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THE NUCLEAR CRITICALITY SAFETY ASPECTS OF PLUTONIUM-238

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ABSTRACT

Plutonium-238 is an important heat producing isotope which is being used in increasing amounts as fuel in isotopic power generators for space, terrestrial, and oceanographic applications. Only within the past few years has the quantity of plutonium-238 become large enough to be considered as a potential nuclear criticality hazard. In order to insure nuclear criticality safety in the storage, processing and assembly of devices containing plutonium-238, a program has been established at Mound Laboratory to investigate the nuclear criticality properties of this isotope. This paper will summarize what is presently known about the criticality behavior of plutonium-238, what are some of the criticality controls used at Mound Laboratory for processing plutonium-238, and what measurements are needed in order to establish a Nuclear Safety Guide for Plutonium-238.

The Nuclear Criticality Safety Aspects of Plutonium-238

I. Introduction

Plutonium-238 is an important heat producing isotope which is being used in increasing amounts as fuel in isotopic power generators for space, terrestrial, and oceanographic application. As larger and larger quantities of plutonium-238 are produced there is a greater need to know more about its nuclear properties. The nuclear criticality properties are needed in order to establish realistic criticality safety guidelines for the processing, storage, handling, and use of plutonium-238.

Mound Laboratory has become actively engaged in the assembly of isotopic power heat sources that contain large quantities of the highly enriched plutonium-238 isotope. Only within the past few years has the quantity of plutonium-238 become large enough to be considered as a potential nuclear criticality hazard. In order to insure nuclear criticality safety in the storage, processing, and assembly of devices containing plutonium-238, a program has been established at Mound Laboratory for performing sub-critical neutron multiplication experiments whenever significant quantities of plutonium-238 are available.

The evaluation of the nuclear criticality hazards of plutonium-238 and the establishment of reasonable process guidelines has been a difficult task for two basic reasons. First, only limited data on the basic nuclear parameters of plutonium-238 are available. Secondly, only limited quantities of plutonium-238 have been available for critical-assembly type experiments. A series of criticality calculations of various types have been performed for plutonium-238 systems, but the reliability of these calculational results have not been confirmed by experimental results. There still are insufficient nuclear data to allow reliable calculations of the criticality properties of plutonium-238. As a result, all process facilities at Mound Laboratory have been designed with what is believed a considerable degree of conservatism.

The primary purpose of this paper is to describe what is presently known about the nuclear criticality behavior of plutonium-238, what are some of the criticality controls used

at Mound Laboratory for processing plutonium-238, and what measurements are needed in order to establish a Nuclear Safety Guide for Plutonium-238.

II. Nuclear Characteristics of Plutonium-238

Plutonium-238 was the first isotope of plutonium to be discovered, but its impact on nuclear technology has not been as dramatic as its closest relative, plutonium-239. Seaborg⁽¹⁾ suggested that "plutonium-238 may prove to be one of the most valuable assets of mankind." In recent years a demand for many kilograms of plutonium-238 has arisen because its alpha radioactive decay provides an important source of energy for sophisticated space and terrestrial applications.

Plutonium-238 is an even-even nucleus whose atomic number is 94 and neutron number is 144. It decays by alpha emission to uranium-234 with a half life of $87.40 \pm .04$ years.⁽²⁾ Plutonium-238 has a high specific activity of 17.17 curies per gram which makes it a formidable material to handle and a good source of energy. The alpha energy of 5.5 Mev is converted to heat at the rate of 0.57 watt per gram. It has a series of low energy gamma rays with an important level at 0.044 MeV. The combination of low gamma energy and high atomic number is favorable for a large internal conversion rate rather than direct gamma emission. A gram of plutonium-238 produces a gamma dose rate of approximately 0.64 roentgens per hour at a distance of one meter in air. The emission of neutrons from plutonium-238 may give rise to significant radiation exposure problems depending upon the means of handling. The spontaneous fission half life of plutonium-238 is reported⁽³⁾ as $5.0 \pm 0.6 \times 10^{10}$ years so the neutron yield is nearly 3×10^3 neutrons per second per gram if there is, as expected, about three neutrons on the average released per fission. During the past few years, considerable experimental data have been generated for the neutron-induced fission cross section of plutonium-238. The most complete fission cross section data have recently been published for the neutron energy range between 17 eV to 3 MeV obtained from the Persimmon Nuclear explosion⁽⁴⁾. Another measurement performed at LRL by Bowman, Coops, Stubbins, and Auchompangh⁽⁵⁾ has shown evidence that a new and unexpected phenomenon of fission may be associated with the fissioning of plutonium-238. This fission mechanism

