst it is AGHT.

The amounts and location of our graphite pallets in the storage shed are as follows:

Place	Type	Amount
Bay G	4 x 12 x 24 chunks	6 pallets
Bay D	4 x 3 x 30 or better	20 pallets
Bay D	4 x 3 x 24 or shorter	7 pallets
Bay E	4 x 3 x 30 or better	10 pallets
Bay E	4 x 3 x 24 or shorter	2 pallets

This is a total of 45 pallets with about 2-1/2 tons per pallet, giving roughly 110 tons of nuclear grade graphite for the MIT reactor. If any pallets have to be cut from this amount, they should be pallets numbered 21 through 26 in Bay D. We can purchase this graphite at 3¢ per lb. plus shipping costs.

Brookhaven is willing to load our material for us at cost, and based on past experience, this will amount to $20 per ton, or $2200 handling.

Brookhaven can keep the material until June, but they would like to clear it from their books before then. Therefore, we should send them a purchase order for the cost of the material plus the packing and handling. I propose to do this as soon as the Budget Committee gives me the go ahead.

Charles H. Keenan at Brookhaven told us about the AEC surplus property lists and suggested we get them. Yale has purchased equipment from this list, and Keenan thought we could also. For example, Savannah River has surplus stainless steel pipe, and also helium leak detectors. Keenan gave us several sample lists and promised to send us lists of interest to us. Prices are 50% of original on new equipment and 35% of original on good used equipment.

D.4 *Quotation NE-2195-Revised*

NC 1360C (NE) PRINTED IN U. S. A.

NATIONAL CARBON COMPANY

A DIVISION OF UNION CARBIDE AND CARBON CORPORATION

UCC

292 MADISON AVENUE

NEW YORK 17, N. Y. December 20, 1955.

Massachusetts Institute of Technology,
Cambridge, Mass.

Attn: Prof. T. J. Thompson

QUOTATION

Number NE5-2195-Revised

Gentlemen:

In reply to your inquiry Dec. 15, 1955. , we are pleased to quote you subject to the conditions on the reverse side hereof as follows:

QUANTITY		DESCRIPTION	*PRICE
A	100 -	3-1/2" x 3-1/2" x 48" stringers with 1-1/2" dia. thru hole along length. Hole to have no step and to be centered plus/minus 1/8".	$780.00 lot,net
B	1000 or over	3-1/2" x 3-1/2" x miscellaneous lg. (24" to 48") stringers	3.10 each
		Special Notes: See attached sheet which is a part of this quotation.	
		Above Prices F. O. B. Shipping Point Cleveland, Ohio.	

Estimated Shipping Date 800 pcs. in 4 to 6 wks. after receipt of stock on factory. Bal. at 800 pcs. per wk. subject to confirmation upon receipt of order. If earlier delivery is required, please advise this office.

Terms 30 days net - no cash discount

Limits ~~Item A - wd. & thk. plus/minus.010~~ plus 1/8" minus 0.
~~Item B - wd. & thk. plus/minus .010"~~

*Prices are subject to change to Seller's standard prices in effect at the time of delivery.

We thank you for your inquiry and shall be pleased to receive your order.

Very truly yours,

NATIONAL CARBON COMPANY
A DIVISION OF UNION CARBIDE AND CARBON CORPORATION

By L. S. Fox.

Massachusetts Institute of Technology,
Cambridge, Mass.

NE-5-2195- Revised

1. If Item A is ordered with Item B the price will then be $523.00 lot, net for Item A.

2. Prices are based on customer supplying sound AGHT stock. 110 pieces of 49" length or over to be segregated by M.I.T. for manufacture of Item A. The balance of stock will be of miscellaneous lengths from 24" to 48" long.

3. Item A tolerance on I.D. to be plus/minus 1/16". For tolerance of plus/minus 1/32" add $0.69 per piece to price.

4. Machining of Item "A" based on 10% machining scrap. M.I.T. to ship 110 pieces to received 100 finished pieces. Machining of Item "B" based on 5% machining scrap. M.I.T. to ship 105 pieces to receive 100 finished pieces. All pieces which meet specifications will be shipped to M.I.T.

5. Ends of all items to be band sawed. If milled ends are desired add $0.24 per piece to price. If pieces for Item A are not 49" long it will be necessary to mill to end in order to obtain 48" pieces. In this case add $0.24 per piece milled.

6. All length edges not to exceed 1/32" deep feathering.

7. Prices are based on receiving stock on pallets in a box car. Prices include a $0.28 per piece packing charge for suitable packaging of return shipment.

8. This quotation is to give M.I.T. a maximum price of machining for the stock which is now at Brookhaven National Laboratory, Upton, N. Y. and is therefore subject to confirmation.

D.5 *Estimate of Cost of Graphite Machining*

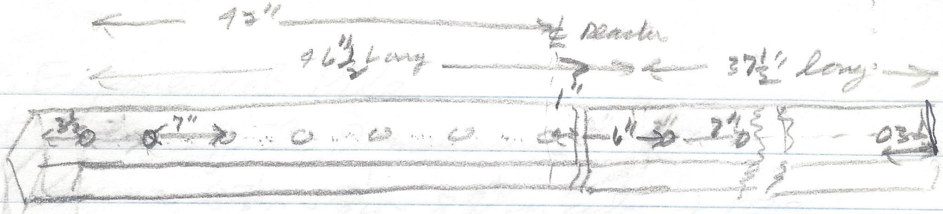
File
MITR
graphite

Estimate of Cost of Graphite Machining

April 23, 1956

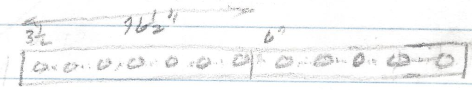
Machining 340 blocks with holes at $5.23 block	$ 1,778.20
Machining 3500 pieces at $3.10 per piece	10,850.00
Shipping costs at $1.10/100 pounds (134,400 pounds at $1.18 cwt to Cleveland)	1,585.92
Shipping costs - Cleveland to Cambridge (96,000 pounds at $1.09/cwt)	1.046.40
TOTAL	$15,260.52

T. J. Thompson



These Pieces to hold samples

12 gaps = 13 holes.



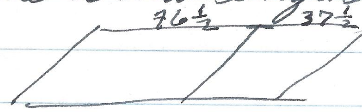
93"
3½
1
———
96½"

96½
18¾
———
65¼

For Exponential Pile.

1) set basic pile Dimensions
(assume 87½ x 87½ x 87½ in cube + Pedestal
better to have odd number of blocks > (25 blocks - if blocks bigger assume 24 x Blockage)
Pedestal is 7 blocks deep.

2) Divide it into lengths such as

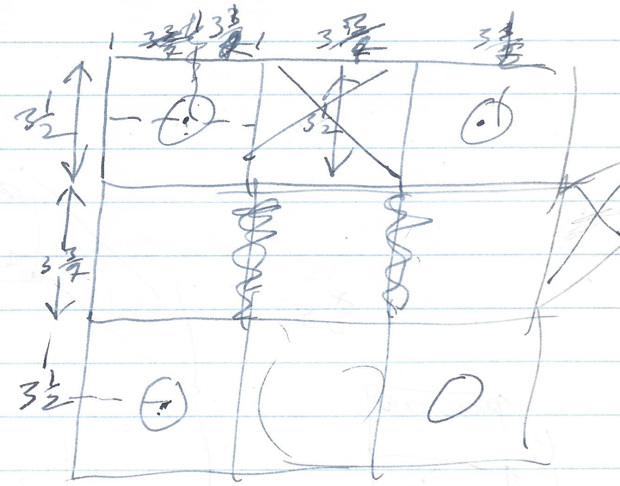


3) Cut all stringers to these dimensions and drill out 170 stringers 76½" long and 120 stringers 37½" long.

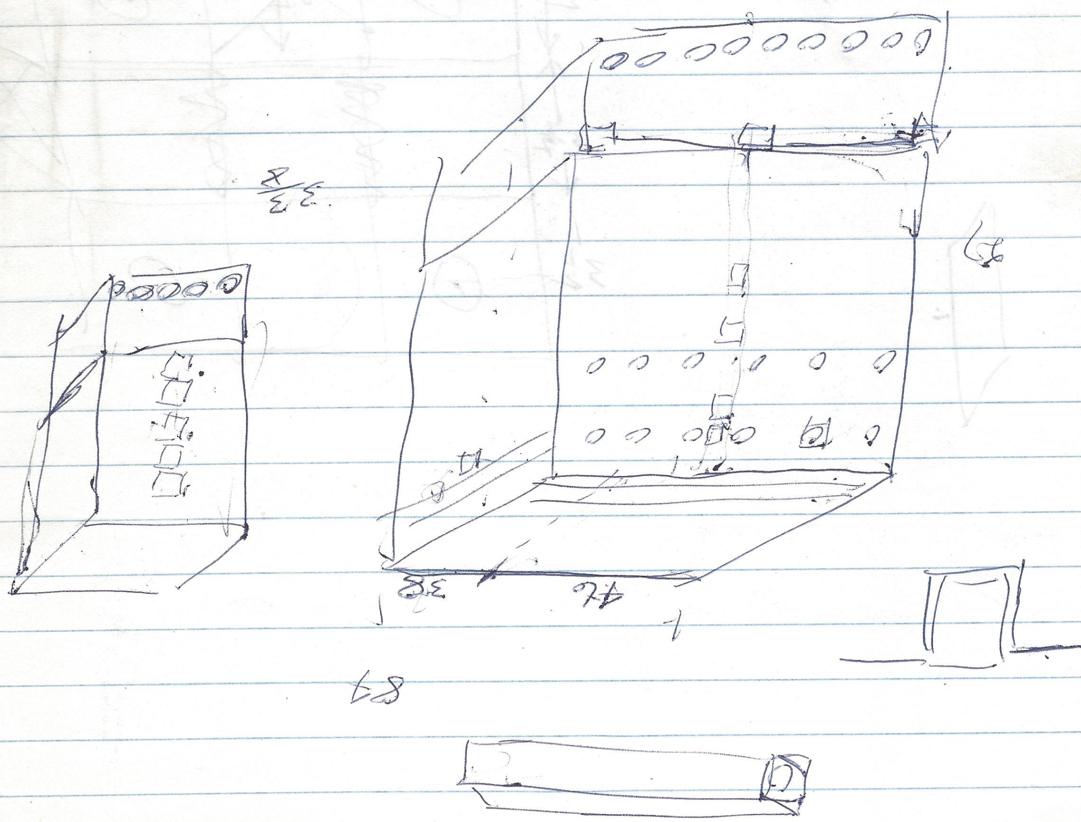
4) make 110 blocks slightly smaller so as to slide easily in others & drill out as shown

5) need one layer of full length blocks to support pedestal.

1) cost of shipping & Transport
2) weight of graphite shipped
3) Discuss job costs
4) Maximum size of blocks that can be done
5)



(1) Have removed shielding from control room door on permanent concrete & will replace with shielding blocks or separate pour.



D.6 *Letter to George A. Anderson on updated plans for graphite machinig*

File

- 2 -

George A. Anderson S. V. Nicastro

MIT File May 1, 56 jk

GRAPHITE MACHINING (MIT REACTOR)

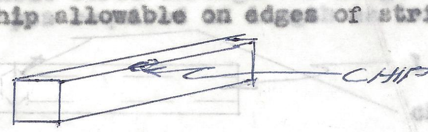
I) Machining of graphite stringers will be started 5-2-56 at National Carbon, West 117th St. & Madison Ave., Cleveland, Ohio.

a) All pcs that will clean up to 3 1/2" on the narrow dimension will be machined. The other two sides will be machined when National Carbon obtains additional information from ACF and Dr. Thompson. This information is:

1) Number of pcs to be machined to a 3 1/2" x 3 1/2" cross section (all the long pcs should be used for Thermal Column and Exponential Piles).

