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 subcritical 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	\mathbf{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

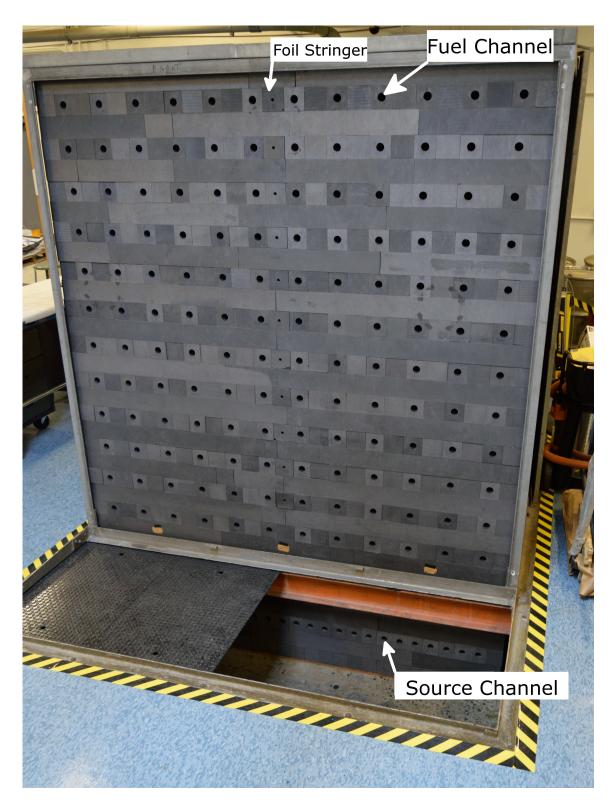


Figure 2.1: The north face of the Graphite Exponential Pile with the covers removed. Half of the floor grates have been removed to show the source channels as well. The fuel channels will normally be filled the uranium fuel slugs. The foil stringers in the center of the pile can be removed and loaded 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: \pm 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: $\pm 2^{\circ}$ [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]
$ ho_{Al}$	$2.7 \frac{g}{cm^3}$ [19]
N_A	6.0221415×10^{23} [20]
M_U	237.98[21]
$ ho_U$	$18.702 \frac{g}{cm^3}$
$ ho_t$	$15.77 \frac{g}{cm^3}$
X	0.8169
V_U	$103.9cm^{3}$
$mass_U$	1.94 kg
Т	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

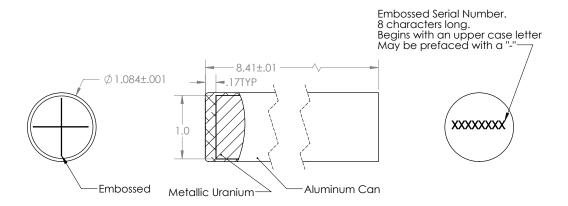


Figure 2.3: The design of the Uranium fuel slugs used in the MGEP. The values shown are nominal and are not universal.

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.

$${}^{115}In + {}^{1}_{0}n \rightarrow \begin{cases} \gamma_{1} + {}^{116m}In \\ \gamma_{2} + {}^{116}In \end{cases}$$
 (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.

$$C = \eta N_0 \int_{\lambda t_1}^{\lambda t_2} e^{-u} du$$

$$C = \eta N_0 \left[-e^{-u} \right]_{\lambda t_1}^{\lambda t_2}$$

$$C = \eta N_0 \left(e^{-\lambda t_1} - e^{-\lambda t_2} \right)$$
(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.

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

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

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

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

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

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.

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

$$-\nabla \cdot D\nabla \phi(x, y, z) + \Sigma_a \phi(x, y, z) = \nu \Sigma_f \phi(x, y, z)$$
(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.

$$\nabla^2 \phi(x, y, z) + B_m^2 \phi(x, y, z) = 0$$
(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.

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

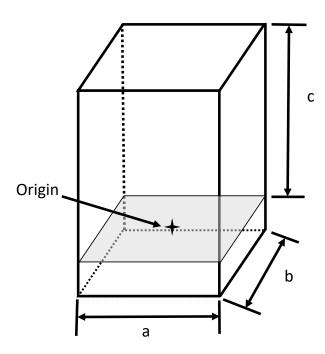


Figure 3.1: The geometry used for the diffusion model. the origin is centered in x and y and located on the plane of the bottom of the lattice. X is aligned with a and Y with b.

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.

$$\Phi(x) = A\cos(Fx) + B\sin(Fx) \tag{3.31}$$

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.

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

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

$$\theta(z) = C\cosh(\gamma z) + D\sinh(\gamma z) \tag{3.38}$$

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

$$\theta(c) = 0 = C\cosh(\gamma c) + D\sinh(\gamma c) \tag{3.39}$$

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

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

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

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

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

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

$$sinh(x - y) = sinh(x)cosh(y) - cosh(x)sinh(y)$$
(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.

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

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.

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

$$(3.46)$$

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.

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

$$(3.49)$$

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:

$$B_q = B_m (3.52)$$

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 $3\frac{1^n}{2} \pm \frac{1^n}{8}$ from the north face. For channels with 4 slugs they were pushed to be $28\frac{3^n}{4} \pm \frac{1^n}{8}$ 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	В	С	D	Е	F	G	Н	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 $\pm 1/8$ ".

Layer	East	West	Offset
11	О	О	
10	F	О	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 $14^{\rm th}$ 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.

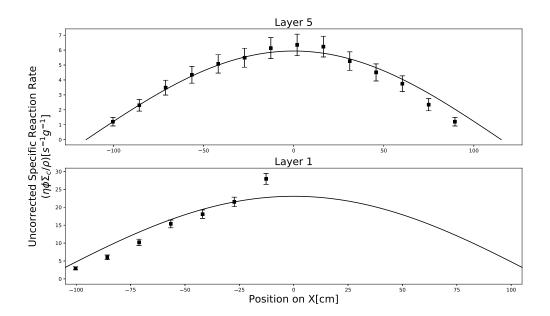


Figure 5.1: The uncorrected specific reaction rate radial profiles for the MIT graphite Exponential pile with a full loading of fuel. The data are uncorrected since the detector efficiency was not included in the calculations, however all measurements used the same detector set-up. On Layer 5 a full 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	
$\gamma_{1,1}$	$0.01621 \ cm^{-1}$	
$R^{\gamma_{1,1}}$	0.944	
B_m^2	$107.9 \times 10^{-6} cm^{-2}$	
B_m	$0.01039 \ cm^{-1}$	
\mathbf{s}	5.24m (206")	

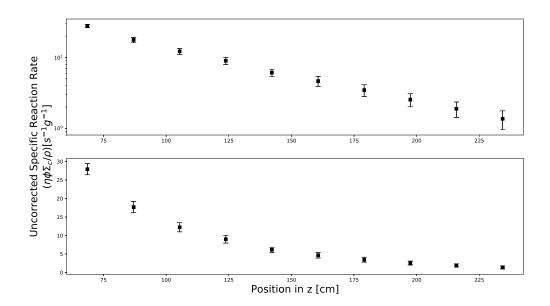


Figure 5.2: The uncorrected specific reaction rate rate axial profile as measured from foil position 7, which is just east of center($x\approx-12\text{cm}$). The detector efficiency was not factored into these calculations, however the same detector setup was used for all measurements. The axial profile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

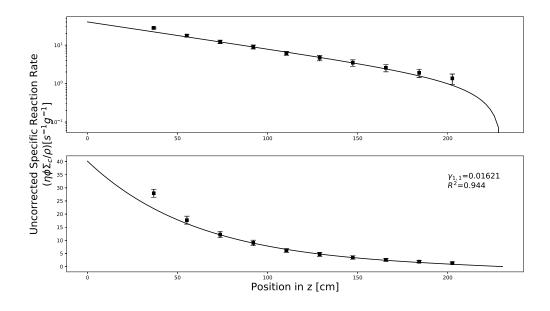


Figure 5.3: The axial reaction rate profile with the $\gamma_{1,1}$ regression super-imposed on the plot. The regression is the least accurate near the source, which is to be expected as the higher modes have not died out at that distance yet. Due to these higher harmonics the first two data points were 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
В	0.95	0.0096	0.7511
С	0.95	0.0092	0.7380
D	0.95	0.0096	0.7485
Е	0.95	0.0099	0.7492
F	0.95	0.0096	0.7607
G	0.95	0.0095	0.7508
Н	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
О	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
Т	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	
В	5	2	-85.725	0	110.49	5/7/2018 10:30	
С	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	
Е	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	
Н	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	
О	1	1	-100.33	0	36.83	5/7/2018 15:23	
Р	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	
Т	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 AA	5/7/2018 11:28 5/7/2018 13:30	5/7/2018 11:30 5/7/2018 13:32	48 199	9 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 AB	5/7/2018 14:08 5/7/2018 14:28	5/7/2018 14:10 5/7/2018 14:30	94	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
В	5/7/2018 10:38	5/7/2018 10:40	221	9	10
B B	5/7/2018 10:56 5/7/2018 11:13	5/7/2018 10:58 5/7/2018 11:15	151 120	9	10
В	5/7/2018 11:13	5/7/2018 11:13	94	9	10
C	5/7/2018 10:40	5/7/2018 10:43	302	9	10
Č	5/7/2018 10:58	5/7/2018 11:00	228	9	10
С	5/7/2018 11:15	5/7/2018 11:17	168	9	10
С	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 D	5/7/2018 11:18 5/7/2018 11:35	5/7/2018 11:20 5/7/2018 11:37	221 181	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 11:40	5/7/2018 11:25 5/7/2018 11:42	247	9	10
G	5/7/2018 11:40	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
Н	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 I	5/7/2018 13:09 5/7/2018 12:14	5/7/2018 13:11 5/7/2018 12:16	258 439	9	10
I	5/7/2018 12:14	5/7/2018 12:16	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 12:09	5/7/2018 13:06	210	9	10
K K	5/7/2018 12:09 5/7/2018 12:26	5/7/2018 12:11 5/7/2018 12:29	351 307	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 5/7/2018 12:24	183	9 9	10
M M	5/7/2018 12:22 5/7/2018 12:39	5/7/2018 12:24 5/7/2018 12:41	152 153	9	10
M	5/7/2018 12:39	5/7/2018 12:41	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
О	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)
0	5/7/2018 15:45	5/7/2018 15:47	198	9	10
0	5/7/2018 16:02	5/7/2018 16:04	145	9	10
О	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
Т	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
Т	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
	5/1/2010 14:00	5/1/2010 14.00	110	L V	10

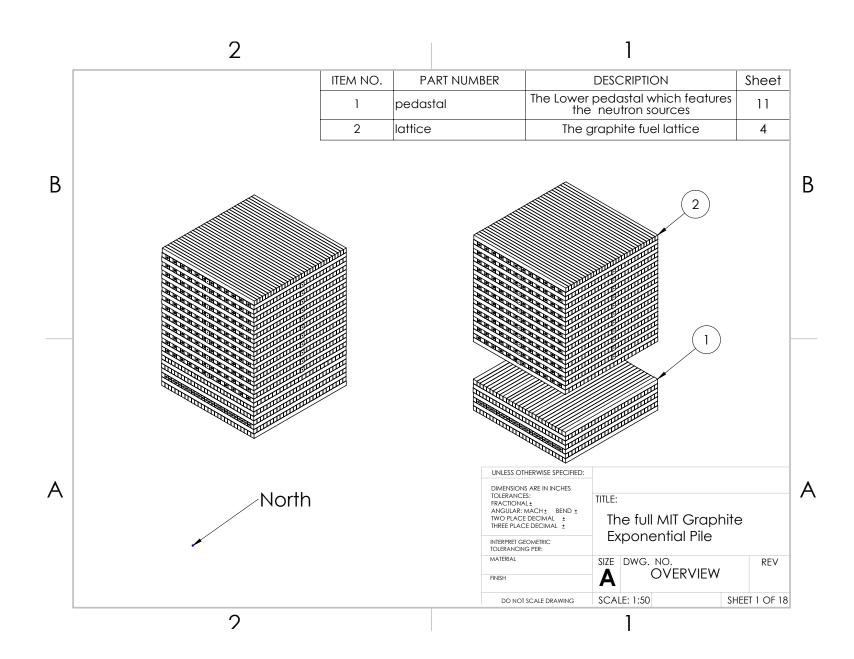
The data above were entered into an Office Open XML (Excel) spreadsheet, which was then parsed and analyzed by a script written in Python3. The interpreted data of the uncorrected activity, and specific reaction rates are presented in table A.4.

