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## NUCLEAR CRITICALITY CONTROL IN THE EBR-II FUEL CYCLE FACILITY

by

J. C. Hesson and L. Burris, Jr.

Chem. Eng.

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Chemical Engineering Division

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# NUCLEAR CRITICALITY CONTROL IN THE EBR-II FUEL CYCLE FACILITY

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## I. SUMMARY

An investigation has been made of criticality problems which might be encountered in the EBR-II Fuel Cycle Facility. The purpose of the investigation was to determine quantity and configuration limits for EBR-II fuel of the first core composition during storage, handling and processing of this fuel material in the EBR-II Fuel Cycle Facility. Brief consideration was also given to criticality problems which might be encountered in processing future EBR-II cores which are expected to contain plutonium as a fissionable material.

The philosophy adopted was the establishment of maximum quantities of fuel materials which could be handled, without risk of a nuclear incident, in all fuel processing operations under assumed conditions of "full reflection" and with a safety factor of greater than two to take care of inadvertent double batching. The assumption of "full reflection" (water at least 3 in. thick or its nuclear equivalent) obviates the need for consideration of the proximity of materials other than fuel or fissionable material. Since "full reflection" is not easily achieved, the assumption that "full reflection" exists provides a considerable safety factor.

The total allowable quantity of fuel materials in a given area is a function of the weight of fuel in "fuel units" and the spacing of the fuel units. Thus, the smaller a fuel unit and the greater the distance between fuel units, the greater is the total allowable quantity of fuel material. This relationship for Core-I fuel for a factor of safety of much greater than that required by the Nuclear Safety Guide is shown in Table 2, p. 15. For Core-I fuel a minimum center-to-center distance between fuel units of 24 in. with at least 8 in. of intervening clear space has been established. For these spacings, the maximum sizes of Core-I fuel units (which permit inadvertent double batching) will be the following:

| Fissionable Material | Maximum Weight of Unit Quantity (kg)* |
|---|---|
| Core I fuel (46 w/o $U^{235}$) | 32 as total fuel |
| Plutonium initially in blanket material at concentrations of less than one percent | 2.6 as $Pu^{239}$ |
| Fully enriched uranium (93 w/o $U^{235}$) | 10 as total U |

*This criticality review has been made for Core-I fuel, which is an enriched $U^{235}$ fuel, and for the associated uranium blanket. If, later, plutonium cores are employed, criticality problems should be re-assessed.

The limits on the total quantities of fuel materials present simultaneously in the EBR-II Fuel Cycle Facility are:

| Fissionable Material | Maximum Weight of Unit Quantity (kg)* |
| --- | --- |
| Core I fuel (46 w/o $U^{235}$) | 500 kg (This corresponds to 16 maximum-size fuel units, i.e., 32 kg of fuel per unit.) |
| Plutonium from blanket material* | 13 kg (This corresponds to 5 maximum-size units, each containing not more than 2.6 kg of plutonium.) |
| Fully enriched uranium (93 w/o $U^{235}$) | 10 kg (Storage in the cell in quantities greater than this should not be necessary.) |

The enriched uranium (employed as makeup fissionable material) will be received and, therefore, may be stored in 18-kg-capacity, geometrically safe shipping containers. The 10-kg limitation is, therefore, waived when this material is received and stored in geometrically safe containers, but will be adhered to in subsequent handling. The total of all fissionable materials in all of the liquid waste holdup tanks will be limited to a maximum of 200 g.

The requirement that there be at least 8 in. of open or clear space between fuel units assures separation of units and is in accordance with information presented in the Nuclear Safety Guide which would allow a thick, close-fitting reflector about a cubic array (see Fig. 22, p. 26, of TID-7016, Rev. 1, see Ref. 1 of Bibliography). In TID-7016, p. 26, it is stated that this spacing criterion is also met if the units are separated by a layer of water or concrete at least 8 in. in thickness.

The amount of potential moderators, graphite (or carbon) and beryllia, will be limited to an accumulation in each cell of 600 kg of graphite and 300 kg of beryllia.