2) The remainder will be machined to the largest possible cross section (3 3/4" x 3 1/2") and (3 1/2" X possible 3" or 3 1/2").

II) Maximum chip allowable on edges of stringer 1/4" deep x 1/2" LG.



(Do not use a grinding wheel. Use a steel cutting tool for machining graphite.)

III) Finish of graphite stringer surface ok, as shown 4-30-56 to ACF representative and Dr. Thompson when they visited the National Carbon Company.

IV) Square off both ends? (Last operation)

V) Flatness: The stringers will be flat within 10 mils (comparing the upper face of the stringer lying on an optical flat, with the optical flat, by means of a gauge).

VI) The sides of the stringers will be perpendicular and not vary from the perpendicular by more than 10 mils in 4 inches.

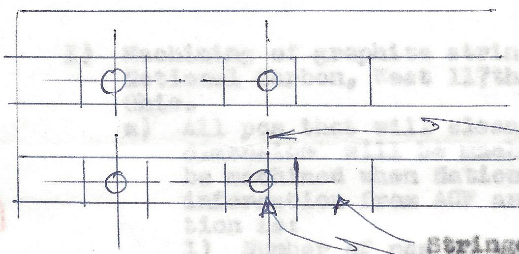
VII) Length of stringer - if ACF decides to have them cut to a set length. Representative from ACF will notify National Carbon. (See IV)

COPY

File MITR

VIII) Possible delivery 4-5 months. (A carload at a time will be shipped to MIT.)

IX) Exponential Piles:

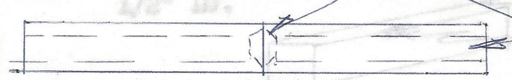


Lattice must be sq. (7 1/4" sq.)

Stringer 3 3/4" x 3 1/2" cross section
(Stringer with holes 3 1/2" x 3 1/2" cross section, 1 1/4" dia. holes)

Dia. of cylinder to be placed in these holes is 1 1/16"

a) Use longest stringer for pcs 3 1/2" x 3 1/2" with 1 1/4" dia. hole bored through the length. (340 pcs required) (more pcs required if length is less than 48")



1 1/4" dia. hole

chamber butt ends

b) Holes to have no step and to be centered plus or minus 1/8".

c) Removable stringer. (Dr. Thompson)

X) Packing must be road dust proof.

XI) Obtain Bill of Lading.

XII) National Carbon would like to quote on stacking reactor graphite and cutting all necessary holes.

S. V. Nicastro

D.7 *Quotation NE6-1286 for Graphite Foil Stringer*

NC 1360C (NE) PRINTED IN U. S. A.

File National carbon

NATIONAL CARBON COMPANY

A DIVISION OF UNION CARBIDE AND CARBON CORPORATION

UCC

292 MADISON AVENUE
NEW YORK 17, N. Y.

H N Townsend
18689 Hillard
Edison 1-3299

Massachusetts Institute of Technology
Cambridge,
Massachusetts

May 31, 1956

Attention - Prof. T.J. Thompson

QUOTATION

Number NE6-1286

Gentlemen:

In reply to your inquiry May 7, 1956, we are pleased to quote you subject to the conditions on the reverse side hereof as follows:

	QUANTITY	DESCRIPTION	*PRICE
A	100	Machining of holes per the attached sketch in 3.735 x 3.485 x 46.5 graphite stringers furnished by M.I.T. from National Carbon Co. order No. 66-A-2485.	$2.50 each
		Above Prices F. O. B. Shipping Point Cleveland, Ohio	

Estimated Shipping Date 7-1-56 subject to confirmation upon receipt of order. If earlier delivery is required, please advise this office.

Terms 30 days net - no cash discount

Limits per attached sketch

*Prices are subject to change to Seller's standard prices in effect at the time of delivery.

We thank you for your inquiry and shall be pleased to receive your order.

Very truly yours,

NATIONAL CARBON COMPANY
A DIVISION OF UNION CARBIDE AND CARBON CORPORATION

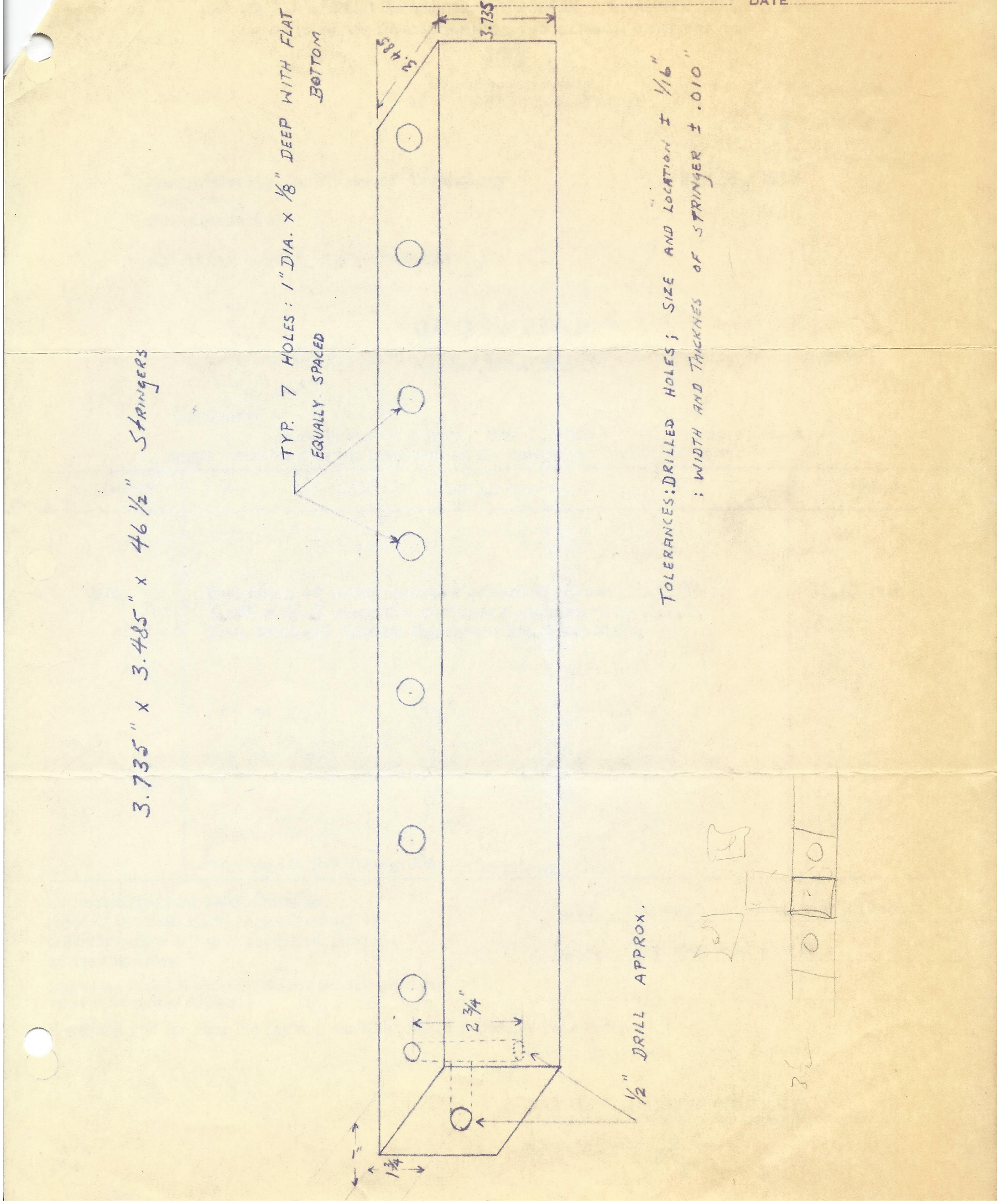
By T. J. Foulk

T.J. Foulk
jsm

NATIONAL CARBON CO. SUBJECT Graphite Stringer for M.I.T. Exponential Pile. SKETCH NO.

BY SHEET NO. OF

DATE



D.8 *Letter to Mr. H. N. Townsend.*

COPY

June 28, 1956

Mr. H. N. Townsend
National Carbon Company
West 117th Street and Madison Avenue
Cleveland, Ohio

Dear Mr. Townsend:

I am writing to confirm our somewhat sketchy arrangements made by telephone this afternoon concerning disposal of the graphite.

According to your statement, the entire stock of 3 1/2" x 3 1/2" cross section stringers will amount to approximately 225 pieces with lengths of 46 1/2" or greater. In addition, there are about 225 pieces whose cross section is 3 3/4" x 3 1/4" with lengths greater than 46 1/2". Also, there are approximately sixty pieces whose length is 46 1/2" or greater which have already been machined whose cross section is 3 3/4" x 3 1/2". From your statement it would appear that there do not exist any other stringers with these lengths and cross sections.

700 For the special pieces required by ACF and MIT a total of 940 long stringers are needed. These are split into 440 300 pieces with a cross section 3 1/2" x 3 1/2" required by ACF for use in the thermal column; 400 pieces with a 1 1/4" hole through the length of the pieces and 3 1/2" x 3 1/2" in cross section required by MIT for the exponential pile; ~~100~~ pieces specially prepared for samples required by MIT. It is clear that these requirements cannot be met by the long stringers presently available.

In view of the situation, it is suggested that the following procedure by adopted:

(1) The sixty pieces which have already been machined ($3\frac{1}{2} \times 3\frac{3}{4} \times 46\frac{1}{2}$) should be prepared as sample containing pieces for the exponential as per the sketch supplied earlier by National Carbon. with their [illegible] of May 31

You also stated today on the telephone that it still appears that approximately eighty percent of the stringers were cleaned up to a cross section

COPY

of 3 1/2" x 3 3/4". Apparently, ~~none~~ Most of these pieces have lengths between 40" and 42". Please do not machine any further stringers in this form. The necessary requirements for stringers with the 1 1/4" hole through the center will have to be met from shorter stock. Required for this purpose will be 169 pieces each 92" long. (This accounts for the 340 figure given previously for 46" long stock.) The cross section of these pieces should be 3 1/2" x 3 1/2".

(2) Thirty pieces are required each of which must be 92" long. The cross section of these pieces may be 3 3/4" x 3 1/4".

(3) In the case of all stringers containing the 1 1/4" hole, the stringers will be faced off at one end only (the end from which the hole is drilled in order to insure centering as near as possible) and a taper sunk at this point so as to insure that one inch diameter eight inch long fuel slugs will slide easily from one section to the next. These pieces will be cut to length at MIT and a taper put on the other end of the hole as required. The pieces should be made from as long a stock as possible, but not including any stock which can be used by ACF for their special 3 1/2" x 3 1/4" thermal column stock.

(4) The 225 3 1/2" x 3 1/2" x 46" pieces now available will be turned over to ACF for thermal column use. All of the remaining longest stock will be turned over to ACF to help with the construction of the thermal column. A real effort should be made to find sufficient stock which can be trimmed to 3 1/2" x 3 1/2" so that the entire thermal column requirements of ACF can be met.

(Aside to ACF: In no case should stock other than 3 1/2" x 3 1/2" in cross section be used in the thermal column above the bottom edge of the lowest port. Briefly, the entire thermal column should still be made from 3 1/2" x 3 1/2" stock.)

It is our hope that the cost on the graphite machining can be maintained at the lowest possible price. We realize the difficulties you have encountered on this job and very much appreciate your help and assistance in regard to its completion. Please feel free to call or write at any time. In order to insure accord on this problem, I am sending a copy of this letter to Mr. Nicastro and to George Anderson at ACF Industries.

Thank you very much.