Table A.4: Interpreted Activity Data

Layer	X po-	Y po-	Z po-	Net Counts	Uncorrect- ed Initial	Uncorrect- ed Specific	Standard Deviation
	[cm]	[cm]	[cm]		Activity [Bq]	$ \begin{array}{c} \mathbf{Reaction} \\ \mathbf{Rate}[g^{-1}s^{-1}] \end{array} $	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	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
В	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

В

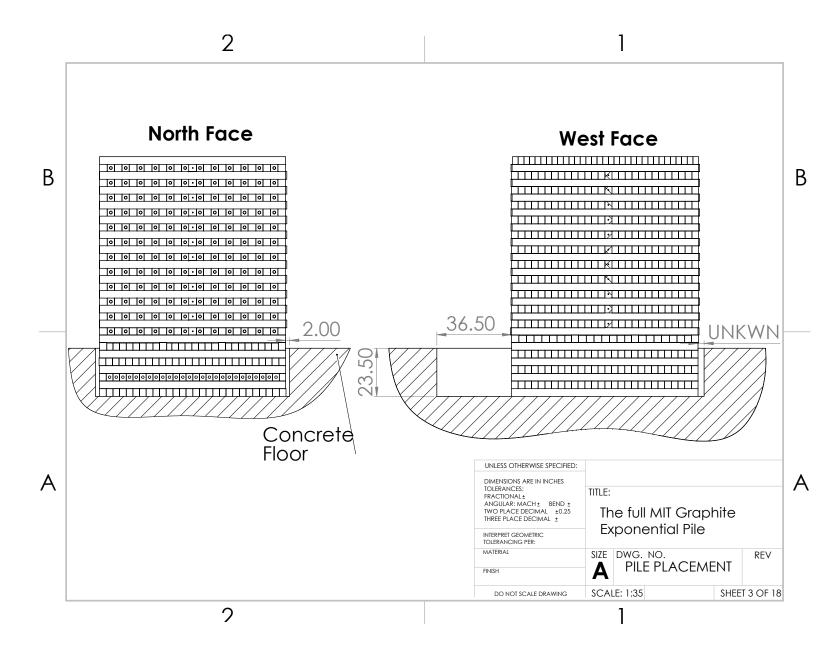
Α

- 3. Within 0.010" of flat for whole surface
- 4. Perpendicularity vary by <0.010" in 4"

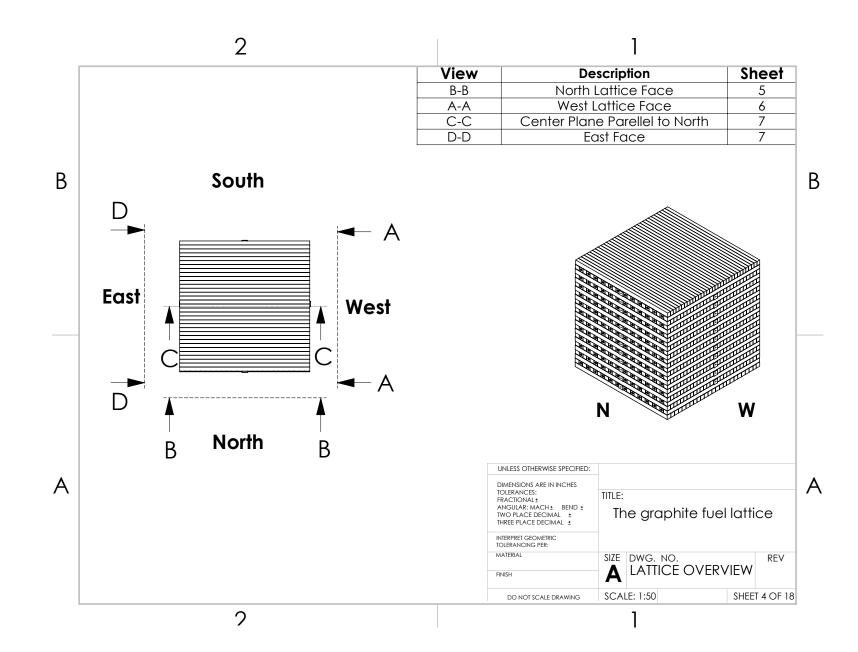
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± TITLE: ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±0.010 The full MIT Graphite **Exponential Pile** INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL SIZE DWG. NO. REV A BILL OF MATERIALS FINISH SCALE: 1:25 SHEET 2 OF 18 DO NOT SCALE DRAWING