For storage of fuel, TID-7016 permits a relaxation of the customary double-batching safety factors on the assumption that control of individual fuel units in storage is more stringent than in process operations. The minimum spacing for 32-kg fuel units in storage is 12 in. between centers with not less than 8 in. of clear space between units. The spacing of storage pits in the Argon and Air Cells of EBR-II is such that these minimum required distances are in all cases exceeded. Even though a 12-in. spacing of stored 32-kg fuel units is adequate, a uniform set of rules has been adopted for both storage and handling of fuel in the cells, namely, 2 ft between adjacent fuel units with 8 in. of intervening space.

*See previous page.

Although the 32-kg limitation also applies to the storage of melt refining skulls or skull oxide in a storage pit, additional precautions must be taken in the storage of these materials because of the remote possibility that, through water inleakage, the pits may flood with water. It is required that the skull oxide be stored in geometries which provide a safe condition even though the containers and pits fill with water. Two permissible geometries are: (1) containers with safe diameters, i.e., less than 5 in. in diameter, and (2) containers 8 in. in diameter and 4 in. high with at least 10 in. of clear space between containers. An unsafe condition would not result even if the cans filled with water, but oxide must not be permitted to escape from the cans into the storage pit of larger diameter. Because the oxides will have a particle density of around 10 $g/cm^3$,* movement of oxide even in an open can filled with water would be unlikely. Nevertheless, the cans must have tight-fitting lids, and the integrity of the cans must be assured.

Fuel subassemblies awaiting processing or return to the reactor may be stored in storage pits in the Air Cell. Water flooding of the ventilated pits in the Air Cell is not considered credible; however, not more than four fuel subassemblies are allowed to be stored in a storage pit.**

Mechanical aids and administrative control will be required to ensure that unit quantities are not exceeded and that geometrically safe configurations are maintained. The following mechanical aids are needed for maintaining the spacings required for geometrically safe configurations and for preventing an accumulation of fuel in amounts in excess of the maximum recommended quantities:

1) Mechanical apparatus to limit the maximum number of assemblies in any one Air Cell storage pit to four (4) subassemblies.**

2) Mechanical apparatus to limit storage of oxide or fuel in the argon cell storage pits to geometrically safe configurations described above.

3) In the case that fuel elements are cleaned (as has been occasionally proposed) in a halogenated carbon fluid (such as trichloroethylene), the cleaning container will have geometrically safe dimensions (less than 5 in. in diameter). The halogenated carbon fluid would not be an effective moderator, but there is the possibility of inadvertent substitution of water.

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* The bulk density of the oxide powder is about 3 $g/cm^3$.

** The storage of four subassemblies in an Air Cell pit was approved by the Argonne Criticality Hazards Control Committee on the basis that flooding of the present Air Cell pits with water is not considered credible. Therefore, the use of water or aqueous solutions in the Air Cell or any changes in the method of water cooling or ventilating the Air Cell pits should not be undertaken without a criticality review.

These limitations are regarded as practical for conditions encountered in processing Core-I fuel. Maximum unit quantities would be about the same (perhaps 10 percent less) for plutonium-containing fuel materials of the type being contemplated for future EBR-II cores, i.e., uranium-plutonium alloys containing 10 to 15 percent plutonium with the balance of the fissionable material requirement being supplied with $U^{235}$. However, criticality problems should again be examined for each future core material.

## II. OBJECTIVES OF CRITICALITY STUDY

The purpose of this discussion of criticality problems associated with the EBR-II Fuel Cycle Facility is (1) to establish quantity and configuration limits for the fuel materials during reprocessing of the first-cycle fuel loading, and (2) to establish the limitations on or exclusion of certain possible moderators. The needs for administrative control and mechanical devices to maintain proper spacing of fuel materials are pointed out, and the actual design of physical apparatus to limit fuel quantities and maintain proper fuel separation will be discussed. However, the actual administrative procedures employed for criticality control will be the responsibility of operating personnel to set up and maintain.

The first-cycle fuel loading will contain approximately 46 w/o $U^{235}$ as the major fissionable material. The actual composition of the fuel is shown in Table 1.