shows evidence of a release of a gamma ray immediately prior to the fission process. The fission cross section of plutonium-238 by thermal neutrons is 17 barns⁽⁶⁾ and the capture cross section is 403 barns⁽⁶⁾. The fission of an even-even nucleus by thermal neutrons is not found in uranium-238 but has been observed in other nuclei of the even-even type. The large ratio of capture to fission cross section leads one to view plutonium-238 as a safe material from a criticality standpoint in a fully moderated neutron flux and indeed several of the neutron multiplication experiments^(7,8) performed at Mound Laboratory tend to support this conclusion.

The confirmation that plutonium-238 could form a fast critical system was made by a replacement measurement at Los Alamos by Stubbins, Barton, and Lonadier⁽⁹⁾. A ten gram sample of 80% plutonium-238 metal was compared with a similar amount of plutonium-239 placed in a plutonium-239 metal spherical critical reactor called Dirty Jezebel. These results indicated that the reactivity worth of the plutonium-238 sample was equivalent to the worth of the plutonium-239. Thus, since plutonium-239 has a small critical mass of about 15 kilograms as a bare metal sphere, it is believed that plutonium-238 metal can also form a fast critical system of about the same mass. With a thick heavy metal reflector, the critical mass of a sphere of plutonium-238 metal has been calculated to be 7.8 kilograms or even less^(10,11,12).

Neutron Multiplication Experimental Results with Plutonium-238

In 1965, the AEC's Operational Safety Division of the Albuquerque Operators Office became concerned about the quantity of plutonium-238 being processed in solution form in large diameter process vessels at Mound Laboratory. This laboratory was then requested to evaluate or verify experimentally that no criticality hazard existed with those operations which involved the processing of plutonium-238.

Plutonium-238 in Solution. In 1961, Mound Laboratory began to receive small quantities of plutonium-238. At that time, very little was known about the nuclear fission characteristics of this isotope. In fact, because of its even-even nuclei structure, some questioned whether a critical mass could ever be assembled. The process vessels which were to handle plutonium-238 in a solution form were designed about the only two pieces

of nuclear data that were known. These data were the thermal fission and capture cross section which had been experimentally determined. The fission cross section was 17 barns and the capture cross section was 403 barns. These results clearly indicated that there were a higher probability of the capture of thermal neutrons than the fission by thermal neutrons. Upon these data, the decision was made to use large diameter vessels for processing plutonium-238 in solution.

Criticality calculations were first used to describe the degree of criticality existing in solutions containing plutonium-238. These calculations in conjunction with some neutron multiplication experiments confirmed the suspicion that plutonium-238 behaves similar to a neutron poison in a well moderated medium. The isotopic distribution of plutonium that is normally used in the present processes at Mound Laboratory consists of approximately 80 per cent plutonium-238, 16 per cent plutonium-239, 3 per cent plutonium-240, and 1 per cent plutonium-241. At this isotopic distribution, when placed in a solution or moderated medium, the large capture cross section of plutonium-238 over compensates for any contribution which may result from the fission of plutonium-239; and therefore, behaves as a neutron poison. A series of criticality calculations were performed to demonstrate the poisoning effect of plutonium-238 on the criticality of a plutonium-239 water solution. These calculations were based on the one group thermal diffusion equation, in which it was supposed that all production, diffusion leakage, and absorption of neutrons occurred at a single thermal energy. The results of these calculations are shown in Figures 1, 2, and 3. Figure 1 illustrates the critical mass as a function of the concentration of the solution. For example, curve 4 (80 per cent plutonium-239, 20 per cent plutonium-238) indicated that an infinitely large system cannot be made critical providing the concentration was less than approximately 14 grams fuel per liter of solution; and, a finite system cannot be made critical providing the total quantity of fuel is less than approximately 3.0 kilograms. Figure 3 illustrates the critical mass as a function of the atomic ratio, i.e., the number of hydrogen atoms per fuel atom. The atomic ratio and concentration both give an indication of the moderation existing in the system. From a comparison of the curves in Figure 1 and 2, the minimum critical conditions were determined and plotted in Figure 3. Figure 3 shows a direct indication of the effect plutonium-238 has as a thermal neutron poison in a moderated medium.