Sincerely yours,

T. J. Thompson
Director, MIT Reactor Project

TJT:sm
cc: Mr. Anderson
Mr. Nicastro

D.9 *MIT Graphite Machining, Trip to National Carbon Co., Cleveland, Ohio, July 10,1956*

File MITR Graphite

NUCLEAR ENERGY PRODUCTS DIVISION

acf INDUSTRIES INCORPORATED

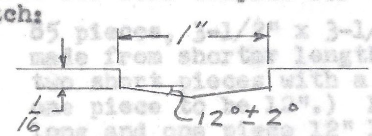
508 Kennedy Street, N. W.
Washington 11, D. C.

July 11, 1956

MEMORANDUM

Re: MIT Graphite Machining
(Trip to National Carbon Co.,
Cleveland, Ohio, July 10, 1956)

(1) All available pieces up to 100 pieces that measure 3-3/4" x 3-1/2" over 46" long which have already been machined will be specially prepared for foil samples for the exponential pile as per following sketch:



One end only on these blocks will be trimmed.

(2) The necessary requirements for stringers with the 1-1/4" hole through the center will have to be met from shorter stock. Required for this purpose will be 169 pieces each 92" long. (This accounts for the 340 figure given previously for 46" long stock.) The cross section of these pieces should be 3-1/2" x 3-1/2".

In the case of all stringers containing the 1-1/4" hole, the stringers will be faced off at one end only (the end from which the hole is drilled in order to insure centering as near as possible) and a taper sunk at this point so as to insure that one inch diameter eight inch long fuel slugs will slide easily from one section to the next. These pieces will be cut to length at MIT and a taper put on the other end of the hole as required. The pieces should be made from as long a stock as possible, but not including any stock which can be used by ACF for their special 3-1/2" x 3-1/2" thermal column stock.

(3) Thirty pieces containing the 1-1/4" diameter hole are required each of which must be 92" long or longer. The cross section of these pieces may be 3-3/4" x 3-1/4". The 225 pieces 46" long or longer can be used to supply this stock. They will be finished at one end and tapered as in (2).

(4) The 225 3-1/2" x 3-1/2" x 46" pieces now available will be turned over to ACF for thermal column use. All of the remaining longest stock will be turned over to ACF to help with the

construction of the thermal column. A real effort should be made to find sufficient stock which can be trimmed to 3-1/2" x 3-1/2" so that the entire thermal column requirements of ACF can be met.

(Aside to ACF: In no case should stock other than 3-1/2" x 3-1/2" in cross section be used in the thermal column above the bottom edge of the lowest port. Briefly, the entire thermal column should still be made from 3-1/2" x 3-1/2" stock.)

(5) The remainder of the stock will be cleaned up to 3-1/2" x 3-3/4" or 3-3/4" x 3-1/4" or 3-3/4" x 3" or 3-3/4" x 2-1/2" using the largest possible cross section, and the ends will be left untrimmed.

(6) The following additional graphite stringers will be machined as follows:

(a) 85 pieces, 3-1/2" x 3-1/2" x 46" long will be made from shorter length pieces. (Made from two short pieces with a minimum length of any one piece to be 12".) Example: one pc. 34" long and one piece 12" long.

(b) 61 pieces, 3-1/2" x 3-1/2" x 24-1/2" long.

(c) 22 pieces, 3-1/2" x 3-1/2" x 21" long.

(d) 22 pieces, 3-1/2" x 3-1/2" x 14" long.

(e) 81 pieces, 3-1/2" x 3-1/2" x 11" long.

*Note: Item (6), ([illegible]), (b), (c), (d), and (e) will be made from the nearest size stringer to give the desired length stated or any two sizes will be made by a combination of lengths to minimize graphite waste.

(7) Machining waste for National Carbon Company standard 4-3/16" sq. stringer is approximately 3%.

(8) Machining waste for the MIT (Brookhaven) graphite is approximately 18-20%.

S. V. Nicastro

S. V. Nicastro

cc: Dr. T.J. Thompson
G.A. Anderson
E. Barnett

D.10 *Work Order 6711-5: Shipping Data: Plutonium Neutron Source*

O-582
REV 1-29-59

SHIPPING DATA
PLUTONIUM NEUTRON SOURCE
MONSANTO CHEMICAL COMPANY

Work Order 6711-5
MOUND LABORATORY
MIAMISBURG, OHIO

TO: Professor T. J. Thompson
Department of Nuclear Engineering
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

DATE OF SHIPMENT & CALIBRATION: August 4, 1961
VIA: Railway Express
YOUR P.O. No.: GA-6456
LICENSE No.: SNM-81
SS ALLOTMENT QUOTA No.: 7000
WITHDRAWN FROM: SBX-3101

NEUTRON SOURCE No. M-52

1. TYPE OF SOURCE - PuBe
2. GRAMS OF BE - 7.92
3. GRAMS OF PU - 16.03
4. CONTAINER MATERIAL - Tantalum and stainless steel
5. DIMENSIONS OF CONTAINER - INSIDE -
   OUTSIDE - 1.07" O. D. x 1.40"
6. METHOD OF SEALING - WELDED
7. NEUTRON EMISSION - 1.63×10^6 N/SEC
8. TOLERANCE DISTANCE IN AIR FOR 8 HOURS - 21 INCHES
   (BASED ON [illegible] N/SEC/CM^2)
   55

SHIPPING CONTAINER IS A PARAFFIN-FILLED 15 GALLON DRUM

SOURCE(S) IS IN A SLOT AT THE BOTTOM OF A PARAFFIN-FILLED TUBE WHICH MAY BE LIFTED AFTER REMOVING THE SEALED CLOSURE OF THE DRUM.

PRICE OF SOURCE .... Recanned
PLUS COST OF SHIPPING CONTAINER .... No Charge
TOTAL ....

REMARKS: EDUCATIONAL
THE TITLE TO THE PLUTONIUM USED IN THIS SOURCE REMAINS WITH THE ATOMIC ENERGY COMMISSION.

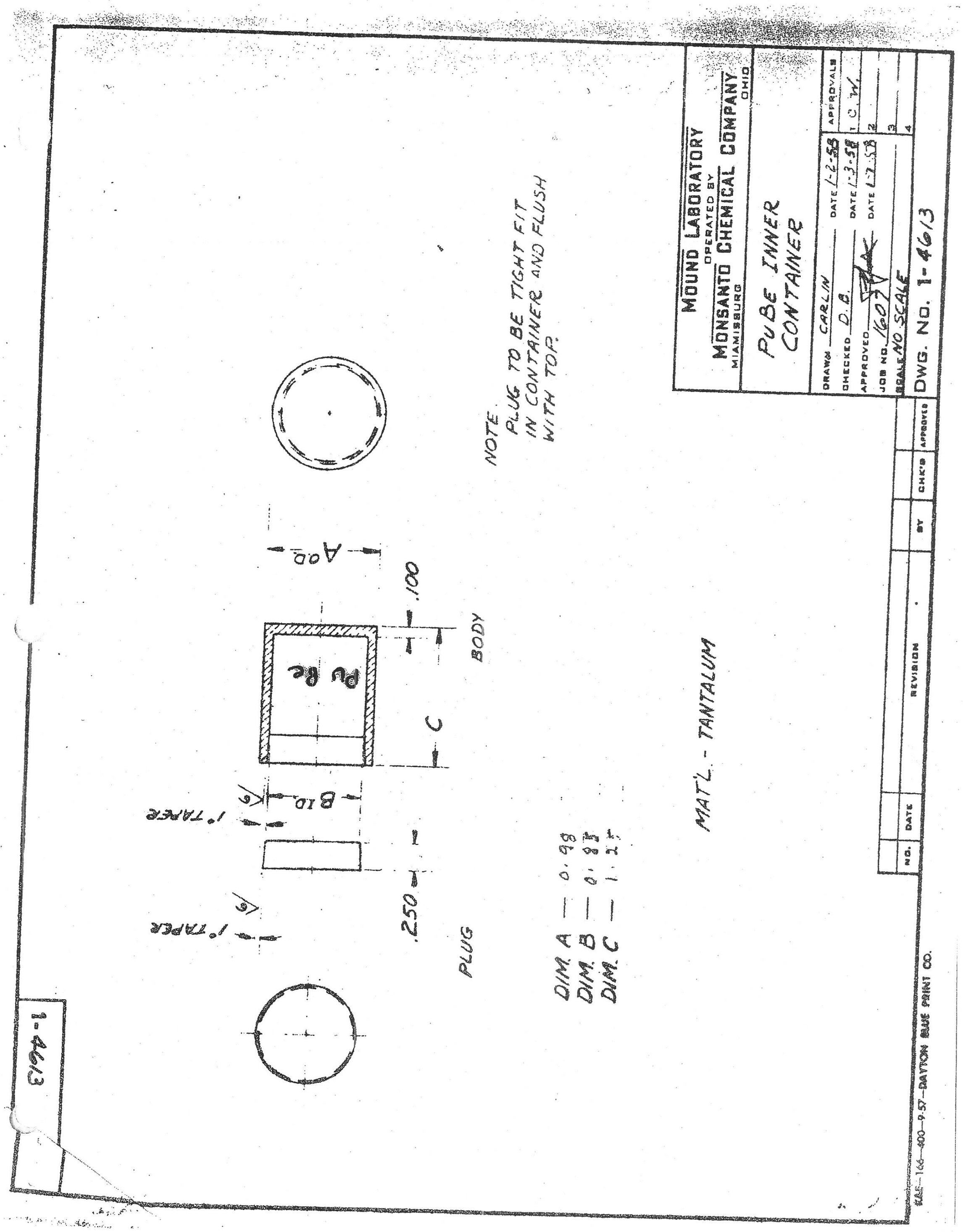
CC: Professor T. J. Thompson

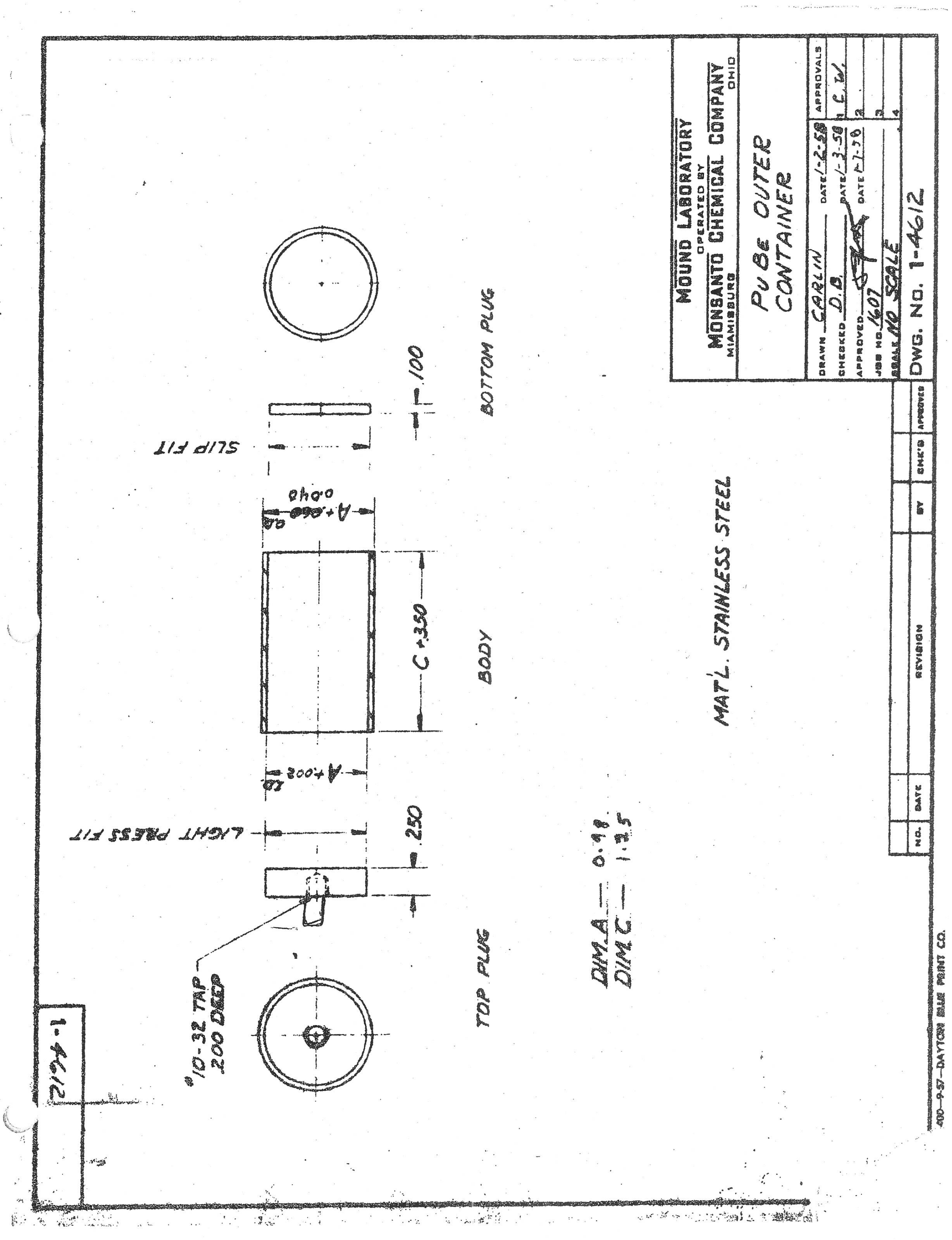
J.L. Richmond / E.E.W.