 $\stackrel{\smile}{\sim}$

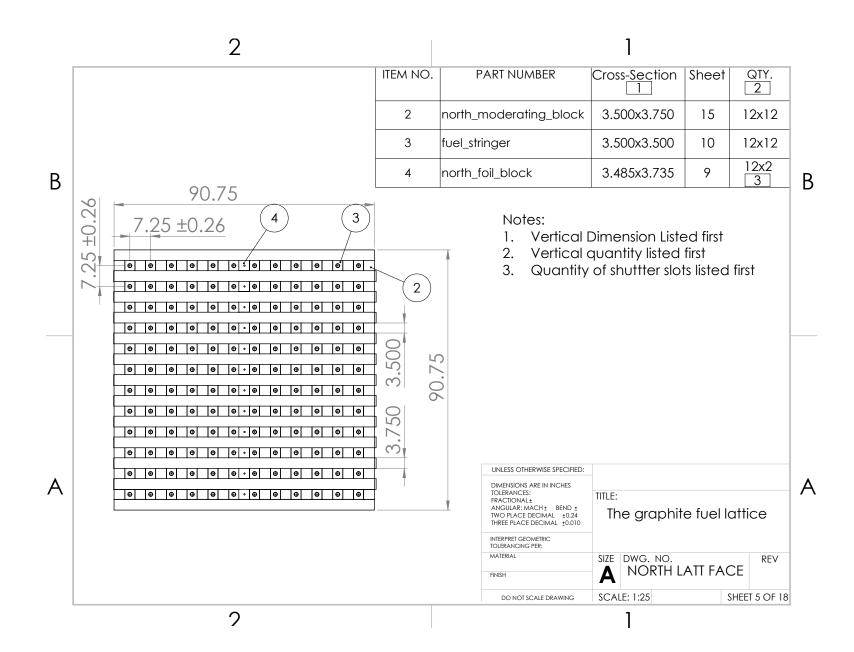
7

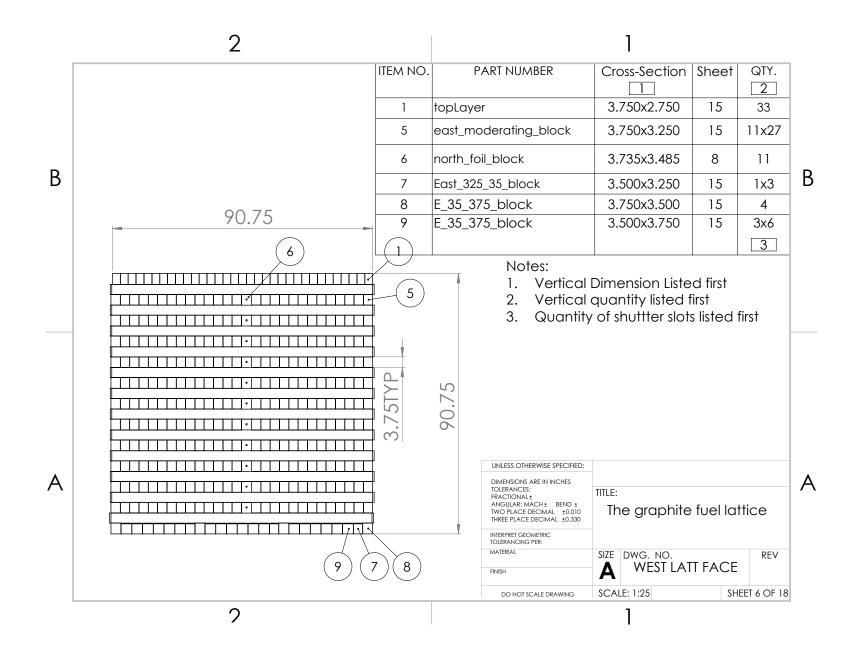




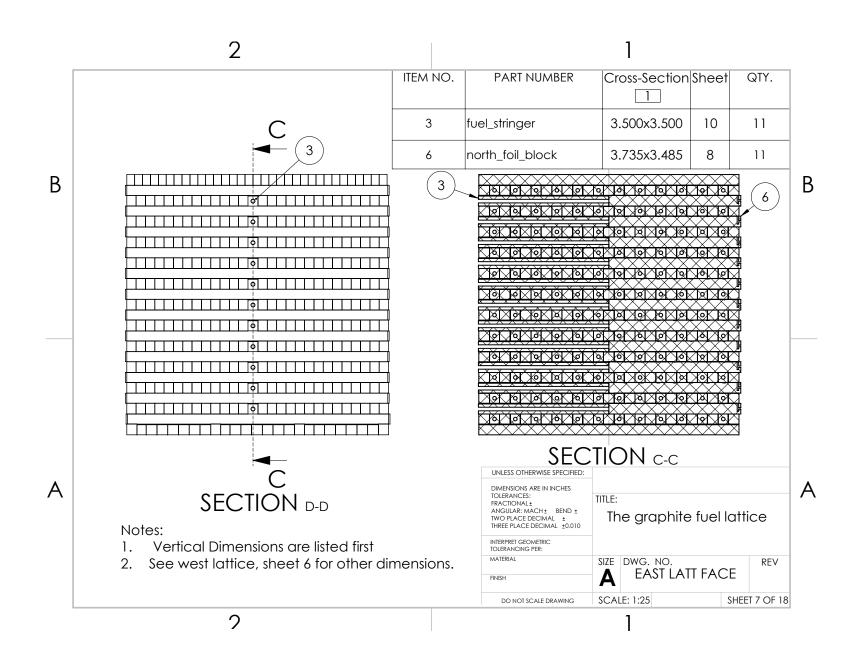


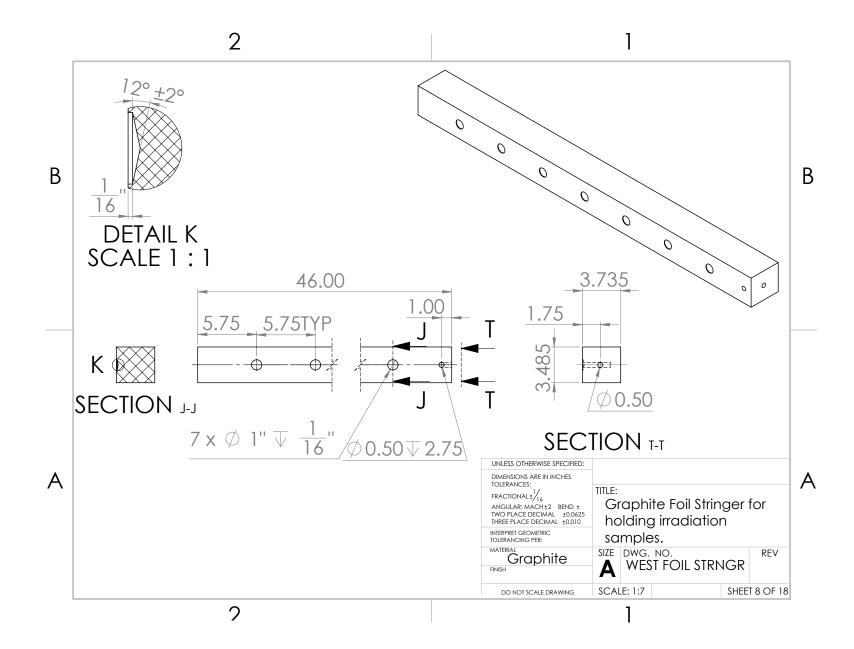


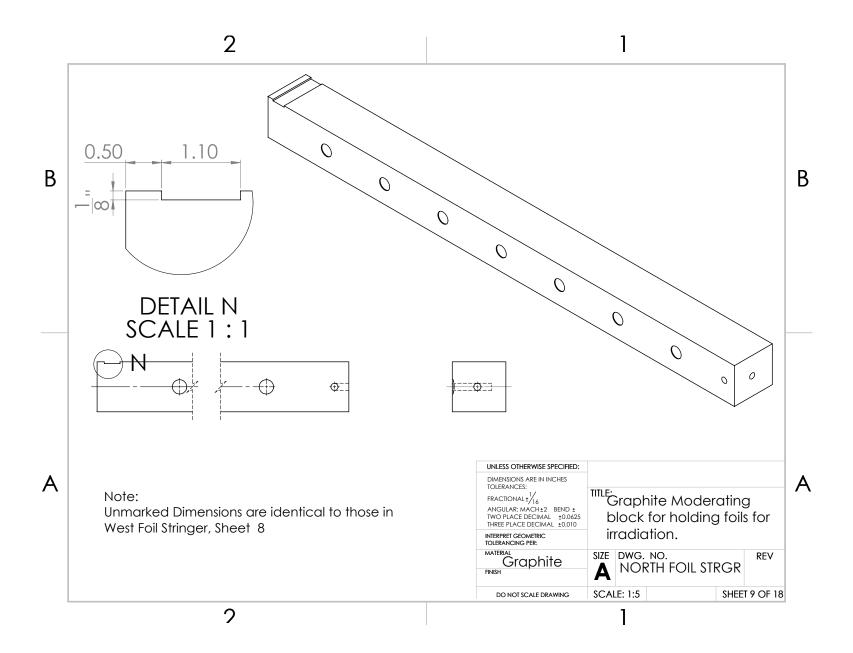


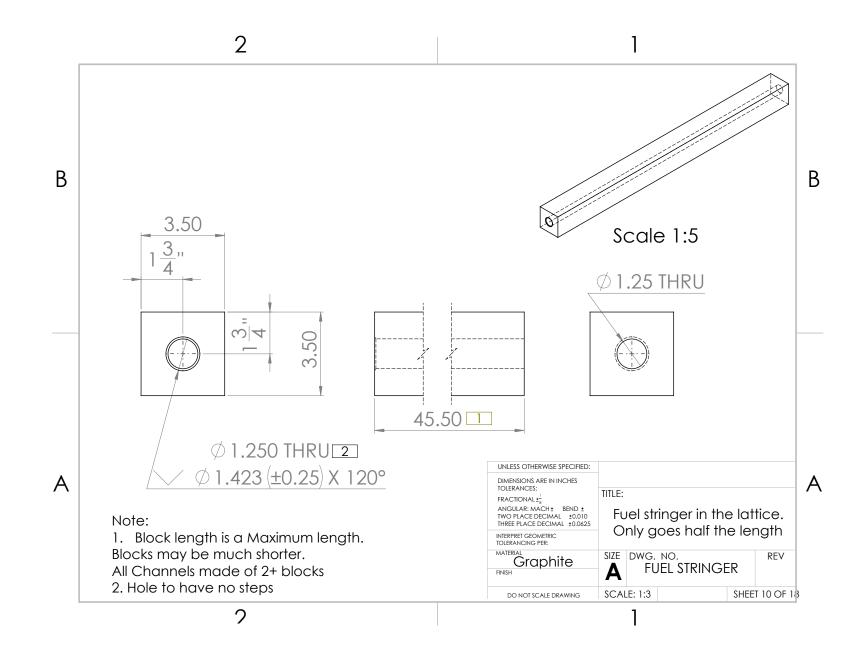




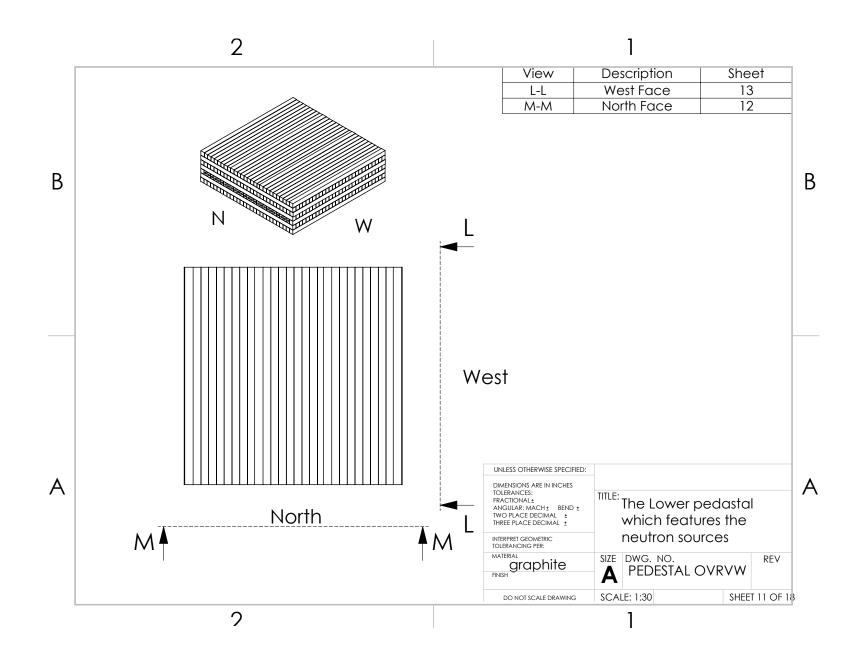




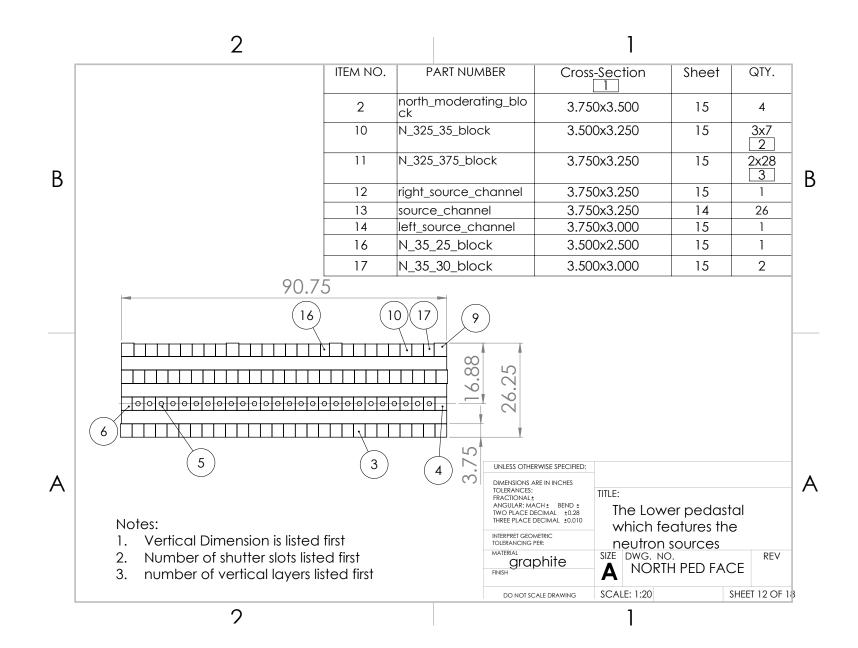


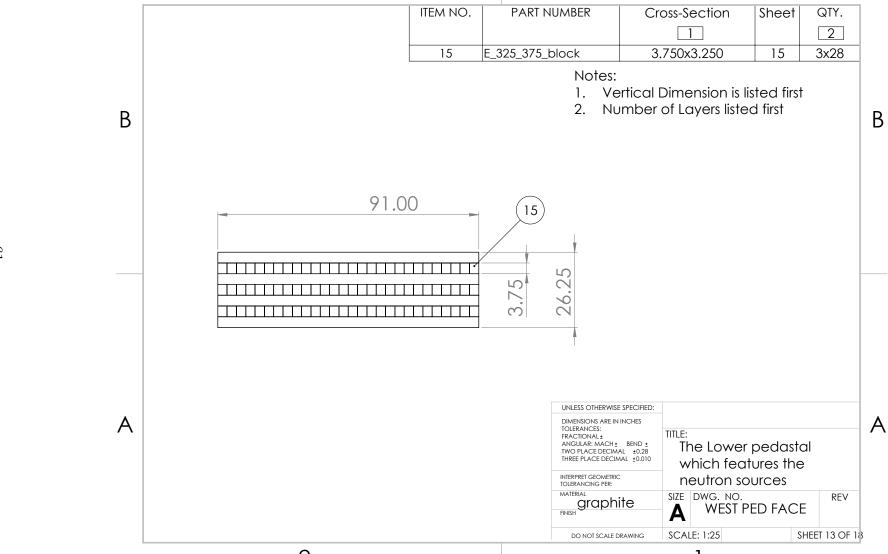






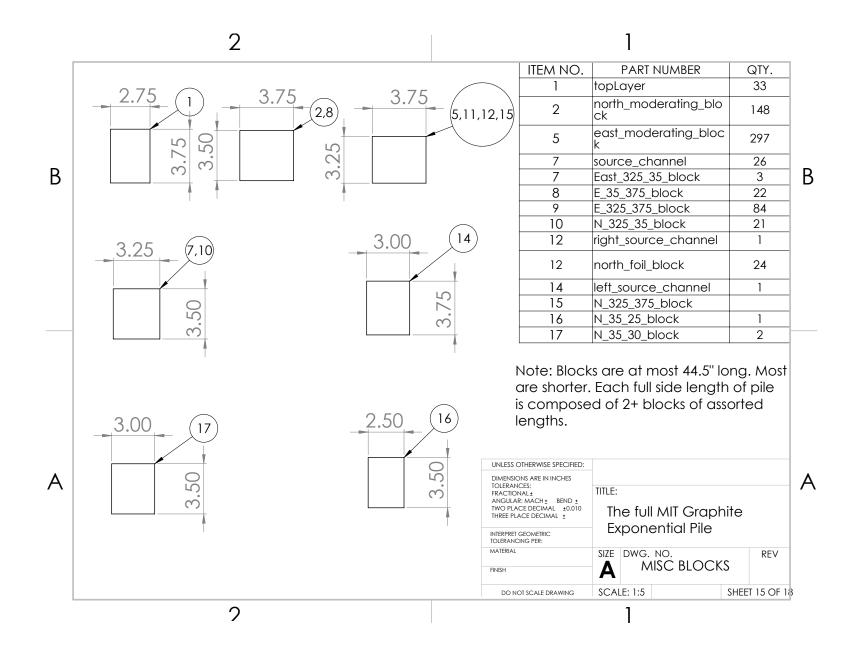




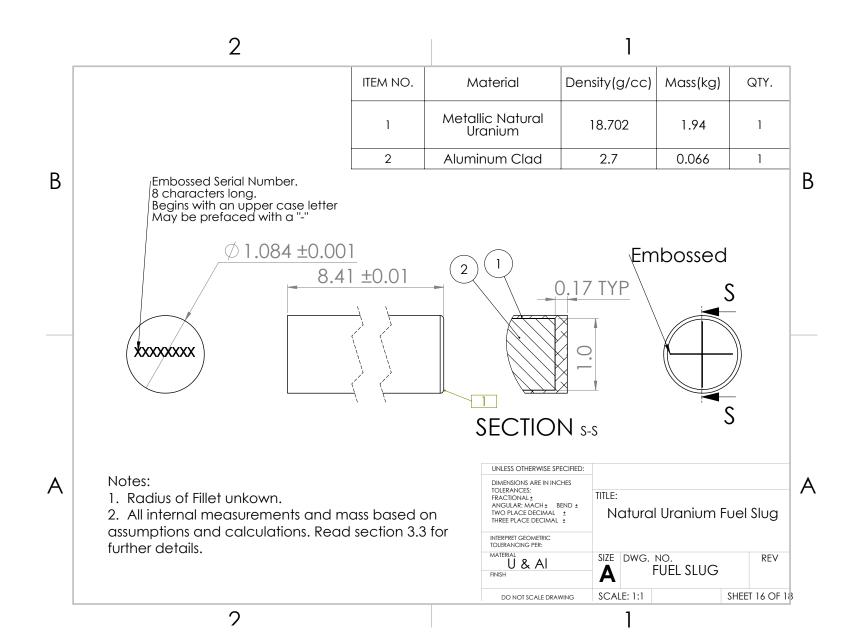


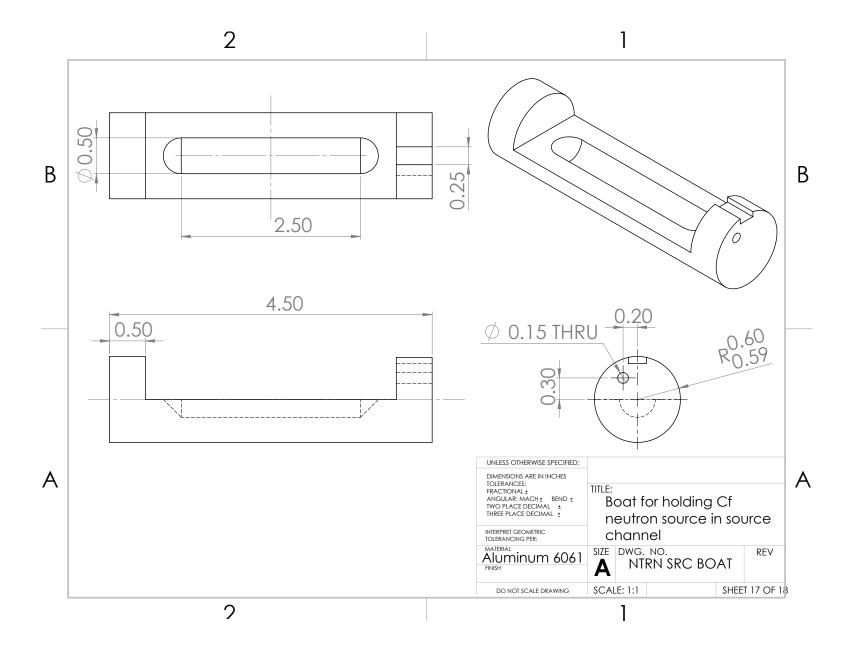
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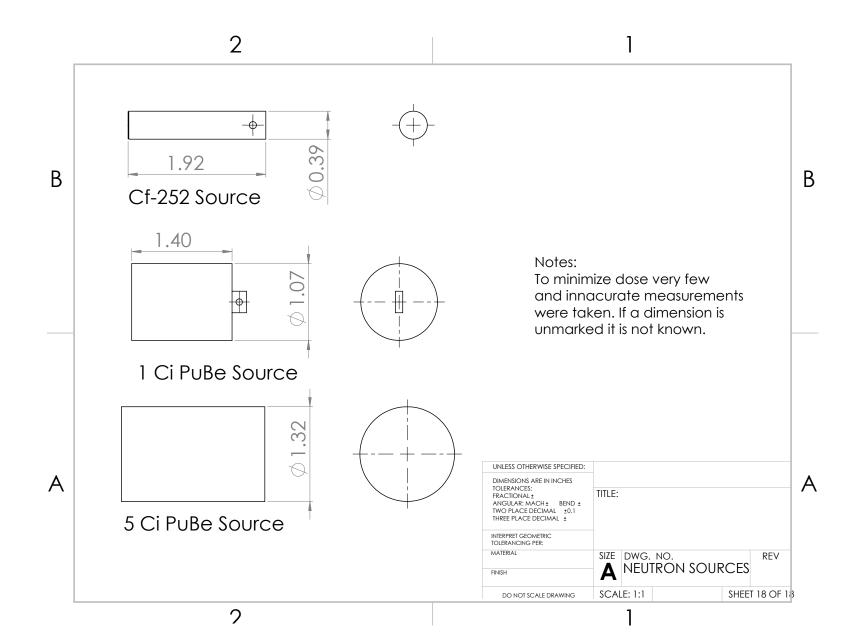












Appendix C

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)	$\overline{\mathbf{NAA}}\ 1\sigma$ 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
Со	< 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
Се	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 36 per pound, while the going market price is 41-446 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 ALC 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 36 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: LJM

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

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, 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:

P	Lace				£	LADE	2		Amo	punt
Bay		l	x	12	2 :	x 24	+ cl	nunks	6	pallets
Bay	D	4	X	3	K	30	or	better	20	pallets
Bay								shorter	7	pallets
Bay	E	4	X	3	X	30	or	better	10	pallets
Bay	E.	do	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 1b. 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

THE

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:

, we are pleased to In reply to your inquiry Dec. 15, 1955. 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		
В	1000 or over	Special Notes: See attached sheet which is a part of this quotation.	3,10 each		
		Above Prices F. O. B. Shipping Point Cleveland, Ohio.			

Estimated Shipping Date 800 pcs. in 4 to 6 wks. after 30 days net - no cash discount subject to confirmation upon receipt of receipt of stock Terms_ order. If earlier delivery is required, please on factory. Bal. at 800 pes. Limits Item A - wd. & thk. plus/minus.010 advise this office. plus 1/8 minus 0. *Prices are subject to change to Seller's standard prices in per wk.

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

Item B - wd. & thk. plus/minus .010"

Massachusetts Institute of Technology, Cambridge, Mass.