Concentration of Plutonium Fuel in Solution (Grams Fuel/Liter Solution)

FIGURE 1 - Critical mass of the plutonium fuel containing various percentages of Pu²³⁸ isotope as a function of the concentration of plutonium-H₂O solution in a bare spherical system.

FIGURE 2 - Critical mass of plutonium fuel-water solution containing various percentages of Pu²³⁸ isotope as a function of the atomic ratio in a bare spherical system.

FIGURE 3 - The effect of the isotopic abundance of ²³⁸Pu in the fuel on the minimum critical mass.

Several experiments were performed to verify experimentally if a criticality hazard existed in the large diameter plutonium-238 processing and storage vessels used at Mound Laboratory. Two experiments were performed which included monitoring the neutron count rate as large diameter 130-liter vessels were incrementally filled with plutonium-238 nitrate solution. None of these experiments revealed any detectable neutron multiplication. Based upon these experimental results and the calculated results shown in Figure 1, it is believed that no criticality hazard exists in a well-moderated system when containing at least 80 per cent plutonium-238.

One of the primary concerns that exist with plutonium-238 in solution is the possibility of sludge build-up; i.e., the plutonium-238 precipitating to the bottom of the tank, thus forming a non-moderated medium. The techniques used at Mound Laboratory to indicate sludge build-up will be discussed in the section on Criticality Control.

Experiments with Plutonium-238 in Storage Capsules. The primary purpose of performing experiments with storage capsules was to obtain experimental data which could be used to design realistic storage facilities and to verify the safety of the present storage arrays. Two neutron multiplication experiments (18,19) have been performed with storage capsules of different design which contained plutonium dioxide. The isotopic distribution of the plutonium was approximately 80 per cent plutonium-238, 16 per cent plutonium-239, 3 per cent plutonium-240, and 1 per cent plutonium-241. The results of these experiments indicated that a small neutron multiplication, less than 1.30, existed in the air medium, and no measurable neutron multiplication existed in the water moderated medium. Figure 4 shows a schematic of one of the experimental arrangements and Figures 5 and 6 show the neutron multiplication obtained. These results indicated that no criticality hazard exists in those storage methods presently used at Mound Laboratory.

Figure 4. Neutron Multiplication Experimental Arrangement for $^{238}\text{Pu O}_2$ Storage Capsules in an Air Medium. (Dimensions in Inches)

Figure 5. Neutron Multiplication of Calorimeter Cans Containing $^{238}\text{Pu O}_2$ as a Function of the Quantity of ^{238}Pu Isotope When Assembled in a Planar Array of 3-inch Edge-to-Edge Spacing in an Air Medium.

Figure 6. Neutron Multiplication of Calorimeter Cans Containing $^{238}\text{Pu O}_2$ as a Function of the Quantity of ^{238}Pu Isotope When Assembled in a Planar Array of 1/16-inch Edge-to-Edge Spacing in an Air Medium.

Experiments with Plutonium-238 in Heat Source Capsules.
Several subcritical neutron multiplication experiments^(7, 8) have been performed with SNAP heat sources of various designs. Only the results of the most recent experiment which provided significant supporting evidence as to the nuclear behavior of plutonium-238 will be discussed in this section. The results of these experiments have been beneficial in establishing nuclear criticality safety guidelines for the processing, assembling and storing of heat sources containing plutonium-238.

A neutron multiplication experiment was conducted with four SNAP-19B (IRHS, Intact Reentry Heat Source) heat sources containing plutonium-238. The heat sources were assembled in three planar arrays which had edge-to-edge spacings between heat sources of 3, 3/4, and 1/8 inch. The fuel in the SNAP-19B (IRHS) heat sources is a "high grade" plutonium dioxide. The isotopic abundance of the "high grade" plutonium was approximately 80% plutonium-238, 16% plutonium-239, 3% plutonium-240, and 1% plutonium-241. Each source contained approximately 995 grams of plutonium-238. A schematic of the experimental arrangements and reflector configurations evaluated is shown in Figure 7. Several adjacent laboratory views of the experimental arrangements are shown in Figures 8 and 9.

FIGURE 7 - Neutron multiplication experimental arrangement for SNAP-19B (IRHS) heat sources and reflector configurations.