/lg

J. L. Richmond
GROUP LEADER, SOURCES

U.S. GOVERNMENT CONTRACT NO. AT-33-1-GEN-53


MOUND LABORATORY
OPERATED BY
MONSANTO CHEMICAL COMPANY
MIAMISBURG
OHIO
PuBe INNER CONTAINER
DRAWN CARLIN DATE 1-2-58
CHECKED D.B. DATE 1-3-58
APPROVED DATE 1-7-58
JOB NO. 1607
SCALE NO SCALE
DWG. NO. 1-4613
APPROVALS
1 C.W.
NO.
DATE
REVISION
BY
CHK'D
APPROVED
NOTE:
PLUG TO BE TIGHT FIT IN CONTAINER AND FLUSH WITH TOP.
A O.D.
.100
BODY
C
Pu Be
B I.D.
1° TAPER
1° TAPER
.250
PLUG
DIM. A — 0.98
DIM. B —
DIM. C —
MAT'L. - TANTALUM
1-4613
DAYTON BLUE PRINT CO.


MOUND LABORATORY
OPERATED BY
MONSANTO CHEMICAL COMPANY
MIAMISBURG OHIO
PuBe OUTER CONTAINER
DRAWN CARLIN DATE 1-2-58
CHECKED D.B. DATE 1-3-58
APPROVED DATE
JOB NO. 1607
SCALE NO SCALE
APPROVALS
DWG. No. 1-4612
NO. DATE REVISION BY CHK'D APPROVED
TOP PLUG
BODY
BOTTOM PLUG
#10-32 TAP .200 DEEP
LIGHT PRESS FIT
SLIP FIT
.250
.100
A+.002 OD
A+.060 OD
0.040
C+.350
MAT'L. STAINLESS STEEL
DIM. A — 0.98
DIM. C — 1.25
1-4612
400-9-57—DAYTON BLUE PRINT CO.

Appendix E

Data Analysis Scripts

E.1 Data Parser And Plotting Script

data/foilDataParser.py

```
#!/bin/python3

'''
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obtaining a copy of this software and associated documentation
files (the "Software"), to deal in the Software without
restriction, including without limitation the rights to use,
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copies of the Software, and to permit persons to whom the Software
is furnished to do so, subject to the following conditions:

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EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF
MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT.
IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY
CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT,
TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE
SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.
'''


import xlrd
import csv
import matplotlib.pyplot as plt
import numpy as np
from scipy import stats #for the linear regressioni
from scipy.optimize import least_squares #regression
import math
#internal API
from dataStruct import position, foil, count, DAY_TO_SEC

'''
Parser object that just parses all of the positions with foils
and counts.
'''
class foilExper():
    '''
    A class for parsing foil activation excel filesi
    @param Name- the filename of the .xlsx file
    '''
    def __init__(self, Name):
        self.book=xlrd.open_workbook(filename=Name)
        self.foil=''
        self.parse()

    '''
    Discovers all foils and creates an internal array of foils
    '''
    def parseFoils(self):
        if (self.foil==''): #if foilMass isn't set populate it
            #pulls out the excel sheet with the foil properties
            sheet=self.book.sheet_by_name('foilData')

```

```
            #pulls out the header row and searches for the right columns
            #makes it tolerant to people moving around columns
            headers=sheet.row(0)
            maxR=   sheet.nrows  #get the number of rows
            massCol=foilExper.findColumn(headers,'Mass')
            foilCol=foilExper.findColumn(headers,'Foil')
            thickCol=foilExper.findColumn(headers,'Thickness')

            self.foil={}

            for i in range(1,maxR):
                #add all of the foil masses to the dictionary
                #TODO actually care about the materials which are used
                buffer=foil('In',sheet.cell(i,thickCol).value,sheet.cell(i,massCol).value)
                #parses the foil object properties
                self.foil[sheet.cell(i,foilCol).value]=buffer

    '''
    Parses the counts data, and stores them inside the appropriate foils
    '''
    def parseCounts(self):
        sheet=self.book.sheet_by_name('CountData')
        headers=sheet.row(0) #get the header row

        #finds the columns which are desired.
        foilCol=foilExper.findColumn(headers,'Foil')
        startCol=foilExper.findColumn(headers,'Count Start')
        endCol=foilExper.findColumn(headers,  'Count End')
        countCol=foilExper.findColumn(headers, 'Counts')
        bgCol=foilExper.findColumn(headers,'Background')
        bgTimeCol=foilExper.findColumn(headers,'BG_TIME')

        end=sheet.nrows

        #parses the data
        for i in range(1,end):
            if( sheet.cell(i,foilCol).value!=''): #if an actual data row
                buffer=count(sheet.cell(i,startCol).value,sheet.cell(i,endCol).value,
                        sheet.cell(i,countCol).value,sheet.cell(i,bgCol).value,
                        sheet.cell(i,bgTimeCol).value)
                #add the counts to the appropriate foil
                self.foil[sheet.cell(i,foilCol).value].addCount(buffer)
    '''
    Parses the position data. Adds foils to appropriate positions.
    '''
    def parsePosition(self):
        sheet=self.book.sheet_by_name('PositionData')
        header=sheet.row(0)
        foilCol=foilExper.findColumn(header,'Foil')
        layerCol=foilExper.findColumn(header,'Layer')
        posCol=foilExper.findColumn(header,'Position')
        endCol=foilExper.findColumn(header,'Finish Activation')
        xCol=foilExper.findColumn(header,'X [cm]')
        yCol=foilExper.findColumn(header,'Y [cm]')
        zCol=foilExper.findColumn(header,'Z [cm]')

        #pulls out all of the layer numbers
        #finds the max one and then useds that to initialize
        #the list of dictionaries
        layers=[]
        for cell in sheet.col(layerCol):
            if(cell.ctype==2): #if this cell is a number
                layers.append(cell.value)

        end= sheet.nrows
        #initializes the list with enough space to breath
        self.positions=[{} for i in range(0,int(max(layers))+1)]
        for i in range(1,end):
            if(sheet.cell(i,foilCol).value!=''): #if it isn't blank
                foil=sheet.cell(i,foilCol).value
                self.foil[foil].addEndTime(sheet.cell(i,endCol).value)

                #update the end of the irradiation for the foil
                layer=int(sheet.cell(i,layerCol).value)
                pos=int(sheet.cell(i,posCol).value)
                X=sheet.cell(i,xCol).value
                Y=sheet.cell(i,yCol).value
                Z=sheet.cell(i,zCol).value

                #check for initialization
                if layer not in self.positions or pos not in self.positions[layer]:
                    self.positions[layer][pos]=position(self.foil[foil],X,Y,Z)
                    #if the object doesn't exist make it and add the foil
                else:
                    #otherwise just pop the appropriate foil onto the stack
                    self.positions[layer][pos].addFoil(self.foil[foil])
    '''
    Parses the start time for the experiment.
    '''
    def parseStart(self):
        global DAY_TO_SEC
        sheet=self.book.sheet_by_name('ExperimentInfo')
```

```python
        header=sheet.row(0)
        col=foilExper.findColumn(header,'TimeStamp')
        header=sheet.col(0)
        row=foilExper.findColumn(header,'Source Insertion')
        self.start=sheet.cell(row,col).value*DAY_TO_SEC  #caches the
        #experiment start time in seconds
    '''
    Automatically parse all data
    Runs:
    parseFoils()
    parseCounts()
    parsePosition()
    parseStart()
    '''
    def parse(self):
        self.parseFoils()
        self.parseCounts()
        self.parsePosition()
        self.parseStart()

    '''
    Pulls out the radial specific reaction rate data for a layer

    @param layer the layer to examine
    @return (pos,flux,sigma) Pos=position in x data
        flux=specific reaction rate
        sigma=uncertainty
    '''
    def getRadData(self,level):
        row=self.positions[level] #pull out underlying dict
        size=len(row)
        pos=np.zeros(size)
        flux=np.zeros(size)
        sigma=np.zeros(size)

        pointer=0

        for  key, val in row.items(): #iterate over the things
            try: #catches exception for unitialized object
                if(val.getCounts()>0): #tests that there is actual data aswell
                    pos[pointer]=val.X
                    ret=val.calcSpecRxRate(self.start)
                    flux[pointer]=ret[0]
                    sigma[pointer]=ret[1]
                    pointer=pointer+1
            except NameError: #if uninit have no data and don't care
                pass

        return (pos,flux,sigma)


    '''
    Plots the radial specific reaction rate for a given level


    @param level the level at which to do the radial traverse
    @param fileName the fileName to which to save the pdf do not include
    extension
    @param ax   the subplot object. This allows you to combine plots on a
        figure
    @param font the font specification for the axis labels
    <https://matplotlib.org/api/matplotlib_configuration_api.html#matplotlib.rc>
    @param save If true the plot will be saved to FileName
    @param xAxisLabel If true will add a X axis Label
    @param yAxisLabel if True will add y axis label. Usefule for making a
    common label
    @param title the title for the plot. Useful for combined plots
    '''
    def plotRadial(self, level,ax,fileName=None, font={'family':'normal',
            'weight':'normal',
                'size' :18},save=True,xAxisLabel=True, yAxisLabel=True,title=''):

        ret=self.getRadData(level)
        pos=ret[0]
        flux=ret[1]
        sigma=ret[2]
        #plot it!
        ax.errorbar(pos,flux,yerr=sigma, fmt='s',color='k',capsize=5)
        #add labels
        if(xAxisLabel):
            ax.set_xlabel("Position on X[cm]",**font)

        if(yAxisLabel): #sets the yaxis
            ax.set_ylabel("Uncorrected Specific "\
                    "Reaction Rate\n($\\eta\\phi\\Sigma_c/\\rho$)[$s^{-1}g^{-1}]$", **font)
        plt.xlim((-105,105)) #statically sets the x-axis. Change for non-GEP
        ax.set_title(title,**font) #sets the title
        if(save):
            plt.savefig(fileName+'.pdf')

    '''
    Gets the axial spec. reaction rate data for a specific position.
```

```

    @param position the radial position to use
    @return (pos, flux,sigma) pos=axial position in z
            flux=spec reaction rate
            sigma=uncertainty
    '''
    def getAxialData(self,position):
        size=len(self.positions)-1
        pos=np.zeros(size)
        flux=np.zeros(size)
        sigma=np.zeros(size)

        pointer=0

        for  key, val in enumerate(self.positions): #iterate over the things
            if(val!={}):
                if(val[position].getCounts()>0):
                    pos[pointer]=val[position].Z
                    ret=val[position].calcSpecRxRate(self.start)
                    flux[pointer]=ret[0]
                    sigma[pointer]=ret[1]
                    pointer=pointer+1

        return (pos,flux,sigma)

    '''
    Plots the axial specific reaction rate for a given position

    @param level the level at which to do the radial traverse
    @param fileName the fileName to which to save the pdf do not include
    extension
    @param ax   the subplot object. This allows you to combine plots on a
        figure
    @param font the font specification for the axis labels
    <https://matplotlib.org/api/matplotlib_configuration_api.html#matplotlib.rc>
    @param save If true the plot will be saved to FileName
    @param xAxisLabel If true will add a X axis Label
    @param yAxisLabel if True will add y axis label. Usefule for making a
    common label
    @param If true will create a log-log plot else it will be lin-lin
    @param title the title for the plot. Useful for combined plots
    '''
    def plotAxial(self, position, ax,fileName=None, font={'family':'normal',
             'weight':'normal',
                 'size' :18},save=True,xAxisLabel=True,
                 yAxisLabel=True,logLog=False, title=''):

        ret= self.getAxialData(position) #gets axial data
        pos=ret[0]
        flux=ret[1]
        sigma=ret[2]

        #plot it!
        ax.errorbar(pos,flux,yerr=sigma,fmt='s',color='k',capsize=5)
        #turn on or off log-log
        if(logLog):
            ax.set_yscale('log')
        #    ax.set_xscale('log')
        #add x-label
        if(xAxisLabel):
            ax.set_xlabel('Position in z [cm]',**font)

        #add the y-label
        if(yAxisLabel):
            ax.set_ylabel("Uncorrected Specific "\
                    "Reaction Rate\n($\\eta\\phi\\Sigma_c/\\rho$)[$s^{-1}g^{-1}]$",**font)

        ax.set_title(title,**font)
        if(save):
            plt.savefig(fileName+".pdf")



    '''
    Creates a csv table for viewing raw interpreted data

    @param fileName the fileName to dump the data to
    '''
    def writeTable(self,fileName):
        # open file for writing
        with open(fileName, 'w') as file:
            dumper=csv.writer(file)
            dumper.writerow(['Layer','X','Y','Z','counts','$I_0$','Reaction Rate'
                ,'Error','Relative Error'])

            for key, layer in enumerate(self.positions): #iterate over layers
                if(layer!={}):
                    for key2,pos in layer.items(): #iterate over all positions
                        X=pos.X
                        Y=pos.Y
                        Z=pos.Z
                        counts=pos.getCounts()
```

```
                        I0=pos.calcN0()
                        rx=pos.calcSpecRxRate(self.start)
                        if(counts>0):
                            dumper.writerow([key,X,Y,Z,counts,I0[0],rx[0],rx[1],rx[1]/rx[0]])
    '''
    Looks through the header row provided to find the desired column number

    @param header an array of the column headers
    @param target the string of the column that is desired
    @return the column number

    '''
    def findColumn(header,target):
        i=0
        for col in header:
            if(target in col.value):
                return i
            i=i+1
        return -1


'''
Represents an experimental Subcritical Pile
'''
class subCritPile():

    '''
    Creates an object which isn meant to analyze foil data for a sub-crit pile

    @param fileName the name of the xlsx file which contains the foil counts
    @param a- the width of the pile in X in cm
    @param b- the depth of the pile in Y in cm
    @param c- the height of the pile in Z above the source plane in cm
    '''
    def __init__(self,fileName,a,b,c):
        self.data=foilExper(fileName) #loads the data in
        self.a=a
        self.b=b
        self.c=c

    '''
    Goal function for sinh fit

    @param g the paramaters [0]A [1]gamma
    y=Asinh(gamma(c-x))
    @param x xvalue
    @param y actual y value of data
    '''
    def goalSinh(self,g,x,y):
        return g[0]*np.sinh(g[1]*(self.c-x))-y

    '''
    Goal function for cos amplitude fit

    @param g- the paramters [0]A
    @param x x-value
    @param y y-value from data
    '''
    def goalCos(self,g,x,y):
        return g[0]*np.cos(math.pi*x/self.a)-y


    '''
    Calculates \gamma_{1,1} stores to self.gamma

    gamma[0] is amplitude of mode. gamma[1] is the \gamma

    @param position the radial position to use
    '''
    def calcFundGamma(self,position):

        ret=self.data.getAxialData(position)

        pos=ret[0]
        flux=ret[1]

        pointer=0

        x0=np.ones(2)
        x0=[10, 0.02]
        fit= least_squares(self.goalSinh, x0, args=(pos[2:],flux[2:]))
        self.gamma=fit.x

        fitFunc=fit.x[0]*np.sinh(fit.x[1]*(self.c-pos))

        ####Calculates R^2
        yBar=np.mean(flux) #calculates mean y
        SST=0 #total sum squares
        SSRes=0 #residual sum of squares

        for i in range(0,pos.size): #iterate over all elements
            SST+=(flux[i]-yBar)**2
```

```
            SSRes+=(flux[i]-self.goalSinh(fit.x,pos[i],0))**2 #sum residuals

        self.R2=1-SSRes/SST#saves r^2


    '''
    Plots the axially fitted function on the given subplot

    Note: pulls out self.gamma must be invoked after self.calcFundGamma

    @param ax the subplot object for plotting the figure
    @param printGamma- will print gamma value on the figure if true
    '''
    def plotAxialFunc(self,ax,printGamma=True):
        x=np.linspace(0,self.c,100)
        if(printGamma):
            title="$\\gamma_{1,1}$=%.5f\n$R^2$=%.3f" %(self.gamma[1],self.R2)
            ax.text(200,30,title, fontsize=15)

        line=self.gamma[0]*np.sinh(self.gamma[1]*(self.c-x))
        ax.plot(x,line,color='k')

    '''
    Calculates the Material Buckling, and the critical Reactor size.

    Note: uses self.gamma needs to be invoked after self.calcFundGamma.

    @return (Bm2,s) Bm2=B_m^2-material buckling, s=side length of critical
                    reactor cube
    '''
    def calcGeoBuckle(self,position):
        Bm2=(math.pi/self.a)**2+(math.pi/self.b)**2-self.gamma[1]**2

        s=np.sqrt(3)*math.pi/math.sqrt(Bm2)

        return(Bm2,s)

    '''
    Fits the fundamental cosine to the data.

    @param layer -the layer to examine
    @return the amplitude of the fundamental mode
    '''
    def fitFundRadial(self,layer):
        ret=self.data.getRadData(layer) #pulls out the radial data desired

        x0=[1] #guess 1 first

        fit=least_squares(self.goalCos,x0, args=(ret[0],ret[1])) #fits data

        return fit.x[0] #return the amplitude

    '''
    Plots the cosine fit on the given plot.

    @param ax the given subplot to print on
    @param A the amplitude of the cosine from the fit before
    '''
    def plotFundRad(self,ax,A):

        x=np.linspace(-self.a/2,self.a/2,100) #make dummy x
        line=A*np.cos(math.pi*x/self.a) #defines the line function
        ax.plot(x,line,color='k') #plots it
```