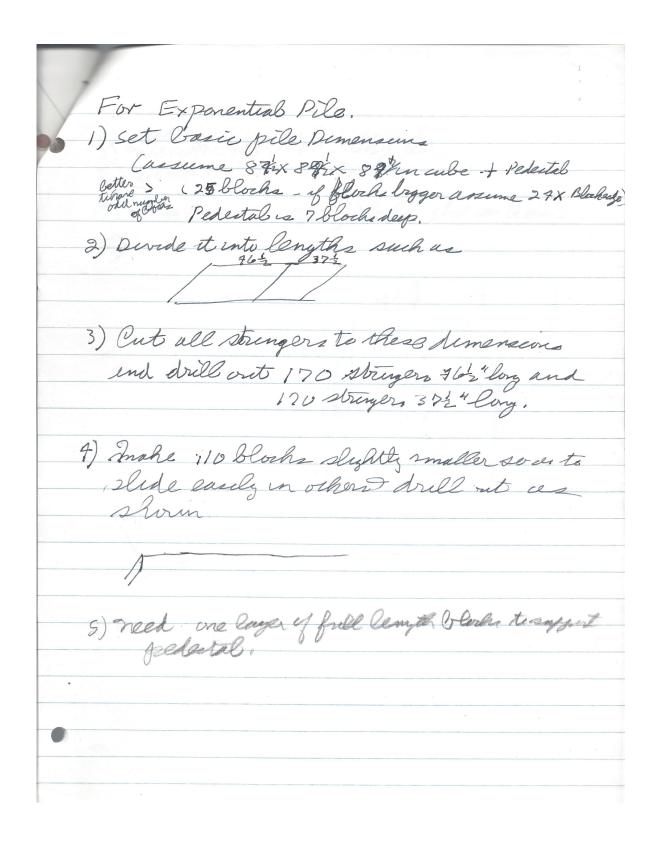
NE-5-2195- Revised

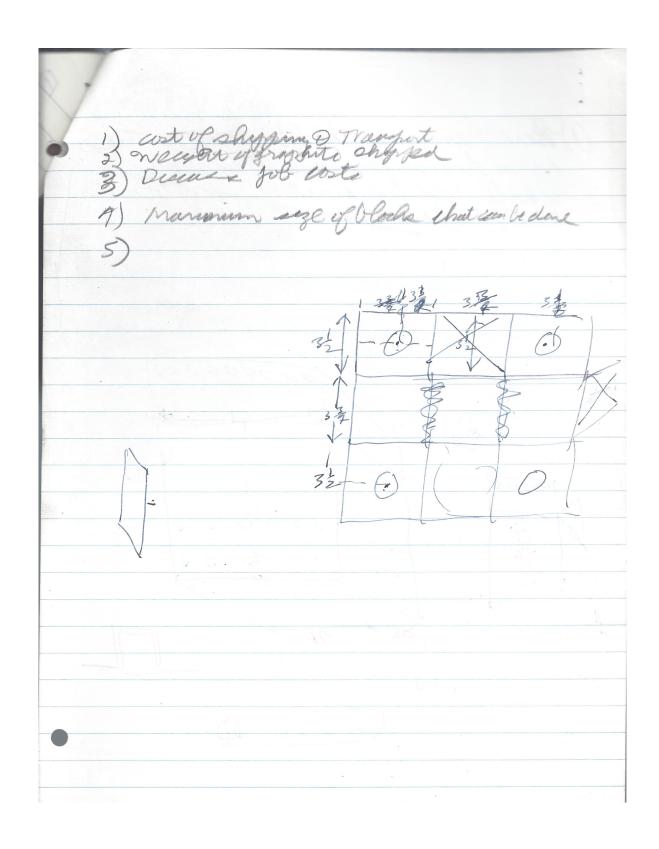
- 1. If Item A is ordered with Item B the price will then be \$523,00 lot, net for Item A.
- 2. Prices are based on customer supplying sound AGHT stock. 110 pieces of 49* length or over to be segregated by M.I.T. for manufacture of Item A. The balance of stock will be of miscellaneous lengths from 24* 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 49th long it will be necessary to mill to end in order to obtain 48th 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 MeI.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

Estimate of Cost of Graphite Machining April 23, 1956 Machining 340 blocks with holes at \$5.23 block Machining 3500 pieces at \$3.10 per piece Shipping costs at \$1.10/100 pounds 1,585.92 (134,400 pounds at \$1.18 ewt to Cleveland) Shipping costs - Cleveland to Gambridge (96,000 pounds at \$1.09/ewt) TOTAL \$15,260.52					File	
Estimate of Cost of Graphite Machining April 23, 1956 Machining 340 blocks with holes at \$5.23 block Machining 3500 pieces at \$3.10 per piece Shipping costs at \$1.10/100 pounds (134,400 pounds at \$1.18 ewt to Cleveland) Shipping costs - Cleveland to Cambridge (96,000 pounds at \$1.09/ewt) TOTAL \$15.260.52		45 "		M. Dimole.	MITA	1 00
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Machining 340 blocks with holes at \$5.23 block Machining 3500 pieces at \$3.10 per piece Shipping costs at \$1.10/100 pounds (134,400 pounds at \$1.18 ewt to Cleveland) Shipping costs - Cleveland to Cambridge (96,000 pounds at \$1.09/cwt) TOTAL \$15.260.52	NAV	April 2	3, 1956			
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Machining 3500 pieces at \$3.10 per piece Shipping costs at \$1.10/100 pounds (134,400 pounds at \$1.18 ewt to Cleveland) Shipping costs - Cleveland to Cambridge (96,000 pounds at \$1.09/cwt) TOTAL \$15,260.52						
Shipping costs at \$1.10/100 pounds 1,585.92 (134,400 pounds at \$1.18 cwt to Cleveland) Shipping costs - Cleveland to 1.046.40 Cambridge (96,000 pounds at \$1.09/cwt) TOTAL \$15.260.52	Machini	ing 340 blocks with he \$5.23 block	oles); ge	\$ 1,778	.20	
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Shipping costs - Cleveland to 1.046.40 Cambridge (96,000 pounds at \$1.09/cwt) TOTAL \$15.260.52	Shippin (:	ng costs at \$1.10/100 134,400 pounds at \$1.3 Cleveland)	pounds 18 ewt	1,585	.92	
(96,000 pounds at \$1.09/cwt) TOTAL \$15.260.52 T. J. Thompson	Shippin	ng costs - Cleveland		1.046	.40	
T. J. Thompson	G	mbridge 6,000 pounds at \$1.09	9/ewt)			
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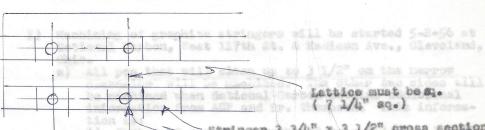
D.6 Letter to George A. Anderson on updated plans for graphite machinig

S. V. Nicastro 5 months. George A. Anderson MIT File 56 Jic May 1. GRAPHITE MACHINING (MIT REACTOR) Machining of graphite stringers will be started 5-2-56 at National Carbon, West 117th St. & Madison Ave., Cleveland, a) All pes 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 pes to be machined to a 3 1/2" x 3 1/2" Dis. of cylind cross section (all the long pes should be used for 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"). Maximum chip allowable on edges of stringer 1/4" deep x 1/2" LO. CHIP 1/10 dia, hole chumber butt ands (Do not use a grinding wheel. Use a steel cutting tool for machining graphite.) Finish of graphite stringer surface ok, as shown 4-30-56 III) to ACF representative and Dr. Thompson when they visited the Mational Carbon Company. . . . Souare off both ends? (Last operation) (VI V) Platness: The stringers will be flat within 10 mils (com-paring the upper face of the stringer lying on an optical flat, with the optical flat, by means of a gauge). The sides of the stringers will be perpendicular and not vary from the perpendicular by more than 10 mils in 4 inches. Length of stringer - if ACF decides to have them cut to a set length. Representative from ACF will notify National Carbon. (See IV) VII)

File

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

IX) Exponential Piles:



Dia. of cylinder to be (Stringer with holes 3 1/2" x 3 1/2") placed in these holes is (cross section, 2 1/4" dia. holes) 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

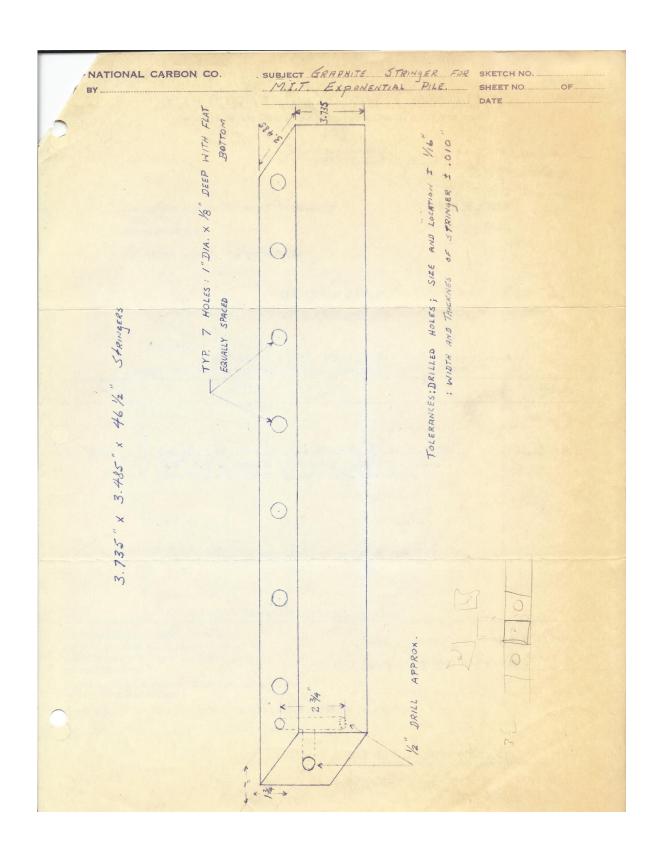
- b) Holes to have no step and to be centered plus or minus
- c) Removable stringer (Dr. Thompson) | 1000000 100000
 - X) Packing must be road dust proof.
- XI) Obtain Bill of Lading. (Last operation)
- XII) National Carbon would like to quote on stacking resetor graphite and cutting all necessary holes.
- VI) The sides of the atringers will be perpendicular and not vary from the perpendicular by more than 10 mils in h

S. V. Nicastro

VII) Length of stringer * if ACF decides to have them out to a set length. Representative from ACF will notify Hatlonal Carbon. (See IV)

${\bf D.7} \quad Quotation \ NE 6\text{-}1286 \ for \ Graphite \ Foil \ Stringer$

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Atte	ention - Prof. T.J. Thompson	ONDITIONS O		
L	ler will furnish articles of its	se specified herein. Sel		
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We thank you for	your inquiry and shall be pleased	to receive your order. Very truly you	ırs,	
		NATIONAL (CARBON COMPAN	Y CORPORATION
T.J. Foulk jsm		Ву	J. Jany	(.



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



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.

For the special pieces required by ACF and MIT a total of 940 long stringers are needed. These are split into 440 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 (31 × 34 × 465 should be prepared as sample containing pieces for the exponential as per the sketch supplied earlier by National Carbon. with their land of Many 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

Mr. H. N. Townser 28, 1956

of 3 1/2" x 3 3/4". Apparently, none 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.
- (h) 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 $3 \frac{1}{2}$ x $3 \frac{1}{2}$ 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 $3 \frac{1}{2}$ x $3 \frac{1}{2}$ 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

Mr. H. N. Townsend 3-3- June 28, 1956

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

MIT Graphite Machining, Trip to National Car-D.9 bon Co., Cleveland, Ohio, July 10,1956

Nuclear Energy Products Division MITR prophite

QCf INDUSTRIES

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

(Aside to ACF: In to 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 levest port. Briefly, the MEMORANDUM entire thermal column should still be made from 3-1/2"

x 3-1/2" stock.)

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:

ne to from shorts length pieces. (Made from the stores with a sinisum length of any 1 pieces (12° ± 2° s) Example: one po. 34 "

One end only on these blocks will be trimmed. X 24-1/2 long.

(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 and of the hole as required. The pieces should be made from 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), (5), (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%.

of those pieces may be 3-3/6" x 3-1/4". S. V. Nicastro one end and tapered as 12 (2).