Table 1

FIRST-CYCLE FUEL LOADING FOR EBR-II

(5 Weight Percent Fissium)
(Specification from ANL-6290)

| Element or Isotope | Atomic Weight | Atom Percent | Weight Percent |
|---|---|---|---|
| Uranium-235 | 235.12 | 42.99 | 45.68 |
| Uranium-238* | 238.12 | 45.83 | 49.32 |
| Molybdenum | 95.95 | 5.67 | 2.46 |
| Ruthenium | 101.10 | 4.25 | 1.96 |
| Rhodium | 102.91 | 0.60 | 0.28 |
| Palladium | 106.40 | 0.39 | 0.19 |
| Zirconium | 91.22 | 0.25 | 0.10 |
| Niobium | 92.91 | 0.02 | 0.01 |
| | | 100.00 | 100.00 |

*Includes other uranium isotopes

The criticality problems were determined for a composition of 50 w/o uranium-235 and 50 w/o uranium-238. This, in itself, gives an additional small factor of safety since the fuel will have less reactivity, both because of the slightly lower fissionable material content and because of the presence of fission product alloying elements.

Consideration was given to the effect of an inadvertent fully enriched batch. The criticality problems were considered for the case of a "full reflector," which obviates the need for consideration of the proximity of materials other than fuel or fissionable materials. A "full reflector" is water at least 3 in. thick or its nuclear equivalent. This also affords an additional safety factor, since a full reflector does not easily occur. In establishing allowable quantities, a factor of safety of at least two was used for all normal operational conditions.

The publications TID-7016[1] (Rev. 1), LAMS-2415,[2] and LA-1958[2] were the major references used for information on criticality. Reference was also made to K-1019,[8] K-1380,[9] ANL-5800,[10] LA-1305,[7] LA-1623,[6] LA-1671,[5] and LA-1732.[3] Additional information about these references is supplied by a bibliography at the end of this report.

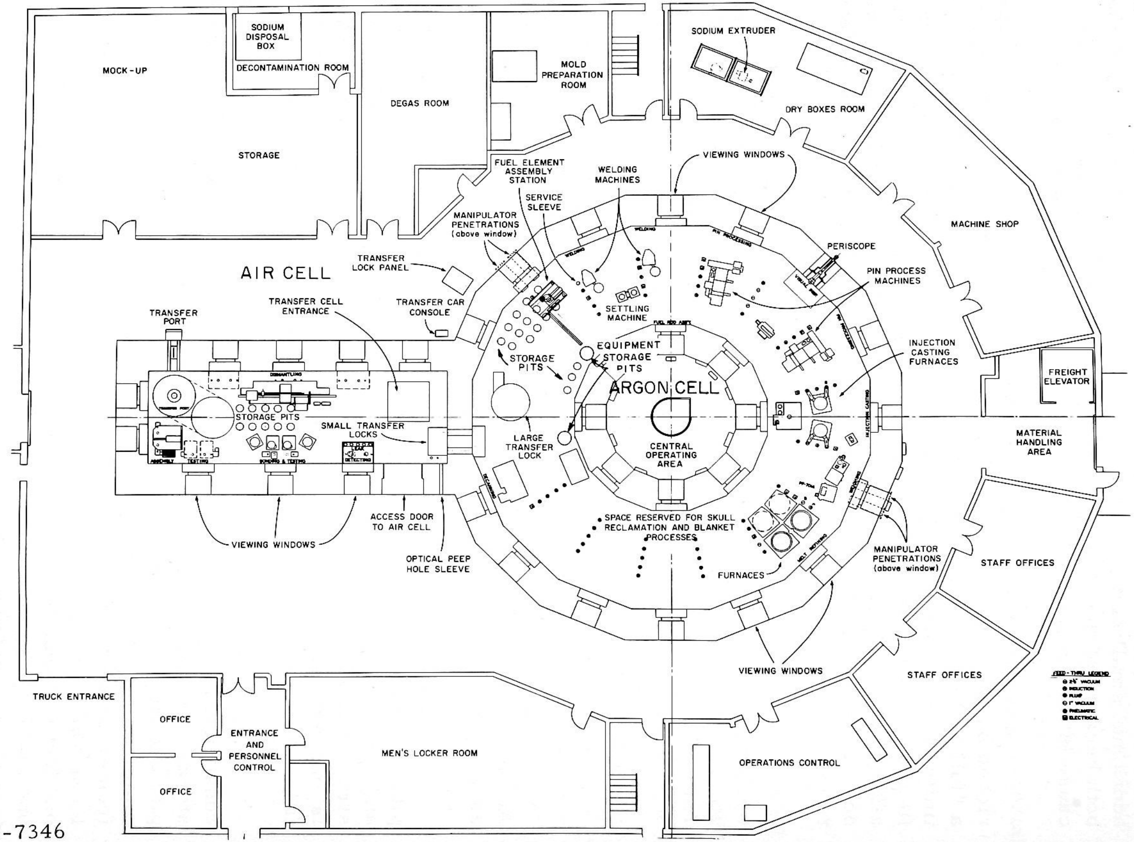
## III. FUEL HANDLING AND STORAGE CONFIGURATIONS

Figure 1 shows a plan view of the fuel processing facility, including Air and Argon Cells, with equipment locations. Figure 2 shows fuel subassembly coffin movements between the reactor building and the Air Cell.