E.2 Data Structures for Activity Calculations

data/dataStruct.py

```
#!/bin/python3

'''
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```

```python
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TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE
SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.
'''

import math

#"constant" for converting days to seconds
DAY_TO_SEC=86400
MIN_TO_SEC=60 #const for minutes to seconds
'''
Represents a single location in the pile. May contain multiple foils.

'''
class position():
    '''
    @param foil a single foil object at this postion
    @param X position in x in cm
    @param y ""
    @param z ""
    '''
    def __init__(self,foil,X,Y,Z):
        self.foil=[foil]
        self.X=X
        self.Y=Y
        self.Z=Z
    '''
    Appends another foil to list of foils at position

    @param the new foil object
    '''
    def addFoil(self,foil):
        self.foil.append(foil)

    '''
    Calculates the total initial activity here.
    Sums over all foils
    '''
    def calcN0(self):

        N0=0
        sigmaAcum=0

        for foil in self.foil:
            ret=foil.calcN0()
            N0=N0+ret[0]    #accumulates the total
            sigmaAcum=sigmaAcum+ret[1]**2  #add std dev in quadrature

        return (N0, math.sqrt(sigmaAcum)) #return tuple of value and std dev

    '''
    Calculates the specific reaction rate for this position.

    This should just be a pass through for a single foil position, but can
    handle multiple foils if neeeded. See foil.calcSpecRxRate() for math

    @param startAct- the start time of the foil activation in seconds.
    @return (rx,sigma) rx-the specific reaction rate
    '''
    def calcSpecRxRate(self,start):
        rx=0
        sigmaAcum=0

        for foil in self.foil: #iterate over all foils
            ret=foil.calcSpecRxRate(start)
            rx=rx+ret[0]
            sigmaAcum=sigmaAcum+ret[1]**2
        return (rx,math.sqrt(sigmaAcum))
    '''
    Just gets the total number of counts at positon
    @return total counts detected
    '''
    def getCounts(self):
        sum=0
        for foil in self.foil:
            sum=sum+foil.getCounts()
        return sum

    def __repr__(self):
        return self.__str__()

    def __str__(self):
        out=''
        i=0
        for foil in self.foil:
            out=out+"\nFoil "+str(i)+": "+foil.__str__()
            i=i+1
        return out
```

```python


'''
Represents a single foil. Holds it properties and the counts which were taken
of it
'''
class foil():
    '''
    @param mat- foil material
    @param thick-foil thicness
    @param mass-foil mass in g
    '''
    def __init__(self,mat,thick,mass):
        self.mat=mat
        self.thick=thick
        self.mass=mass
        self.counts=[] #the child counts for this dohickey

    '''
    Adds the end time of the foil activation.
    @param the foil activation end time in days
    '''
    def addEndTime(self,end):
        self.end=end*DAY_TO_SEC
    '''
    Adds a count object to the current foil
    @param a completely initialized count object
    '''
    def addCount(self,count):
        self.counts.append(count) #adds it to the array of counts

    '''
    Calculates the specific reaction rate [s^-1g^-1](\phi\Sigma_c/ \rho)

    @param startAct- the starting time of the foil activation in seconds.
                    Not the time of the start of counting!

    '''
    def calcSpecRxRate(self,startAct):
        N0=self.calcN0() #gets quasi initial activity
        #must init deccayConst in calcN0
        #lambda/(m*(1-e^(-lambda t))
        #t is the total time in seconds of the foil activation
        divider=(self.mass*(1-math.exp(-self.decayConst*(self.end-startAct))))
        multiplier=self.decayConst/divider
        rx=N0[0]*multiplier
        sigma=N0[1]*multiplier

        return (rx,sigma)

    '''
    Calculates the Initial activity of the activated foil.

    this isn't a true activity as the detector efficiency isn't factored in.
    Finds \eta N_0. Only gives meaningful data is the exact same detector
    setup is used for all foils.


    '''
    def calcN0(self):
        #TODO switch from hardcoded half-lives
        self.halfLife=3257.4 #[s] half life for Indium 116-m from NuDat 2.7
        self.decayConst=math.log(2)/self.halfLife #calculate the decay constant

        counts=0
        denominator=0
        sigma=0

        for counter in self.counts: #iterate overr all counting sessions
            #retrieves counting cotribution for counting session
            ret=counter.getCountContribs(self.end,self.decayConst)
            counts=counts+ret[0]
            denominator=denominator+ret[2]
            sigma=sigma+(ret[1]/ret[2])**2
        if(counts>0):
            #completes the division of the accumulated sums
            activity=(counts)/denominator #[Bq]
            sigma=math.sqrt(sigma)
        else:           #if no counts were taken say it was 0
            activity=0
            sigma=0

        return (activity,sigma)
    '''
    Gets the total counts
    @return the total counts detected
    '''
    def getCounts(self):
        sum=0
        for count in self.counts:
            sum=sum+count.counts
        return sum
```

```python

    def __repr__(self):
        return self.__str__()
    def __str__(self):
        out="Material: "+str(self.mat)+"\nThickness: "+str(self.thick)
        out=out+"\nMass: "+str(self.mass)+"\nEnd: "+str(self.end)
        i=0
        for count in self.counts:
            out=out+"\nCount "+str(i)+": "+count.__str__()
            i=i+1
        return out

'''
Represents a single counting session for a single foil.
'''
class count():
    '''
    Creates a new count object representing one contiguous counting session.