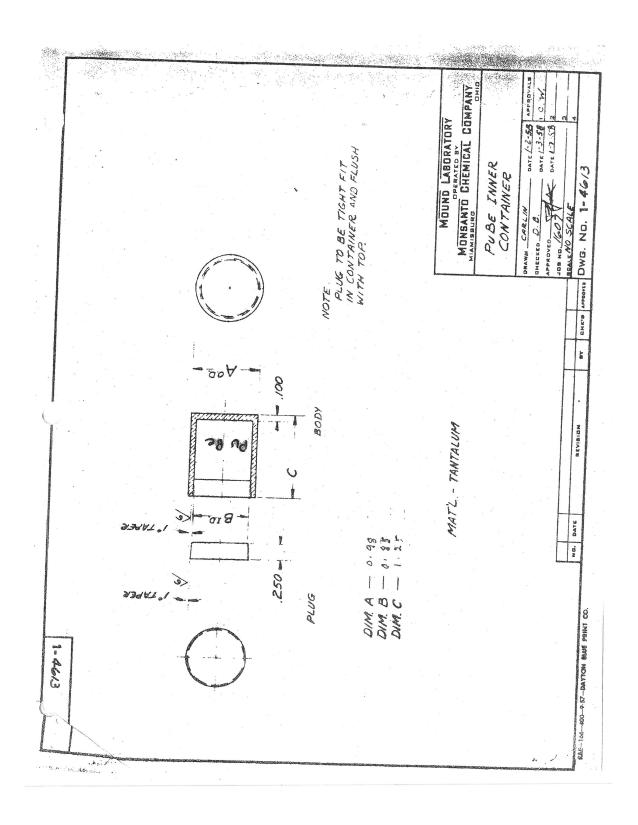
ec: Dr. T.J. Thompson
G.A. Anderson
E. Barnett

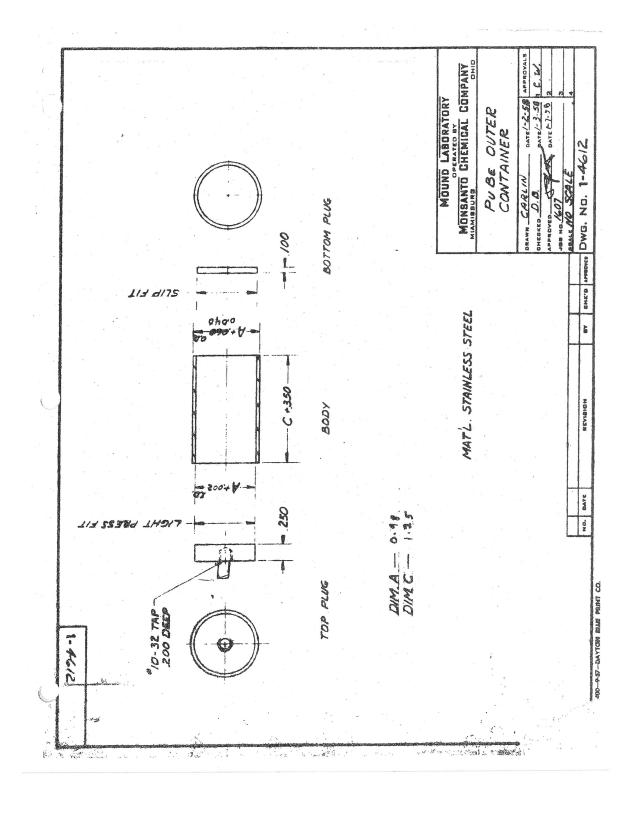
D.10 Work Order 6711-5: Shipping Data: Plutonium Neutron Source

0-582 Rev 1-29-59 SHIPPING DATA
PLUTONIUM NEUTRON SOURCE

MONSANTO CHEMICAL COMPANY

		Work Order 6711-5 Mound Laboratory Miamisburg, Ohio
Professor T. J. Thompson		August 4, 1961
Department of Nuclear Engineeri Massachusetts Institute of		Railway Express
Technology	VIA	GA-6456
Cambridge 39, Massachusetts	YOUR P.O. No.	
	LICENSE No.	SNM-81
	SS ALLOTMENT QUOTA No.	7000
EUTRON SOURCE No	WITHDRAWN FROM	SBX-3101
. TYPE OF SOURCE - PuBe		
GRAMS OF BE - 7.92		
GRAMS OF PU. 16.03		
CONTAINER MATERIAL Tantalum and stainles	s steel	
, dimensions of container - inside - $_{ m cont}$	7" O. D. x 1.40"	
. METHOD OF SEALING . WELDED		
NEUTRON EMISSION . 1.63×10 ⁶ N/SEC		
TOLERANCE DISTANCE IN AIR FOR 8 HOURS - 21 (BASED ON \$\frac{36}{8}\text{ n/sec/cm}^2\) 55 SHIPPING CONTAINER IS A PARAFFIN-FILLED	INCHES	
SOURCE(S) IS IN A SLOT AT THE BOTTOM OF A PARAFFIN-FI	ILLED TUBE WHICH MAY BE LIFT	ED AFTER REMOVING THE SEALED
		Recanned
	E	No Charge
PLUS COST OF S	HIPPING CONTAINER	
	TOTAL	
MARKS: EDUCATIONAL THE TITLE TO THE PLUTONIUM USED IN THIS SOURCE REMAINS WITH THE ATOMIC ENERGY COMMISSION.	cc: Professo	r T. J. Thompson
		J.L. Richmond E. E. W.