There are ten 10-ft-deep pits in the Air Cell in two rows of five pits each (see Fig. 1). The rows are 3 ft apart (center-to-center distance), and the pits in each row are 2 ft apart between centers. Each pit is constructed of 12-in., schedule 20, black steel pipe, the upper part of which is encased in the floor concrete, the lower part of which extends into the fill material.

In the Argon Cell there are seventeen 10-ft-deep fuel storage pits constructed of 12-in., schedule 20, black steel pipe, and two equipment storage pits constructed of 24-in. black steel pipe (see Fig. 1). These pits are encased in concrete. The fuel storage pits are spaced at a minimum of 2 ft between centers. One equipment storage pit is $2\frac{1}{4}$ ft (center-to-center distance) from a fuel storage pit, which places their inner walls 9 in. apart. This is the only case where there is less than one foot between the inner walls of any two pits. A distance of at least one foot between the inner surfaces of the fuel storage pits provides more than the suggested minimum of at least 8 in. of clear space (clear of fuel) between units.

Figure 1. LOCATION OF FUEL PROCESSING EQUIPMENT IN THE EBR-II FUEL CYCLE FACILITY

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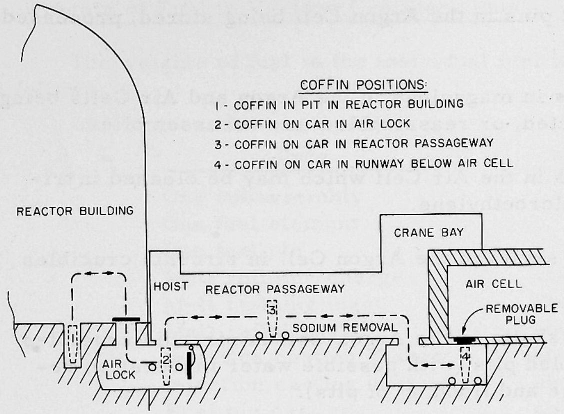


Figure 2

SUBASSEMBLY COFFIN MOVEMENTS

A. Fuel Configurations

The configurations in which the fuel will be handled or stored are as follows:

a. One subassembly (6.1 kg of fuel) in the coffin in transfer between the Reactor and Fuel Cycle Facility. Steel and lead, which are reflector materials, surround the subassembly, and water moderation exists during sodium cleaning.

b. Individual subassemblies in the open air being transported, stored, disassembled, or assembled in the Air Cell.

c. Storage of subassemblies in ventilated water-cooled pits in the Air Cell.

d. Unassembled fuel elements in the open in the Air and Argon Cells being moved, stored, or decanned. Various numbers of fuel elements may be present in random arrays or in regular arrays (as in fuel element magazines).

e. Decanned *and chopped* fuel pins in random arrays in the Argon Cell being moved or stored in steel charging pans or being melt refined in a zirconia crucible within a graphite susceptor or secondary.

f. Melt refined ingots in the Argon Cell being stored or moved, or being melted in the injection casting furnace in a graphite crucible.

g. Injection casting heels, shards, pin rejects, and scrap in the Argon Cell being moved or stored, or being remelted in a graphite, zirconia, or beryllia crucible.

h. Injection cast pins in the Argon Cell being stored, processed, moved, or recanned.

i. Fuel elements in magazines in the Argon and Air Cells being processed, stored, inspected, or reassembled into subassemblies.

j. Fuel elements in the Air Cell which may be cleaned in trichloroethylene or tetrachloroethylene.

k. Melt refining skulls in the Argon Cell in zirconia crucibles being moved or oxidized.

l. Melt refining skulls in the Argon Cell in zirconia crucibles being stored in water-cooled pits (with possible water moderation resulting from water leakage and flooding of pits).