    @param start- the start time is days since some epoch. (Excel default)
                    Do not convert to seconds! Will be done internally
    @param end- the end time of the count. Same formatting as above
    @pararm counts - the number of raw counts
    @paramm bgCounts- number of background counts
    @param  bgTime   -length of background counting in minutes. Will convert
                     to seconds
    '''
    def __init__(self,start,end,counts,bgCounts,bgTime):
        global DAY_TO_SEC
        global MIN_TO_SEC

        self.start=start*DAY_TO_SEC
        self.end=end*DAY_TO_SEC
        bgTime= bgTime*MIN_TO_SEC  #converrts bg time to seconds

        #C_net=C_n-c_bg*t_cn/t_bg
        self.counts=counts-(self.end-self.start)*bgCounts/bgTime
        #calculates std dev
        #s_net=sqrt(s_n^2+(s_bg*t_cn/t_bg)^2)
        #
        #this simplifies to:
        #s_net=sqrt(C_n+C_bg*(t_cn/t_bg)^2)
        self.sigma=math.sqrt(
                float(counts+bgCounts*((self.start-self.end)/bgTime)**2))

    def __repr__(self):
        return self.__str__()
    def __str__(self):
        return "Start: "+str(self.start)+" End: "\
               +str(self.end)+" Counts:"+str(self.counts)

    '''
    returns the data necessary to combine the counts to get an activity term

    The formula used is:

    N_0=(Sum(counts)*lambda)/(e^(-lambda*t_1)-e^(-lambda*t_2))
    @param endAct - the end of activation t_0 in seconds and not days!!
    @param decayCNST- the decay constant lambda in s^-1
    @return touple (counts, sigma, exponential term)
    '''
    def getCountContribs(self,endAct,decayConst):