Appendix E

Data Analysis Scripts

E.1 Data Parser And Plotting Script

data/foilDataParser.py

```
#!/bin/python3
       Copyright 2018 Micah Gale
      Permission is hereby granted, free of charge, to any person 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, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom the Software is furnished to do so, subject to the following conditions:
      The above copyright notice and this permission notice shall be included in all copies or substantial portions of the Software.
     THE SOFTWARE IS PROVIDED "AS IS", WITHOUT WARRANTY OF ANY KIND, 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.
23
       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
40
       class foilExper():
42
               A class for parsing foil activation excel filesi @param Name- the filename of the .xlsx file
43
45
                      f __init__(self, Name):
self.book=xlrd.open_workbook(filename=Name)
self.foil=''
46
48
49
50
51
52
53
54
55
56
57
58
                       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)
 61
                             maxR= sheet.nrows #get the number of rows massCol=foilExper.findColumn(headers, 'Mass') foilCol=foilExper.findColumn(headers, 'Foil')
 62
 63
 64
 65
                             thickCol=foilExper.findColumn(headers, 'Thickness')
 66
 67
                             self.foil={}
 68
                             for i in range(1,maxR):
    #add all of the foil masses to the dictionary
 69
70
71
72
73
74
75
76
77
78
79
80
                                    #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
 81
 82
83
                     #finds the columns which are desired.
 84
                      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')
 85
86
 87
 88
 89
 90
 91
                     end=sheet.nrows
 92
 93
                     #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,
 94
 95
 96
97
                                                   sheet.\,cell\,(i\,,countCol\,).\,value\,,sheet.\,cell\,(i\,,bgCol\,).\,value\,,sheet.\,cell\,(i\,,bgTimeCol\,).\,value\,)
 98
 99
                                    #add the counts to the appropriate foil
self.foil[sheet.cell(i,foilCol).value].addCount(buffer)
100
              Parses the position data. Adds foils to appropriate positions.
              def parsePosition(self):
                      sheet=self.book.sheet_by_name('PositionData')
header=sheet.row(0)
106
                      foilCol=foilExper.findColumn(header, 'Foil
                     layer Col=foilExper.findColumn (header, 'Layer')
posCol=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]')
108
109
112
114
                     #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
119
120
                                    layers.append(cell.value)
123
                     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)
124
126
128
130
                                    #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
136
                                    Z=sheet.cell(i,zCol).value
138
                                    #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
140
141
142
                                     else:
143
                                            #otherwise just pop the appropriate foil onto the stack
                                            self.positions[layer][pos].addFoil(self.foil[foil])
144
145
146
              Parses the start time for the experiment.
147
148
              def parseStart(self):
                      palsectal DAY_TO_SEC sheet=self.book.sheet_by_name('ExperimentInfo')
149
```

```
header=sheet.row(0)
152
153
                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
155
156
157
           Automatically parse all data
158
159
           Runs:
           parseFoils()
           parseCounts()
162
           parsePosition()
           parseStart()
163
164
165
           def parse (self):
166
167
                self.parseFoils()
self.parseCounts()
168
                self.parsePosition()
169
                self.parseStart()
          Pulls out the radial specific reaction rate data for a layer
172
173
          @param layer the layer to examine
@return (pos,flux,sigma) Pos=position in x data
    flux=specific reaction rate
174
176
177
178
                sigma=uncertainty
179
          def getRadData(self,level):
180
                row=self.positions[level] #pull out underlying dict
size=len(row)
181
182
                pos=np.zeros (size)
183
                flux = np.zeros(size)
184
                sigma=np.zeros(size)
185
186
                pointer=0
187
                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
188
189
190
191
                                 pos[pointer]=val.X
ret=val.calcSpecRxRate(self.start)
193
                                 flux [pointer]=ret[0]
194
                                 sigma[pointer]=ret[1]
195
                     pointer=pointer+1
except NameError: #if uninit have no data and don't care
196
198
199
                return (pos, flux, sigma)
200
201
202
203
          Plots the radial specific reaction rate for a given level
204
205
          @param level the level at which to do the radial traverse @param fileName the fileName to which to save the pdf do not include \paramale
206
207
208
           extension
                          the subplot object. This allows you to combine plots on a
209
          @param ax
210
                figure
          @param font the font specification for the axis labels
<https://matplotlib.org/api/matplotlib_configuration_api.html#matplotlib.rc>
211
212
          @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
213
214
215
216
217
          @param title the title for the plot. Useful for combined plots
          \begin{array}{lll} \textbf{def} & \texttt{plotRadial(self, level,ax,fileName=None, font=\{'family': 'normal', \\ \end{array} \\ \end{array}
219
                      'weight': 'normal',
'size' :18},save=True,xAxisLabel=True, yAxisLabel=True,title=''):
222
223
                ret=self.getRadData(level)
224
                flux=ret[1]
226
                sigma=ret [2]
228
                ax.errorbar(pos, flux, yerr=sigma, fmt='s', color='k', capsize=5)
                #add labels
230
                if (xAxisLabel):
                     ax.set\_xlabel("Position_{\sqcup}on_{\sqcup}X[cm]", **font)
231
                233
234
235
236
238
                     plt.savefig(fileName+'.pdf')
239
240
          Gets the axial spec, reaction rate data for a specific position.
242
```

```
244
         @param position the radial position to use
         @return (pos, flux, sigma) pos=axial position in z flux=spec reaction rate
245
247
                  sigma=uncertainty
248
249
         def getAxialData(self, position):
             size=len(self.positions)-1
pos=np.zeros(size)
flux=np.zeros(size)
250
251
253
             sigma=np.zeros(size)
255
256
                  key, val in enumerate (self.positions): #iterate over the things
                  if(val!={}):
    if(val[position].getCounts()>0):
        pos[pointer]=val[position].Z
258
259
260
                            ret=val[position].calcSpecRxRate(self.start)
flux[pointer]=ret[0]
261
262
                            sigma [pointer] = ret [1]
264
                            pointer=pointer+1
265
266
             return (pos, flux, sigma)
267
268
269
         Plots the axial specific reaction rate for a given position
270
         @param level the level at which to do the radial traverse
272
         oparam fileName the fileName to which to save the pdf do not include
273
         extension
274
                       the subplot object. This allows you to combine plots on a
         @param ax
             figure
         Oparam font the font specification for the axis labels
276
         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
280
         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
281
283
284
         def plotAxial(self, position, ax,fileName=None, font={'family':'normal',
                     weight': 'normal',
    'size' :18},save=True,xAxisLabel=True,
    yAxisLabel=True,logLog=False, title=''):
286
287
289
290
             ret= self.getAxialData(position) #gets axial data
291
              flux=ret [1
292
293
             sigma=ret[2]
294
295
             #plot it!
296
              ax.errorbar(pos, flux, yerr=sigma, fmt='s', color='k', capsize=5)
297
              #turn on or off log-log
              if (logLog):
                  ax.set_yscale('log')
             # ax.set_xscale('log')
#add x-label
300
301
              if (xAxisLabel)
                  ax.set_xlabel('Positionuinuzu[cm]',**font)
303
304
305
             #add the y-label
              if (yAxisLabel):
306
                  307
308
309
              ax.set_title(title, **font)
311
              if (save):
                  plt.savefig(fileName+".pdf")
312
314
315
316
         Creates a csv table for viewing raw interpreted data
317
318
319
         @param fileName the fileName to dump the data to
320
         def writeTable(self, fileName):
             322
325
328
329
330
                            for key2, pos in layer.items(): #iterate over all positions
331
                                X=pos.X
332
                                 Y=pos.Y
                                 Z=pos.Z
                                 counts=pos.getCounts()
334
```

```
I0=pos.calcN0()
                                           rx=pos.calcSpecRxRate(self.start)
if(counts>0):
336
337
338
                                                 dumper. writerow ([key, X, Y, Z, counts, I0[0], rx[0], rx[1], rx[1]/rx[0]])
339
            Looks through the header row provided to find the desired column number
340
341
            @param header an array of the column headers
@param target the string of the column that is desired
@return the column number
342
343
344
345
346
347
            def findColumn(header, target):
348
                 i = 0
349
                 for col in header:
350
                       if(target in col.value):
351
                            return i
                       i = i + 1
353
354
                 return -1
355
356
357
      Represents an experimental Subcritical Pile
358
359
      class subCritPile():
360
361
            Creates an object which isn meant to analyze foil data for a sub-crit pile
362
363
           @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
364
365
366
367
            @param c- the height of the pile in Z above the source plane in cm
368
            \begin{array}{lll} def & \underline{\quad } init\underline{\quad } (self \,, fileName \,, a \,, b \,, c \,) \colon \\ self \,. \, data=foilExper (fileName) \ \#loads \ the \ data \ in \ self \,. \, a=a \end{array}
369
370
371
372
                  s \; e \; l \; f . b {=} b
\frac{373}{374}
                  self.c=c
375
376
            Goal function for sinh fit
378
379
            @param g the paramaters [0]A [1]gamma y=A sinh (gamma(c-x))
            @param x xvalue
@param y actual y value of data
381
382
            \begin{array}{ll} def & goalSinh \, (\, self \, , g \, , x \, , y \, ) \, : \\ & return & g \, [\, 0\, ] *np. \, sinh \, (\, g \, [\, 1\, ] * \, (\, self \, . \, c-x \, )) \, -y \end{array}
383
384
385
386
387
            Goal function for cos amplitude fit
388
389
            @param g- the paramters [0]A
390
            @param x x-value
391
            @param y y-value from data
392
            def goalCos(self,g,x,y):
    return g[0]*np.cos(math.pi*x/self.a)-y
393
394
395
396
397
            {\tt Calculates \ \backslash gamma\_\{1,1\} \ stores \ to \ self.gamma}
398
399
400
            \operatorname{gamma}[0] is amplitude of mode. \operatorname{gamma}[1] is the \operatorname{\gamma}[1]
401
402
            @param position the radial position to use
403
            def calcFundGamma(self, position):
404
405
                  {\tt ret} {=} {\tt self.data.getAxialData(position)}
406
407
408
                  pos=ret[0]
409
                  flux=ret[1]
410
                  \mathtt{pointer}\!=\!\!0
412
413
                  x0=np.ones(2)
414
                  \mathbf{x} 0 = [10, 0.02]
                   \begin{array}{ll} \text{fit= least\_squares(self.goalSinh}\;,\;\;x0\;,\;\;args{=}(pos\,[\,2{:}]\;,flux\,[\,2{:}]\,)) \\ \text{self.gamma=fit.x} \end{array} 
415
416
417
                  fitFunc=fit.x[0]*np.sinh(fit.x[1]*(self.c-pos))
418
419
420
                  ####Calculates R^2
                  yBar=np.mean(flux) #calculates mean y
421
                  SST=0 #total sum squares
SSRes=0 #residual sum of squares
422
423
424
                  for i in range(0,pos.size): #iterate over all elements SST+=(flux[i]-yBar)**2
425
426
```

```
SSRes+=(flux[i]-self.goalSinh(fit.x,pos[i],0))**2 #sum residuals
428
429
              self.R2=1-SSRes/SST#saves r^2
430
431
432
433
         Plots the axially fitted function on the given subplot
434
435
         Note: pulls out self.gamma must be invoked after self.calcFundGamma
436
         @param ax the subplot object for plotting the figure
437
         @param printGamma- will print gamma value on the figure if true
438
439
         def plotAxialFunc(self, ax, printGamma=True):
440
              x=np.linspace(0, self.c,100)
442
              if (printGamma):
                  443
445
              \label{eq:line} {\tt line} = {\tt self.gamma} \, [\, 0\, ] * {\tt np.sinh} \, (\, \, {\tt self.gamma} \, [\, 1\, ] * (\, \, {\tt self.c-x} \, ) \, )
446
              ax.plot(x,line,color='k')
448
449
450
         Calculates the Material Buckling, and the critical Reactor size.
451
452
         Note: uses self.gamma needs to be invoked after self.calcFundGamma.
453
         @return (Bm2,s) Bm2=B_m^2-material buckling, s=side length of critical
454
456
          \begin{array}{ll} \textbf{def} & \texttt{calcGeoBuckle(self,position):} \\ & \texttt{Bm2=(math.pi/self.a)**2+(math.pi/self.b)**2-self.gamma[1]**2} \end{array} 
457
459
              s=np.sqrt(3)*math.pi/math.sqrt(Bm2)
460
              return (Bm2, s)
462
463
464
465
         Fits the fundamental cosine to the data.
466
467
         @param layer -the layer to examine @return the amplitude of the fundamental mode
468
470 \\ 471
         def fitFundRadial(self,layer):
    ret=self.data.getRadData(layer) #pulls out the radial data desired
              x0 = [1] #guess 1 first
474
              fit = least\_squares \left( \ self \ . \ goalCos \ , x0 \ , \ args = \left( ret \left[ 0 \right] \ , ret \left[ 1 \right] \right) \right) \ \#fits \ data
476
              return fit.x[0] #return the amplitude
479
480
         Plots the cosine fit on the given plot.
481
         @param ax the given subplot to print on
482
         @param A the amplitude of the cosine from the fit before
484
         def plotFundRad(self,ax,A):
485
486
              487
```

E.2 Data Structures for Activity Calculations

data/dataStruct.py

```
#!/bin/python3

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```

```
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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.
  24
   26
             import math
  27
              #"constant" for converting days to seconds
             DAY_TO_SEC=86400
MIN_TO_SEC=60 #const for minutes to seconds
  29
30
  32
33
               Represents a single location in the pile. May contain multiple foils.
  35
36
               class position ():
                              Qparam foil a single foil object at this postion Qparam X position in x in cm Qparam y ""
  38
  39
                              @param v
    40
   41
                              def __init__(self,foil,X,Y,Z):
    self.foil=[foil]
    self.X=X
    42
   43
   44
    45
                                               self.Y=Y
                               self.Z=Z
   46
   47
    48
                              Appends another foil to list of foils at position
   49
50
                              @param the new foil object
   51
52
53
                              def addFoil(self,foil):
    self.foil.append(foil)
   54
55
56
                             Calculates the total initial activity here. Sums over all foils % \left( \frac{1}{2}\right) =\frac{1}{2}\left( \frac
   57
58
    59
                              def calcN0(self):
  60
61
                                             N0=0
    62
                                             {\scriptstyle \texttt{sigmaAcum} = 0}
  63
  64
                                               for foil in self.foil:
   65
                                                               ret = foil.calcN0()
                                                              N0=N0+ret[0]
  66
                                                                                                                            #accumulates the total
   67
                                                               sigmaAcum=sigmaAcum+ret[1]**2 #add std dev in quadrature
  68
                                              return (NO, math.sqrt(sigmaAcum)) #return tuple of value and std dev
  69
   70
    71
72
73
                              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 needed. See foil.calcSpecRxRate() for math
    74
75
76
                              @param startAct- the start time of the foil activation in seconds. 
 @return (rx,sigma) rx-the specific reaction rate
    77
78
   79
80
                              def calcSpecRxRate(self, start):
    81
                                              rx=0
   82
83
                                              sigmaAcum=0
                                               for foil in self.foil: #iterate over all foils
                                                             ret=foil.calcSpecRxRate(start)
rx=rx+ret[0]
   85
   86
                                             sigmaAcum=sigmaAcum+ret[1]**2
return (rx,math.sqrt(sigmaAcum))
   88
   89
                              Just gets the total number of counts at positon @return total counts detected
   90
  91
   92
   93
                               def getCounts(self):
  94
                                               sum=0
   95
                                               for foil in self.foil:
  96
97
                                                             sum = sum + foil.getCounts()
                                               return sum
   98
                                              __repr___(self):
return self.__str___()
  99
100
102
103
                               def _
                                                       _str___( self ):
                                              out=
104
                                               i = 0
                                               for foil in self. foil:
                                                              out=out+"\nFoil_"+str(i)+":_"+foil.__str__()
106
                                                             i = i + 1
                                              return out
108
```

```
Represents a single foil. Holds it properties and the counts which were taken
\frac{113}{114}
     of it
     class foil():
116
           @param mat— foil material @param thick—foil thicness
119
           @param mass-foil mass in g
120
121
                    _{\rm init} (self, mat, thick, mass):
                 self.mat=mat
self.thick=thick
                 self.mass=mass
self.counts=[] #the child counts for this dohickey
124
125
126
127
128
           Adds the end time of the foil activation.
           @param the foil activation end time in days
129
130
           def addEndTime(self,end):
    self.end=end*DAY_TO_SEC
, , ,
131
           Adds a count object to the current foil @param a completely initialized count object
134
135
136
137
           def addCount(self,count):
138
                 self.counts.append(count) #adds it to the array of counts
140
           Calculates the specific reaction rate [s^-1g^-1](\phi\Sigma_c/ \rho)
141
142
143
           @param startAct- the starting time of the foil activation in seconds.
144
                                  Not the time of the start of counting!
146
           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
147
148
149
                 divider=(self.mass*(1-math.exp(-self.decayConst*(self.end-startAct))))
multiplier=self.decayConst/divider
153
                 rx=N0[0] * multiplier
sigma=N0[1] * multiplier
156
                 return (rx, sigma)
158
159
160
           Calculates the Initial activity of the activated foil.
161
           this isn't a true activity as the detector efficiency isn't factored in. Finds \ensuremath{\setminus} eta N_O. Only gives meaningful data is the exact same detector setup is used for all foils.
162
163
164
166
           def calcN0(self):
                 #IODO 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
169
170
171
172
                 counts=0
174
175
                 {\tt denominator}{=}0
                 sigma=0
                 for counter in self.counts: #iterate overr all counting sessions #retrieves counting cotribution for counting session
177
178
                       ret=counter.getCountContribs(self.end,self.decayConst)
                       counts=counts+ret[0]
denominator=denominator+ret[2]
180
181
                       sigma=sigma+(ret[1]/ret[2])**2
                 if (counts >0):
183
                       #completes the division of the accumulated sums
184
185
                       activity=(counts)/denominator #[Bq]
186
                      sigma=math.sqrt(sigma)
e: #if no counts were taken say it was 0
187
188
                       activity=0
189
                      sigma=0
190
           return (activity, sigma)
191
193
           Gets the total counts
194
           @return the total counts detected
195
196
           def getCounts(self):
                 sum=0
198
                 for count in self.counts:
199
                      sum=sum+count.counts
                 return sum
200
```