Edge-to-Edge Spacing		
	(in.)	(cm)
X	3	7.6
X	3/4	1.9
X	1/8	0.3

Figure 8. Experimental Set-Up with Four SNAP-19B (IRHS) Heat Sources

Figure 9. Four SNAP-19B (IRHS) Heat Sources Assembled in a 3-inch Edge-to-Edge Array with no Reflector

The neutron multiplication was first determined for the array with the largest spacing and, thus the safest configuration. The recorded neutron count rate of each heat source was measured individually in its array position with two helium-3 proportional detectors as illustrated in Figure 7. Actual dummy capsules filled with equivalent weights of lead shot were used in the array placement to correct for the neutron scattering and reflection characteristics of the heat source capsules. The heat sources were added one at a time, each to its unique preassigned location, to build the array as the corresponding dummy capsule was removed. The neutron yield was measured with each increment of added source and a neutron multiplication M was calculated as follows:

$$M = \frac{\text{Recorded Count Rate-Background}}{\text{Accumulative Count Rate-Background}}$$

A plot of the neutron multiplication as a function of plutonium-238 for each array in both an air and water medium is shown in Figures 10 and 11. The results in Figure 10 for the air (non-moderated) medium can be interpreted in the normal fashion, e.g., the neutron multiplication is greater in a more tightly packed array than in a loosely packed array since there are less neutron leakage from the tightly packed array. This behavior is, also, characteristic for the other fissile isotopes, such as, plutonium-239, uranium-233, and uranium-235. The results shown in Figure 11 for the water medium are characteristic of plutonium-238 and uniquely different from the other fissile isotopes. These results show clearly that the neutron multiplication for plutonium-238 system decreases directly as the array becomes moderated, e.g., as the array spacing between capsules increases the more the emitted neutrons are moderated in energy by collisions with the hydrogen atoms in the water and as a result, more neutrons are captured and less neutron cause fission. This nuclear behavior is just the opposite of what is expected with plutonium-239, uranium-233, and uranium-235. With these isotopes, a spacing of about one inch in a water medium gives an optimum neutron moderation which results in a neutron multiplication larger than all the other possible array spacings. Therefore, the results in Figure 11 can be interpreted to indicate that the criticality potential of plutonium-238 is greatly reduced in a neutron moderated medium. Advantage is taken of this unique nuclear characteristic in the design of storage arrays for large quantities of plutonium-238.

FIG. 10 - FOUR SNAP-19B HEAT SOURCES IN AIR

FIG. 11 - FOUR SNAP-19B HEAT SOURCES IN WATER

III. Criticality Controls Used in Processing Plutonium-238 at Mound Laboratory

In the last decade, there has arisen a considerable demand for long-lived, self-contained, and reliable sources of energy in the inaccessible regions of space, the ocean and unattended terrestrial installations. By 1964, the potential of plutonium 238 as a reliable source of energy had been demonstrated. From that time on, Mound Laboratory has participated actively in the manufacturing of heat sources and is presently considered the primary supplier of heat sources containing plutonium-238. Both owing to Mound Laboratory's self interest to assure criticality safety during the processing of plutonium-238 and the necessity to assure the users of heat sources of the potential criticality hazards associated with the heat sources, a small program has been in progress at this laboratory for the past several years to evaluate the nuclear criticality hazards of plutonium-238 and establish reasonable process guidelines.

Criticality Unit Value for Plutonium-238. Based upon calculational and experimental results, many of those results referenced in this paper, several important operating values have been established for processing plutonium-238. Mound Laboratory has adopted the mass limitation technique based upon a criticality unit value for most of the process operations involving plutonium-238. The criticality unit value, as defined in the Nuclear Safety Guide,⁽¹³⁾ is 0.434 times that minimum quantity of fissile material required to make a sphere of material critical when considering total water reflection for thermal systems and heavy metal reflection for a fast system, such as a plutonium-238 system. The criticality unit value established for plutonium-238 is 2.0 kilograms; and, therefore, many rooms and isolated areas are restricted to this limit of plutonium-238. This limit of 2.0 kilograms was established to be rather conservative and recent calculational and experimental data have confirmed our beliefs in the conservatism of this value. As experimental data becomes better established for the critical mass of plutonium-238 in various fuel forms and configurations, the process criticality unit value will be adjusted in accordance with this data.

The criticality unit value was established at Mound Laboratory to be used as an administrative guide for processing fissile material. This means that an isolated area must have criticality

control operating procedures for processing fissile material in excess of 1/10 of the criticality unit value. The criticality unit value may be exceeded provided the proper administrative and process design controls are utilized. In a few specific operations, the criticality unit value for plutonium-238 has been increased to 3.0 kilograms.