        #calculates:
        #(e^(-L*t_1)-e^(-Lt_2))
        decay=math.exp(-decayConst*(self.start-endAct))
        decay=decay-math.exp(-decayConst*(self.end-endAct))
        return (self.counts, self.sigma, decay)
```

Appendix F

Fuel Slug Measurements

F.1 Summary of Measurements

Total slugs in inventory: 1,288.
Total slugs with dimensions measured: 140.
Total slugs with mass measured: 1,286.

Table F.1: Summary of slug measurements made.

Property	Units	mean	Std. Dev.	Maximum	Minimum
Mass	grams	2006	7	2026	1960
Length	inches	8.41	0.01	8.452	8.387
Diameter	inches	1.084	0.001	1.088	1.081

Note: "X" is not used in the serial numbers but the author used "X" to replace characters which were illegible in the serial numbers.

F.2 Complete Slug data

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
B0771923	2010	8.420	1.083	
B0172212	2006	8.401	1.088	
D1371171	2005	8.452	1.084	
B0672078	2008	8.421	1.084	
D0470700	2002	8.405	1.085	
1471045	2008	8.405	1.084	
D472257	2011	8.421	1.084	has been dropped on one end
1472200	2006	8.409	1.084	
B1171998	2004	8.409	1.084	
B1371488	2006	8.418	1.085	
B1170799	2009	8.405	1.084	
B1470458	2008	8.402	1.084	
B0170300	2010	8.406	1.083	small drop on one end
B14xxx59	2004	8.401	1.085	part of serial number has been removed. Marked illegible 1
B2070106	2017	8.415	1.085	
B2071441	2010	8.398	1.083	
D0xxxx57	2008	8.405	1.083	part of serial number illegible. Marked illegible 2
B2070832	2005	8.408	1.085	
2171781	2008	8.416	1.082	
B2872260	2010	8.404	1.085	
D0671299	2001	8.387	1.087	
D1371071	1999	8.418	1.085	

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
B0770725	2014	8.410	1.085	
B0170636	2008	8.426	1.084	
B2171519	2001	8.404	1.087	
B1471132	2010	8.390	1.081	
D0471132	2003	8.420	1.081	
-L2265176	2017	8.422	1.085	
-N2091687	2006	8.417	1.083	
B2778041	2009	8.400	1.084	
D0970113	1994	8.424	1.084	
2671446	2008	8.398	1.084	
B1370963	2008	8.416	1.085	
B0473035	2000	8.413	1.084	
B2570267	2014	8.431	1.087	
B2673275	2015	8.425	1.085	
B1272487	2010	8.406	1.085	
B2770413	2000	8.404	1.084	
B1800803	2000	8.420	1.082	
B1170787	2006	8.403	1.086	
D0870414	1967	8.413	1.083	
D207837	2003	8.407	1.082	
B1472585	2010	8.417	1.084	
B1872239	2007	8.422	1.084	
-D2661234	2008			alpha contamination. Taken from F9. Has pinhole near serial number. Possible contam source. Painted red near pinhole.
B2072930	2012			alpha contamination. Taken from C4. Completely decontaminated by RP
B1271623	2004			alpha contamination. Taken from J4. Completely decontaminated by RP.
xxx72496	2002	8.422	1.082	marked illegible 3
B2670940	2009	8.416	1.085	
B0671319	1989	8.423	1.086	
-L226514	2019	8.425	1.085	
-L2266550	2020	8.421	1.087	
B2773292	2004	8.397	1.085	
x2773228	2011	8.406	1.082	
1370992	1994	8.404	1.085	
B1271815	2007	8.409	1.085	
D1170125	2000	8.413	1.083	
D0871349	1989	8.401	1.082	
B1172132	2009	8.398	1.085	
B2070160	2010	8.412	1.086	
B2870434	2015	8.420	1.087	
B1871744	1988	8.410	1.085	
B1470554	2013	8.425	1.085	
B0671582	2008	8.411	1.086	
-L226391	2013	8.399	1.084	
B2073093	2003	8.421	1.085	
B1572843	2010	8.415	1.083	
B2070768	2010	8.402	1.083	
B137215	2009	8.403	1.084	
B2170838	2005	8.399	1.086	
B7281447	2010	8.417	1.082	
B2671574	2009	8.411	1.084	
B1872215	1996	8.411	1.085	
B2xx2104	2007	8.414	1.085	Marked as illegible 4
D1370855	2006	8.411	1.085	
D2070815	2000	8.403	1.083	
B2671816	2004	8.411	1.085	
B2773202	2011	8.419	1.085	
B1572329	2006	8.416	1.084	
B0472594	2008	8.413	1.085	
B0471997	2002	8.425	1.082	
B0171710	2004	8.405	1.084	
B1872254	2000	8.424	1.081	
B1872007	2007	8.402	1.082	
B0871581	1976	8.421	1.081	
B1370250	2003	8.416	1.082	
B0772939	2013	8.393	1.085	
B1172252	2010	8.406	1.084	
D0771068	2002	8.406	1.085	
B1171166	2010	8.412	1.083	
B177184	2004	8.418	1.086	
B2771793	1999	8.391	1.082	
B1370051	2004	8.413	1.083	
B2670424	2002	8.404	1.085	
B1972932	2010	8.402	1.084	
D1571306	2000	8.436	1.083	
B2770189	2007	8.396	1.084	
B1572466	2008	8.405	1.086	
B0170523	2016	8.408	1.083	
B2770526	2008	8.396	1.084	
-L2166534	2003	8.408	1.085	
B1571808	2011	8.408	1.085	
B1800492	1999	8.401	1.087	
B0471819	2012	8.424	1.083	

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
-L2266545	2019	8.417	1.082	
-L2266566	2019	8.402	1.086	
B2172562	2011	8.408	1.084	
B0671453	2007	8.419	1.085	
B0771376	2004	8.410	1.085	
B1473189	2008	8.391	1.084	
B2772415	2010	8.405	1.082	
B2874376	2015	8.395	1.083	
D1470503	2007	8.417	1.085	
B197272	2007	8.412	1.085	
D0571615	2007	8.417	1.086	
50871605	2010	8.423	1.084	
B2172516	2009	8.439	1.085	
B1472072	2006	8.406	1.082	
B1872911	2004	8.429	1.085	
B2870720	2013	8.411	1.085	
B1970888	2004	8.413	1.083	
B1872358	2004	8.412	1.085	
B0570448	2005	8.400	1.086	
B1500833	1996	8.409	1.085	
B1272184	2014	8.417	1.085	
xxxxxxxx	2010	8.401	1.084	marked illegible 5
B2770679	2000	8.397	1.084	
D0870138	1992	8.399	1.083	
-L2265105	2015	8.418	1.085	
B12782280	2010	8.422	1.084	
B2871216	2011	8.413	1.086	
B207118	2009	8.420	1.083	
B27721430	2011	8.411	1.085	
B1800885	1969	8.401	1.082	
B2772841	2004	8.414	1.085	
D0871133	2007	8.425	1.085	
D0870187	1995	8.399	1.083	
B2170862	2003	8.411	1.084	
B1871758	1995	8.411	1.085	
B0570267	2009	8.415	1.086	
B1570459	2011	8.409	1.085	
B1370660	2008	8.420	1.083	
B2070702	2009			
B0171080	2009			
B0173020	2003			
B0171370	2008			
B0670450	2009			
B0472429	2012			
B1870593	2006			
-L2266522	2018			
B1970420	2007			
D0171281	2001			
B2570443	2011			
B2070184	2015			
B1372056	2006			
B077136	2009			
B19771335	2009			
B0472349	2012			
B072220	2011			
B0473129	2008			
2570186	2011			
B1872418	2001			
B1171806	2009			
B2870634	2008			
D1570113	2004			
D1471015	2007			
-L226655	2021			
B2570115	2007			
D0172080	2001			
B2071938	2012			
B1970657	2004			
B1379288	2009			
D1270621	2008			
B1971310	2009			
B0770120	2009			
D0165822	2003			
D0570746	2005			
B2570468	2008			
B1773078	2006			
D1471504	1997			
B2772363	2004			
D1471002	2008			
B2670332	2015			
2670305	2007			
D0172875	1985			
B1800119	1993			
B2579248	2015			
B2172238	2005			
Bxx7x552	2003			marked illegible 6
B1171105	2011			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
D3070225	2006			
B1573084	2016			
B01772589	2009			
B1800462	1995			
B2170459	2011			
D16770206	2003			
B1800300	1997			
A2971893	2011			
B2672952	2009			
B1271666	2006			
B2776961	2007			
B0671482	2010			
B0172760	2008			
B2771602	2010			
B1471159	2011			
B1872180	2001			
A2970128	2009			
B2671423	2008			
D0870192	2004			
B2770661	2011			
D1470648	1999			
B0173003	2007			
B1572192	2000			
B0172488	1998			
D5731100	2010			
B2872221	2010			
B1872719	2014			
B0770151	2014			
B1970729	2009			
K1853939	2011			
D1371124	2004			
D1171642	2006			
D1471210	2004			
B2570875	2011			
1471097	2007			
B1472041	2010			
A3170236	2007			
2873215	2004			
B1871425	1992			
B0770643	2007			
B0679404	2003			
-L223512	2019			
B27628329	1995			
-L216650	2000			
-L2265118	2011			
B2772501	2016			
B1800649	2002			was dropped on one end
B27714258	2002			was dropped on both ends
D2471203	2004			
D0570331	2012			mild dings
B1472497	2009			
B0771395	2008			
B2570141	2006			
B1570161	2008			
B2570731	2010			
B0770200	2007			
B0670447	2014			
B2172504	2013			
B1972801	2015			
B2571949	2008			
B2870797	2005			
A9070524	2001			
D571859	2009			
B2172836	2011			
B2872972	2004			
1371541	2011			has solder on serrial numbers
D1471099	2006			
B1972849	2012			
B1472871	2010			
B1570348	2007			
B2072162	2013			
B217042	2007			
B2878291	2013			
D1170946	2005			
B2570223	2015			
D0671359	2003			
D1470199	2008			
B1172131	2007			
B2171832	2013			
B2772468	2007			
D0177772	2002			
B0670749	2001			
B1171553	2015			
B1972345	2011			
D047459	2010			
B1471241	2004			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
B017140	2009			
B2871463	2012			
D0870130	1998			
B2870273	2008			
B0172356	2011			
B0772683	2013			
B0570424	2007			
11569059	2000			also has second s/n:00362241
B0771242	2008			
B2670657	2009			
B2770194	2011			
B2771412	2006			
-L2266532	2019			
B2871201	2011			
D14X243	2002			
B1606449	1996			
B0671889	2009			
B1872234	2004			
B0471085	2008			
1800389	1974			
20671993	2014			
B0671174	2006			
D1271379	2000			
B2771948	2005			
-L260368	2017			Has multiple conflicting stamps. Marked illegible 7
B1970656	2006			
B0671238	2004			
B0671750	2008			
B0571236	2008			
D1570191	2006			
B2672289	2013			
B1972341	2008			
-L226655	2016			
B2671868	2010			
D0470453	2008			
D1674179	2006			
B0572057	2010			
D0670234	2004			
B1471167	2007			
B2670361	2002			
D1170357	2001			
B1800445	1973			
B1470549	2004			
B0673011	2011			
B2672869	2008			
D2070877	2008			
51472581	2006			
D0171954	1999			
B2570210	2011			
B2770517	2014			
D0571670	2006			
B0872200	1986			
D1470131	1993			
D0670283	1998			
B2570212	2010			
B2670971	2010			
B2770503	2005			
B1912112	2005			
D1374262	2003			
B2670871	2008			
B2073226	2010			
B1872521	1993			
A2373219	2005			
B0571957	2006			
B0772954	2009			
D1370239	2007			
B0470360	2005			
B2571391	2008			
B1372241	2005			Has long gashes; burs on end
B1800813	2006			
D0570729	2006			
B1800474	2000			
B2671478	2010			
D1370658	2005			
B2570246	2013			
xx271910	1986			
B0874120	1977			
B1372002	2007			
B1471499	2001			
B0771955	2011			
B1870786	2007			
D0172513	2014			
B1371942	2011			
B1871949	1983			
B2671850	2006			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
B1972114	2003			
B2071424	2013			
B1372094	2013			
B2570598	2011			
B1970779	2011			
B1371189	1998			
D0171013	1998			
B1872225	2000			
B1271143	2005			
x1170112	2004			ILLEGIBLE 9
B2570253	2008			
B1571815	2013			
B0670729	2013			
B1X7X143	2004			ILLEGIBLE 10
B2672065	2011			
K195134	2019			
B2070422	2010			
B2070174	2008			
B1571187	2007			
B0573075	2010			
A0070996	1999			
D017008	2011			
B2672296	2007			
-L226659	2018			
B1272377	2010			
B1970677	2014			
-L216656	2010			
-K3164032	2000			
B1800312	2009			
B170988	2013			
B1872085	1982			
D0172807	2001			
D0870660	2001			
B1600792	1996			
B0472606	2006			
B4372384	2010			
B1171910	2006			
B1872154	2000			
D0571544	2004			
B2570247	2006			
D0879459	1997			
472069	2011			BOTH ENDS BANGED UP
B1571921	2008			
B2072615	2006			
D0172600	2008			
A3072416	2009			
B1571483	2009			
B2770224	2007			
B0871072	1993			
91470164	2005			
B2470431	2011			
B2571946	2007			
B0671270	2008			
B1472592	2016			
B2870968	2015			
B271104	2011			
2770490	2010			
B1472620	2013			
B1572792	2011			
B0770148	2006			
D1370680	2003			
B0171863	2010			
B2770579	2004			
D1371120	2004			
A2970740	2017			
A1573094	2015			
B19731131	2011			
B1572975	2012			
B087252	2002			
B0470608	2011			
B2771073	2008			
B1970456	2013			
B1872671	2000			
B0470854	2009			
A0871703	1992			
B2870220	2011			
D171215	2010			
B1572419	2010			
B1573112	2008			
B0573036	2011			
B1572687	2010			
B1372687	2004			
B1870889	2011			
B127145	2003			
B2773229	2010			
D0173072	2004			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
A2972431	2011			
B1370585	2017			
D0670472	2004			
B2572323	2015			
1872050	1986			
B277050	2006			
B0172172	2004			
B1271794	2010			
B1573233	2014			
B1271096	2007			
B1973084	2011			
B1972179	2008			
B1872224	2010			
B0770692	2015			
D036220	2004			
B0472309	2011			
B2770558	2000			
B1472539	2015			
B1271717	2008			
B1970362	2000			
B0872170	2003			
B0671916	2010			
B2070738	2012			
B0670725	2015			
D1570685	2004			
B1470182	2007			
B1273045	2008			
B1471157	2013			
B0871618	1997			
B1471710	2008			
D1871323	2007			
B2570211	2011			
D0171251	2007			
B0671319	2008			
B0573237	2003			
B1800828	2004			
-L226653	2020			
D0770823	2004			
B2572849	2011			
B0572637	2010			
B1500100	2007			
11569072	2000			SECOND S/N: 0036X292
-L1562750	2006			
B1170816	2011			
B1872596	2003			
D1471039	2004			
D2661237	2007			
B1271004	1998			
D1371031	2002			
D671306	2005			
B1271352	2009			
B1370355	2009			
B271548	2010			
D0470733	2004			
B1800883	1981			
B1472687	2012			
B2771371	2006			
D0871316	1999			
D0870145	1999			
D0871306	1997			
B0172524	1998			
B1871391	2004			
D1370924	2006			
B1471120	2009			
B1473192	2009			
B1372794	2004			
B1800354	1996			
B147251	2014			
D1471212	1996			
B1973312	2009			
B1571703	2009			
D1170153	2006			
B1671577	2007			
-N2061689	2004			
B150010	2012			
B1270702	2009			
B2771903	2011			
B0172965	2001			
A3071790	2002			
B2170457	2010			
-L2265164	2016			
D0670432	2001			
A2870158	2010			
50672150	2004			
D0470816	2004			
B26782603	2004			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
B2670317	2007			
1371122	2002			
B0672146	2008			
B1472321	2014			
B2671844	2005			
B1270468	2013			
D0770991	2001			
D1370232	2004			
B2570271	2011			
B0472864	2007			
B1872954	2000			
D1471272	2005			
B0672896	2005			
B1970815	2004			
B2171503	2010			
D0770235	2004			
B1872152	1996			
B1472094	2004			
D1471060	2007			
B2870205	2008			
D0571605	2003			
2070454	2002			
B1800239	1980			DINGS ON BOTH ENDS
B0570405	2009			
D0172720	1989			
B1572806	2011			
B2670815	2011			
D01471595	1997			
B2170474	2013			
B2670455	2012			
B1270245	2012			