```
202
203
          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)
204
205
206
207
                for count in self.counts:

out=out+"\nCount_"+str(i)+":_"+count.__str__()
208
209
210
211
                return out
213
     Represents a single counting session for a single foil.
214
\frac{216}{217}
218
           Creates a new count object representing one contiguous counting session.
219
          221
222
223
          ©paramm bgCounts— number of background counts

@param bgTime—length of background counting in minutes. Will convert
224
225
                                  to seconds
226
227
          def ___init___(self,start,end,counts,bgCounts,bgTime):
    global DAY_TO_SEC
    global MIN_TO_SEC
228
229
230
231
                self.start=start*DAY_TO_SEC
self.end=end*DAY_TO_SEC
bgTime= bgTime*MIN_TO_SEC #converrts bg time to seconds
232
233
234
235
               \frac{236}{237}
238
                #calculates std dev
239
                \#s_{\text{net}} = sqrt(s_n^2 + (s_bg*t_cn/t_bg)^2)
240
                ##this simplifies to:
#s_net=sqrt(C_n+C_bg*(t_cn/t_bg)^2)
241
242
                self.sigma=math.sqrt(
243
                           float (counts+bgCounts*((self.start-self.end)/bgTime)**2))
244
245
          246
248
249
251
252
253
          returns the data necessary to combine the counts to get an activity term
255
256
          The formula used is:
          \label{eq:normalized} $$N_0=(Sum(counts)*lambda)/(e^(-lambda*t_1)-e^(-lambda*t_2))$$ @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)
258
259
260
261
262
           def getCountContribs(self,endAct,decayConst):
263
264
265
                #(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)
266
267
```

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	

B0770725				Notes
	ass (g) I 2014	ength (in) 8.410	Diameter (in)	itoles
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	1.083	
B2570267	2014	8.431	1.084	
B2673275	2014	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. Com-
				pletely decontaminated by RP
B1271623	2004			alpha contamination. Taken from J4. Com-
				pletely decontaminated by RP.
xxx72496	2002	8.422	1.082	marked illegible 3
B2670940	2009	8.416	1.085	Ŭ . · ·
B0671319	1989	8.423	1.086	1
-L226514	2019	8.425	1.085	
-L2266550	2020	8.421	1.087	
B2773292	2004	8.397	1.085	
x2773228	2011	8.406	1.083	
1370992	1994	8.404	1.082	
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	2007	8.411	1.085	Franket as megible 4
D1370855 D2070815	2000	8.411	1.083	
B2671816	2004	8.411	1.085	
B2773202	2011	8.419	1.085	<u> </u>
B1572329		8.416	1.084	1
B0472594	2008	8.413	1.085	1
B0471997	2002	8.425	1.082	1
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	1
B1972932	2010	8.402	1.084	
D1571306	2000	8.436	1.083	
B2770189	2007	8.396	1.083	
B1572466	2007	8.405	1.086	
D1012400	2016	8.405	1.083	
		0.400	1.000	I.
B0170523			1 004	
B0170523 B2770526	2008	8.396	1.084	
B0170523 B2770526 -L2166534	2008 2003	8.396 8.408	1.085	
B0170523 B2770526 -L2166534 B1571808	2008 2003 2011	8.396 8.408 8.408	1.085 1.085	
B0170523 B2770526 -L2166534	2008 2003	8.396 8.408	1.085	

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
-L2266545	2019	8.417	1.082	110003
-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 B2874376	2010 2015	8.405 8.395	1.082 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 B1872358	2004 2004	8.413 8.412	1.083 1.085	
B0570448	2004	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 B207118	2011	8.413 8.420	1.086	
B207118 B27721430	2009 2011	8.420 8.411	1.083 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 B2070702	2008 2009	8.420	1.083	
B0171080	2009			
B0171080 B0173020	2003			
B0173020	2008			
B0670450	2009			
B0472429	2012			
B1870593	2006			
-L2266522	2018			
B1970420	2007			
D0171281	2001			
B2570443	2011			
B2070184 B1372056	2015 2006			
B077136	2009			
B19771335	2009			
B0472349	2012			
B072220	2011			
B0473129	2008			
2570186	2011			
B1872418	2001			
B1171806	2009			
B2870634 D1570113	2008 2004			
D1471015	2004			
-L226655	2021			
B2570115	2007			
D0172080	2001			
B2071938	2012			
B1970657	2004			
B1379288	2009			
D1270621 B1971310	2008 2009			
B1971310 B0770120	2009			
D0165822	2003			
D0570746	2005			
B2570468	2008			
B1773078	2006			
D1471504	1997			
B2772363	2004			
D1471002	2008			
B2670332	2015			
2670305 D0172875	2007 1985			
B1800119	1985			
B2579248	2015			
B2172238	2005			
Bxx7x552	2003			marked illegible 6
B1171105	2011			

D3979225 2006 D397925 D39792	Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
BISO0402 1995 BISO0402 1995 BISO0402 1995 BISO0300 1997 A271803 2011 BISO0300 1997 A271803 2011 BISO0300 1997 BISTO040 2000 BISTO190 2000 BIST			3 ()	,	
B1800402 1905 B271070200 2011 B17070200 2011 B17070200 2011 B2770601 2007 B1771601 2007 B1771601 2007 B1771601 2007 B1771601 2007 B1771601 2008 B1771602 2010 B1771602 2010 B1771702 2010 B1771702 2010 B1771702 2011 B1771702 2011 B1771703 2010 B17717					
D1370409 2003	B01772589	2009			
D16770306 1997	B1800462	1995			
BI S00300					
A2971893 2001					
B8272952 2009 B17776961 2007 B2771602 2010 B3771159 2011 B1872180 2000 B3771159 2011 B1872180 2000 B3771602 2000 B3771602 2000 B3771603 2000 B3771604 2011 B1772061 2011 B1772061 2010 B3772061 2011 B3772190 2000 B3771100 2000 B3772191 2000 B3772191 2010 B3772191 2010 B3772191 2010 B3772192 2000 B3772192 2000 B3772192 2000 B3772192 2000 B3772193 2000 B3772193 2000 B3772194 2000 B3772195 2000 B377220 2000 B377220 2000 B377220 2000 B377220 2000 B3772195 2000 B377220 2000 B3772					
B1271666 2007					
B2776961 2007 100					
B8071482 2010 2008 B771602 2008 B771602 2010 Color					
B0172760 2008 B3471169 2010 B1471159 2011 B1472180 2001 B1471159 2001 B1471150 2001 B1471150 2000 B3477123 2008 B777661 2011 B1770648 1999 B0173003 2007 B0173003 2007 B0173013 2007 B0173013 2007 B0173015 2010 B387221 2010 B387221 2010 B387221 2010 B387219 2014 B0170715 2004 B0170715 2000 B0171104 2000 B0171104 2000 B0171104 2000 B0171104 2000 B0171105 2000 B0171105 2000 B0171106 2000 B0171107 2000 B0171108 2000 B0171109 2000 B0171109 2000 B0171109 2000 B0171101 2000 B017110					
B3771602 2011 B1872180 2011 B1872180 2001 B1872180 2009 B20080 200					
B1471159 2911 B1872180 2001 A2970128 2009 B2671423 2008 B2671423 2008 B2671423 2008 B2671423 2008 B2671423 2008 B2671423 2008 B2671423 2009 B271464 1999 B271464 1999 B271464 1999 B271464 1999 B271464 1999 B271464 1999 B2714765 2009 B2714766 2009 B2714766 2009 B2714767 2009 B2714769					
B1872180 2001					
A2970128 2008					
B2671423 2008					
DOSTO192 2001 D1470648 1999 D1470648 1999 D1470648 1999 D1470648 1999 D1470648 1998 D1470649 D14706					
B2770648 2909 B0173003 2007 B1572192 2000 B0173010 2010 B0172488 1908 B0174488 1908 B07511100 2010 B0872221 2011 B0770151 2014 B0870251 2014 B0870251 2014 B0870251 2014 B0870151 2014 B0870762 2006 B0870763 2011 B0870763 2011 B0870763 2011 B0870763 2010 B0870643 2007 B0870643 2007 B0870643 2007 B0870644 2010 B0870648 2007 B0870648 2007 B0870648 2007 B0870648 2007 B0870648 2007 B0870648 2008 B0870648 2011 B0870648 2011 B0870648 2011 B0870648 2012 2016 B0870648 2016 B0870648 2016 B0870648 2002 was dropped on one end B0870648 2002 Was dropped on both ends B0870641 2016 B0870641 2016 B0870641 2016 B0870641 2016 B0870641 2016 B0870761 2016 B0870761 2016 B0870761 2016 B0870761 2016 B0870761 2016 B0870761 2016 B0870760 2016 B0870761 2016 B0870760 2016 B0870761 2016 B0870762 2016 B087					
D1470648 1999					
B0173093 2007					
B1572192 2000 B1573190 2010 B25732221 2010 B1573190 2014 B1573191 2014 B1577191 2004 B1577191 2009 B1577191					
B0172488 1998					
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B017140	Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
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	B1972558	2012			

Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
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B0771452	2008			
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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			
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D0172743 B2670275	1991 2012			
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B137129	2004			
D0172174	2004			
B0172589	2005			
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D0172864	2001			
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B0771793	2012			
B1972479	2006			
B1470827	2006			
B1472099	2007			
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D0173052	1998			
D1271137	2006			
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B2670005	2019			
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DOSPOLYT 2003 2007 2008 2007 2008 200	Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
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Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
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B1600993	1985			
B0772541	2013			
D0171082	2005			
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K1951338 B1372442 B1471130 B2872040 -L2266500 D0670516 A1472904 B2070180 B1570943 B1873162 B1872223 -D026603 B2872919	2026 2011 2012 2013 2016 2007 2018 2011 2016 2000 1996 2000 2007			

				T 37 .
Serial Number	Mass (g)	Length (in)	Diameter (in)	Notes
B1570410	2013			
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B2572366	2017			
B0472131	2011			
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				1
B0473135	2008			
	2008 1999			