It should be emphasized that no restrictions, other than the criticality unit value, have been established for processing plutonium-238 either in solution form or in metal form. The criticality unit value for plutonium-238 in solution is 2.0 kilograms providing the isotopic distribution is greater than 76 per cent plutonium-238. At this isotopic distribution, when placed in a solution or moderated medium, the large capture cross section of plutonium-238 over-compensates for the neutron contribution which may result from the fissioning of plutonium 239. This phenomenon is extremely important in process design and is uniquely different from other fissile isotopes. As a result of this understanding of the behavior of plutonium-238 in solution, no restrictions have been placed on the process design that require the use of "safe-diameter" process vessels. Many large diameter (> 16 inches) 130-liter vessels have been utilized in arrays for storing plutonium nitrate solution. Due to the heat generation rate and the neutron radiation associated with these solutions, each vessel has been surrounded by an outer vessel containing a six inch thickness of running water. This water layer around each vessels tends to isolate the vessels and thus reduces the neutron coupling between adjacent vessels.

Plutonium Sludge Build-up. One primary criticality safety concern does exists with the processing of plutonium-238 in solutions. This concern is the possibility of a gradual plutonium sludge build-up occurring unbeknownst in the bottom of vessels over a long period of time as illustrated in Figure 12.

Figure 12. Illustration of Possible Plutonium Sludge Build-Up in Process Vessels

The plutonium in a sludge condition no longer exists in a homogeneous medium that provides effective neutron moderation but rather approximates a non-moderated "fast" neutron medium which has the potential of forming a critical system.

Various criticality control methods are being utilized in an attempt to provide effective control of plutonium sludge build-up in process vessels. Accurate process control records are maintained daily as to the quantity of plutonium entering and leaving the process lines. This administrative control provides an indicator of the amount of plutonium remaining in the process line. The design of many process vessels has been modified to include a dome shape bottom, as illustrated in Figure 12, rather than a "flat" bottom. This dome shape design allows a concentrated collection of the sludge that provides more effective removal by the outlet tubing. A separate inlet exist in many of the vessels which allows the system to be agitated by the purging of air into the bottom of the vessel. An additional control technique that has proven to be effective

and has been installed on many of the process vessels has been the use of thermocouples installed at the bottom and the top of the process vessels as shown in Figure 12. Since plutonium-238 emits approximately one-half a watt per gram, a plutonium sludge build-up consequently results in a temperature increase at the bottom of the vessels. The thermocouples are monitored routinely and with any significant temperature increase, efforts are taken to remove the sludge build-up immediately as a precaution against further sludge build-up.

Storage of Plutonium-238 Dioxide. Only within the past five years has the quantities of plutonium-238 become large enough to be considered a potential criticality hazard. Due to Mound Laboratory's activities in the heat source program over that period of time, the present inventory of plutonium-238 isotope at the laboratory has grown to be in excess of 62 kilograms. In 1964, large quantities of plutonium-238 was being received from the Savannah River Plant. A facility was designed and built for storing this incoming material. The storage facility was designed without the benefit of experimental data, but made use of the known nuclear data on the large thermal neutron capture and the small neutron fission cross section of plutonium-238 by utilizing a heterogeneous array of capsules in a water medium. The quantity of plutonium-238 was limited to 100 grams per shipping container and each capsule was spaced at a center-to-center spacing of five inches. The array spacing and the water medium provide moderation of the neutrons in order to take advantage of the known high capture cross section for thermal neutrons. The purpose of the water has proved to be three fold:

- (1) moderates the neutron energy;
- (2) cools the capsules containing the plutonium-238; and
- (3) reduces the neutron exposure to personnel working in the area.

As larger quantities become available, a series of neutron multiplication experiments were performed. The purpose of these experiments with storage capsules was to verify the safety of the present storage array and to obtain experimental data that could be used in designing future storage facilities. The experimental results, described in the previous section of this paper, confirmed that no criticality hazard existed in those storage methods presently used at Mound Laboratory. These experiments were among the first ever attempted with large

quantities of plutonium-238 and necessarily had to be performed under strict administrative control. The experimental procedure for each experiment was reviewed and approved by the Atomic Energy Commission prior to the actual experiment.