B1371653	2001			
D0870637	2000			
-L2266595	2019			
B1271743	2011			
B2073203	2009			
B1471265	1997			
D0870427	1999			
B0670219	2015			
D0571602	2004			
D0770844	2007			
B2770199	2013			
B2670851	2010			
B0871109	1989			
D0571086	2002			
B1372458	2008			
D1471234	2002			
D0870452	1996			
XXX70305	2009			ILLEGIBLE 11
B2873032	2009			
B0172206	2008			
B1273206	2006			
B2670951	2011			
B2670722	2006			
B1872798	2002			
B0872492	2002			
-L2266571	2017			
B0472393	2007			
D0571015	2000			
-N2001685	2005			SECOND S/N: -A1164589
B0772699	2010			
B1571813	2011			
D1371367	2002			
D1371195	2006			
B1970007	2008			
D2070821	2002			
B1372740	2011			
D1571369	2004			
B2070766	2009			
B1472068	2009			
B2078282	2010			
B1970772	2011			
B0571058	2000			
B0772336	2008			
B0773207	2008			
B1871607	1997			
B1872228	2008			
D1470534	2003			
B2851178	2010			
B1972373	2007			
B2170442	2002			
D1472462	2009			
B1472097	2005			
B0172098	2010			
B174098	2005			
D0171794	2004			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
B2771060	2010			
B0772214	2008			
B1872425	1992			
B1670781	2009			
B2070705	2007			
B0772690	2005			
D1370820	2004			
B671365	2008			
B1372913	2008			
B2770554	2001			
D0569273	2001			
B0472377	2013			
B2770591	2004			
B0670629	2012			
B2772533	2015			
B1972621	2014			
D1371372	2006			
B1370855	2007			
B0673176	2011			
B0472883	2008			
B1600417	1973			
D0570402	2010			
B1800362	1995			
B1571810	2012			
D1571305	2003			
B1271590	2004			
B2070495	2009			
B1872411	1996			
B1672340	1995			
B1872060	1989			
D0172059	1986			
D1370819	2007			
B2872297	2011			
B1571857	2011			
B1800195	2000			
D0771026	1999			
B2871329	2012			
B1800605	1994			
B1870462	2005			
B0670436	2011			
B1872119	2011			
B0573262	2009			
B1171650	2008			
B0571317	2010			
B1570665	2009			
B1972471	2007			
B2671892	2008			
B0170735	2012			
D0571682	2005			
B1871659	1986			
B2671324	2008			
D0670961	1982			
B9671597	2005			
B1172227	1999			
B1571223	2008			
B1272848	2004			
B1472717	1994			
B1572525	2011			
B0771334	2012			
B0670449	2005			
B0472694	2009			
B0472422	2010			
B2572381	2015			
B1472155	2009			
X1170168	2000			ONE END DINGED UP
B2570554	2009			
D0171224	1993			
B2771694	2009			
B2870429	2014			
B2570291	2008			
B1170197	2003			
B0571681	2011			
B0770818	2012			
A3071713	2007			
B2770598	2003			
B1171566	2008			
D0171022	2004			
A5072433	2009			
A2273426	1974			
D0172742	2006			
B1871502	1996			
B1672399	2010			
B1800341	1994			
B0870100	1960			
A2470129	2007			
B0470388	2009			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
D0171515	2000			
-L226659	2013			
D0570977	2005			
D1170344	2004			
D0770295	2004			
B0573040	2008			
B0470744	2004			
D0871392	2006			
D0670118	2003			
B2772453	2009			
B0471440	2009			
B1800789	2008			
-L226551	2018			
B2571908	2008			
A2173082	2008			
B0572822	2011			
B2770720	2003			
42170659	2007			
B2570777	2012			
D0172693	1999			
B1470662	2004			
D0770675	1999			
D0172859	1972			
B0575563	2008			
B27703188	2004			
B0171607	2009			
43172766	1999			
B1970675	2004			
B1372178	2009			
D1471045	2003			
B0170635	2008			
B0570182	2010			
B0170991	2012			
B2871354	2014			
B1572231	2006			
B1872528	2000			
D1471843	2008			
B1800579	1972			
-L226656	2018			
B1872247	2005			
B2570565	1999			
B1172425	2007			
B2770160	2008			
B0873184	1997			
B0171838	2010			
D1371188	2006			
11568845	2001			SECOND S/N: -00362238
B1970949	2011			
D1270670	2001			
B1970307	2004			
B2572169	2008			
B1271594	2008			
B2671218	2008			
D1471225	2003			
B19872177	1999			
B1871303	2012			
B2073052	2007			
B047075	2010			
A3072106	2000			
B0470518	2010			
B1970769	2013			
B1970923	2011			
A1873288	2006			
-K2663043	2008			
B1572345	2011			
B1271003	1999			
B2072661	2007			
1170196	2007			
B1572088	2012			
B1572948	2014			
B1970666	2006			
B1471116	2007			
B2570844	2012			
B1572878	2012			
B1571211	2009			
B2571995	2009			
B2773051	2011			
B1971720	2010			
B2770698	2011			
B1171288	2001			
B2776676	2005			
B1871598	1972			
B0771448	2006			
D0770254	2002			
B1871563	2004			
B1471591	2005			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
-D0362267	2000			SECOND S/N: L1569038
B2672288	2003			
D087352	1996			
D0171279	2003			
B0770119	2015			
B1872505	1991			
D1370839	2006			
B1573150	2014			
B1872078	2001			
B2770952	2006			
A7570541	2008			
B0572109	2008			
B2870203	2009			
B1172476	2006			
XXX70273	2009			ILLLEGIBLE 12
B0472338	2008			
0017-097	2000			
B1271537	2004			
B2770994	2005			
D017154	2001			
B2770853	2011			
B1571100	2001			
B1472088	2013			
B0871915	1992			
B01171930	2005			
B0472767	2008			
D1171505	2006			
B1970070	2012			
B1472756	1995			
B2070467	2011			
B2571944	2011			
-D2565319	2007			
B2076771	2011			
B1970665	2008			
B2070459	2005			
B0872104	2001			
D1170865	2005			
B2770973	2010			
B2171415	2011			
B1971379	2012			
B1871506	2004			
D1471004	2006			
B0870243	1970			
B0472196	2011			
B1371007	2005			
B1470749	2007			
B0672442	2010			
B0474436	2010			
B0572892	2011			
-L2268404	2023			
D1370282	2000			
B1171827	2008			
B0170950	2013			
B0172949	2011			
B0771840	2001			
-D026223	2000			
D0870492	1995			
D1171563	2005			
B2771355	2009			
-D0362251	2001			
D0871383	1997			
B1470376	2002			
B2771354	2008			
B1472639	2008			
B1971734	2007			
B1800859	2000			
B1800881	1983			
-L2266559	2015			
B1800743	1983			
B1171231	2003			
B1573161	2015			
A2670279	2007			
-L226511	2016	8.419	1.082	
D1171537	2005			
B1X7X192	2014			ILLEGIBLE 13
B1972034	2010			
B2570252	2009			
B1800466	1993			
B0471778	2017			
-L2266596	2019			
B2770576	2005			
B2071445	2011			
D0470485	2008			
B1471161	2008			
B2570251	2010			HAS AIR POCKETS IN AL
B1972558	2012			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
D1271114	1999			
B17572088	2010			
B0872277	1989			
B1800645	1994			
B0771452	2008			
B2070724	2013			
a2971808	2012			
B2772462	2004			
B2773285	2011			
B0871730	1980			
B1271446	2008			
B0870748	1983			
B2772476	2011			
B0471366	2006			
B1872489	2002			
B2171478	2013			
B2771099	2008			
D0172622	1998			
B1572810	2013			
B254x215	2008			
A2171753	2010			
B0571484	2004			
A3173084	2010			
B1471101	2008			
B2070751	2009			
B01673098	2012			
B0571916	2013			
B2770239	2001			
B2571923	2006			
D0172743	1991			
B2670275	2012			
B2070185	2008			
B137129	2004			
D0172174	2001			
B0172589	2005			
B0871205	2011			
D0172864	2001			
B1672074	1993			
B0771793	2012			
B1972479	2006			
B1470827	2006			
B1472099	2007			
B28727896	2004			
B2671628	2009			
b2771524	2013			
D0173052	1998			
D1271137	2006			
B2772426	2004			
B2670005	2019			
B2671487	2014			
B1800676	1973			
B0470105	2009			
B2771762	2004			
B2872287	2014			
B0870189	1963			
B0771047	2016			
B1800855	1994			
D1370286	2004			
D0172587	1995			
D0672069	2002			
B2070799	2009			
D0553558	2001			
-L2266532	2016			
B2873019	2004			
B0171141	2010			
D1871785	2001			
D1571127	2002			
B1272480	2009			
A2971858	2005			
B1970724	2005			
B1572264	2013			
B2871132	2015			
B2772207	2009			
-L2285112	2017			
B1270564	2009			
D0670586	2003			
B207010X	2014			
B0872913	1994			
D1271188	2011			
B1572298	2017			
D1270864	2005			
B0870826	2010			
B2771710	2011			
B1372436	2009			
D0171205	2007			
B1170362	2006			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
B3872522	2004			
B1478129	2010			
B2571926	2009			
B1270838	2015			
B1172196	2007			
B1572851	2011			
B2770382	2007			
B0873264	2004			
B1800679	2013			
B2871911	2009			
B1800403	1997			
B1472842	2008			
B2772470	2007			
D1170008	2003			
B1871388	1991			
B0770670	2015			
B0171518	2013			
B1472136	2006			
B2171501	2012			
B0873208	2007			
B0671683	2012			
B2772877	2006			
B2070868	2005			
B2870082	2009			
B0870148	1995			
D0172134	2006			
D1470821	2008			
B2570234	2009			
D0871381	1991			
-L2205196	2017			
B1471347	2006			
B2073055	2011			
B1472932	2008			
-L2205133	2016			
B1971729	2006			
B2873087	2009			
B1472516	2015			
D0470712	2006			
B2873057	2005			
B0471156	2008			
-L226652	2021			
D1371327	2007			
B2571582	2009			
B2870417	2007			
D1471061	2007			
-L2266597	2020			
B1672667	2001			
D0870605	2004			
B0172814	2004			
B1272178	2014			
B2770732	2011			
D1271374	2006			
B0770721	2017			
B1970717	2014			
B2270268	2004			
B1472040	2012			
D0670426	2000			
B1800427	2000			
A3071944	2008			
A2570294	2010			
D0670407	2007			
B1272547	2009			
-N1364X7	2015			
B2773225	2014			
D0570708	2011			
D1370601	2004			
D1671409	1994			
B1800768	1987			
B1572600	2013			
B2572255	2011			
B1172134	2013			
B2870216	2010			
B2570126	2010			
D0172871	1996			
-N2283325	2010			
D0770535	2007			
D1271164	2004			
D1371359	2008			
B2570474	2011			
B1970625	2006			
B1472656	2012			
B2771795	1997			
-L2266585	2015			
B2570547	2006			
B2872952	2006			
B1472076	2008			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
D0870477	2003			
B0571436	2011			
B2872809	2008			
B2671402	2008			
B2773082	2013			
B0871460	1984			
B2770959	2008			
B0170183	2011			
XXX70879	2010			
D0870494	1989			
B0472347	2013			
-L2266567	2019			
B0670985	2009			
B0172013	2009			
XXXX831	2010			
B2670862	2008			
B0572522	2012			
B2670824	2015			
B1570165	2015			
B1872236	2003			
B0672559	2011			
B0672931	2011			
B2570200	2015			
B0570928	2008			
B0770888	2013			
h1570661	2012			
B1571413	2002			
B2070575	2010			
B1972549	2012			
B2670754	2011			
A2571528	2012			
B012741X	2010			
B1371332	2011			
B0872379	2002			
B2771461	2005			
B2570447	2011			
B171413	2008			
A0571912	2011			
B2771469	2007			
B2672001	2004			
B2171578	2008			
B1371841	2008			
D0671085	2004			
B1871302	2011			
X2770678	2001			
D1470193	2006			
SB2070444	2011			
B2171508	2011			
B1473067	2013			
D1471254	2003			
B0571250	2009			
B1800320	1995			
D1371102	1989			
D0172857	1963			
B2070752	2012			
B0870304	2001			
B2072993	2010			
B2073231	2007			
B0472557	2012			
B0570446	2010			
B1871101	2005			
D1371310	2002			
B0672606	2013			
-L2366692	2004			
B2873062	2006			
B2770710	2012			
B0671027	2004			
B2572820	2010			
B2571999	2011			
B1571822	2011			
B2673232	2015			
B2171513	2012			
B1471147	2011			
B0771040	2001			
B2572315	2019			
B1970882	2006			
B1572232	2011			
D1570196	2008			
-L2166100	2007			
D3070880	2011			
D1570119	2004			
D1370119	2004			
D1370639	2004			
B2770632	2003			
B2870280	2001			
D0871706	1984			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
B0572342	2011			
A2270545	1996			
-L2265158	2016			
B2770166	2009			
B1272979	2011			
-L2266577	2019			
B0871521	1993			
B1371598	2008			
B0471697	2008			
B2770174	2011			
B07171300	2006			
B207148	2017			
B1871122	2000			
B1600993	1985			
B0772541	2013			
D0171082	2005			
B1871910	1986			
B2570576	2009			
B1371785	2010			
B2670328	2009			
B2870613	2008			
D0071317	2006			
D0470883	2004			
B2670736	2015			
B0871716	2002			
B1571497	2002			
B0671847	2015			
B2571961	2012			
B0670425	2008			
B1471151	2010			
B2070466	2009			
B2772799	2015			
B2572909	2010			
B0770544	2008			
B1872426	1994			
B207271X	2009			
B2672026	2011			
D1470876	2006			
B0571091	2007			
B0971361	1997			
-L1562740	2008			
B2673249	2014			
B0372004	2012			
D2071440	2004			
B0871611	1999			
B2671057	2011			
B2770198	2012			
D1872930	2000			
B1270259	2013			
A3071217	2008			
B2770793	2007			
D1371397	1995			
B1172080	2007			
B1272308	2013			
B1571029	2007			
B1472230	2007			
B1978340	2012			
D1371084	2006			
B2170475	2013			
B187249X	2004			
B2773061	2009			
B2271533	2007			
B0572751	2011			
B2572146	2012			
B0570374	2012			
A3770535	2008			
-L2265117	2017			
B2070790	2005			
D1370241	2005			
B1170668	2006			
K1951338	2026			
B1372442	2011			
B1471130	2012			
B2872040	2013			
-L2266500	2016			
D0670516	2007			
A1472904	2018			
B2070180	2011			
B1570943	2016			
B1873162	2000			
B1872223	1996			
-D026603	2000			
B2872919	2007			
B2573224	2019			
-D2565355	2004			
D1471226	2006			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
B1570410	2013			
B2572950	2013			
A3071645	2011			
B2507X0	2009			
D2172246	2011			
D1371343	2006			
A3170605	2011			
B2570796	2014			
D1470641	2007			
B1570254	2008			
-L0165209	2000			
D0870468	1984			
B2770485	1999			
B0370412	2012			
B4XX0274	2012			
B2771430	2011			
B2673333	2014			
D1370214	2003			
B2671482	2008			
-D0302282	2000			second label: -001x0015
B1571636	2011			
B2770154	2002			
D1270675	2005			
B1471934	2011			
D1470894	2007			
B2270001	1991			
B1800467	2000			
B2872500	2011			
B1571585	2001			
B1371172	2013			
B1371880	2008			
B0473136	2012			
B2572812	2009			
B2070484	2010			
B0172818	1981			
B1972136	2008			
A3172792	2010			
A2971876	2011			
-D1865331	2015			
D0871390	1993			
B2873006	2008			
D1471215	2003			
B1471846	2012			
D0870471	2004			
K1951816	2024			
B0672447	2007			
B18X2612	2001			
B1371115	2007			
X0470278	2007			
B2771220	2008			
B1572609	2015			
B0670346	2004			
B134XX41	2009			
B1300158	2004			
B2572366	2017			
B0472131	2011			
B1971968	2011			
D0172178	2004			
B1271947	2009			
B0770939	2010			
B1471814	2011			
B0570826	2007			
B0X72635	2006			
B0473135	2008			
B4871920	1999			