In order to meet the present and future storage requirements for plutonium-238 at Mound Laboratory, an additional storage facility was designed and built. The storage limitations of this new facility were increased significantly over the limitations imposed in the first storage facility. This increase in the storage limitations was possible without jeopardizing criticality safety only by having experimental data obtained from the previous neutron multiplication experiments. A photograph of the present storage facility designed to store a maximum of 60 kilograms of plutonium-238 is shown in Figure 13.

Figure 13. Storage Vault for Plutonium-238 (Capacity 60 Kilograms)

Several controls have been incorporated into the design of the above storage facility. A water level control alarm has been installed in order to maintain the water level at a sufficiently safe height above the top of the capsules.

The storage facility has been divided into four compartments using eight inch concrete dividers in order to provide neutron isolation between compartments. The array spacing between capsules of five inches center-to-center was established, so as, to provide criticality safety even if the water inadvertently leaked from the facility. As additional experimental criticality data becomes available on plutonium-238 systems, the possibility exists that the storage limitation of 60 kilograms can be increased.

IV. Establishing a Nuclear Safety Guide for Plutonium-238

It is difficult to predict all the different uses that will be developed in the future for systems containing plutonium-238. Due to the unique nuclear properties of this fissile isotope, it is not unreasonable to expect many new applications to be developed in the future for plutonium-238. Larger quantities of plutonium-238 than ever before will be required and as a result, nuclear safety guide for the processing and use of this material must be established.

Several present applications for systems containing plutonium 238 that have been used are as follows: (1) thermal power for thermoelectric generation in satellites and space vehicles; (2) thermal stability of the seismic experimental package left on the lunar surface; (3) thermal power for recovery of waste fluids; (4) thermal power for thermoelectric generation in cardiac pacemaker and artificial heart pumps; (5) thermal heat in swimsuits of sea divers; and (6) calorimetry standards.

Present plans are being made to fabricate heat sources for the Isotope Brayton Program which will require approximately 45 kilograms of plutonium-238 distributed within the Isotope Reentry Vehicle (IRV) heat source assembly. The IRV heat source assembly is a 25 kilowatt thermal radioisotopic heat source coupled to a Brayton cycle power conversion system. Only limited experimental data has been obtained on the basic nuclear parameters of plutonium-238 or the neutron multiplication existing in arrays of heat sources. Therefore, all the present

criticality analysis for heat source assemblies or process facilities have been based on calculational results. Much of the nuclear data used in these calculations have been based on theoretical cross sectional models and on assumptions that the nuclear parameters of plutonium-238 are similar to other isotopes. Recently, criticality calculations⁽¹⁴⁾ for the Isotope Brayton System was conducted using the KENO-monte carlo criticality program at the Oak Ridge Computing Technology Center. These results showed no criticality hazard existed in the Isotope Brayton System, so long as the capsules maintained their integrity.

A proposal has been submitted to the Atomic Energy Commission which outlines those experiments needed in order to provide a firm basis for establishing the criticality safety of plutonium 238. The measurements of the two basic nuclear parameters needed most to improve the reliability of the criticality calculational results for plutonium-238 are the average number of neutrons released per fission, $\bar{\nu}$, and the energy spectrum of neutrons released in fission, $N(E)$. It is anticipated that the measurement of both these parameters will be made at Mound Laboratory during the next two years and prior to the assembly of the Isotope Brayton System. Once the nuclear data for plutonium-238 have been established with reasonable accuracy and the calculational results are shown to predict accurately some neutron multiplication results of finite arrays of heat sources, then those calculational techniques can be used to establish realistic criticality safety guidelines for the processing, storing, shipment, and design of heat sources containing plutonium-238 in various fuel forms and configurations.

In summary, Mound Laboratory plans to conduct the following measurements and calculations in an attempt to establish a firm basis for determining the criticality safety aspects of plutonium-238:

- (1) Measurements of the basic nuclear parameters
 - (a) The number of neutrons released per fission, $\bar{\nu}$.
 - (b) The prompt neutron fission spectrum, $N(E)$.
 - (c) The distribution of mass in fission, $Y(M)$.

- (d) The prompt fission gamma ray spectrum, $\gamma(E)$.
- (2) Conduct criticality calculations for finite arrays of heat sources using both the measured and assumed nuclear data of plutonium-238.
 - (3) Perform neutron multiplication experiments with Isotope Brayton heat sources in different arrays and in various mediums. Establish the reliability between calculational and experimental neutron multiplication results.
 - (4) Establish a Nuclear Safety Guide for the processing and use of plutonium-238 which is based upon both calculational and experimental results.

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