m. Skull oxide in the Argon Cell in metal containers being moved or stored in water-cooled pits (with possible water moderation resulting from water leakage and flooding of pits).

n. Inadvertent mixing of fuel with graphite or beryllia crucible pieces.

o. Waste liquid tanks and evaporators.

p. Uranium-235 in storage or in transit for enrichment of fuel.

q. New unirradiated fuel elements or subassemblies.

r. Skull oxide or reduced uranium in the Argon Cell in halide flux, zinc, and/or magnesium. These materials may be present in tungsten, beryllia, ceramic, or graphite crucibles within graphite secondaries or in small-diameter transfer tubes.

s. Reclaimed uranium in cakes containing zinc and magnesium being moved, stored, or retorted in tungsten, beryllia, ceramic, or graphite crucibles.

t. Uranium lost in waste halide flux, zinc, and/or magnesium wastes.

u. Plutonium in blanket material to extent of about 1 percent.

v. Plutonium concentrates in magnesium after processing.

B. Weights of Fuel in Various Configurations

The weights of fuel in the individual fuel items or configurations are as follows:

| Item | Fuel Weight, g |
|---|---|
| One subassembly | 6070 |
| One fuel element | 67 |
| One fuel pin | 67 |
| Melt refining charge | about 10,000 |
| Melt refining ingot | about 9,000 |
| Melt refining skull | about 1,000 |
| Injection casting charge | about 14,000 |
| Injection casting heel | about 4,000 |
| Fuel pin castings | about 100 |
| Scrap | variable |

## IV. CRITICAL MASS OF INDIVIDUAL MASSES OF UNMODERATED FUEL

The minimum critical masses for unmoderated but reflected spheres of uranium-235 metal at 93.5 and 50 w/o enrichments (density = 18.8 g/cm$^3$) for various conditions of reflection are as follows (LAMS-2415, TID-7016):

| Reflector | Minimum Critical Mass of $U^{235}$, kg, (density = 18.8 g/cm$^3$) for an Enrichment Percentage of: | |
|---|---|---|
| | 93.5 | 50 |
| Unreflected | 48 | 75 |
| Uranium, 2 in. thick | 23 | 37 |
| Uranium, infinitely thick | 16 | 27 |
| Water, 2 in. thick | 25 | 40 |
| Water, infinitely thick | 23 | 37 |
| Graphite, 2 in. thick | 31 | 50 |
| Graphite, infinitely thick | 17 | 27 |
| Beryllia, 2 in. thick | 21 | 34 |
| Beryllia, infinitely thick | 9 | 14 |
| TID-7016, Rev. 1, "Full Reflector"* | 22.8 | 36 |

Only heavy water and beryllium (or its compounds) are better reflectors than uranium for thick sections. The allowance factor for $U^{235}$ at 50 percent enrichment is 1.6 times that for $U^{235}$ at 93.5 percent enrichment (TID-7016, Rev. 1, p. 24).

*A "full reflector" is water at least 3 in. thick or its nuclear equivalent.

The critical mass of uranium-235 contained in uranium spheres varies approximately as (LA-1958):

(Concentration of $U^{235}$)$^{-0.7}$;

(Core Density)$^{-2.0}$ (no reflector);

(Core Density)$^{-1.2}$ (Reflector Density)$^{-0.8}$ (for thick uranium reflector).

Since heavy water and beryllia (except possibly for crucibles with wall thickness of about 1 in.) will not be present in the cells, calculations of allowable quantities of fuel materials were based on the assumption of "full reflection." "Full reflection" is provided by water at least 3 in. thick or its nuclear equivalent (TID-7016, Rev. 1, p. 13). For fully enriched uranium, the minimum critical mass for a "full reflector" is 22.8 kg $U^{235}$, and the recommended limit is 10 kg (TID-7016, Rev. 1, pp. 10 and 14 for a "full reflector").

Application of an allowance factor of 1.6 for uranium metal of 50 percent enrichment (TID-7016, p. 24) results in a limit of 32 kg of Core-I fuel of 50 percent enrichment (10 x 1.6 x 2). This would give a safety factor of 2.3 for fully reflected fuel and would, therefore, permit inadvertent double batching.

The above calculation applies only to individual units of fuel. It is of value in indicating the size of a maximum unit of fuel which, because of a factor of safety of 2.3, can be handled without fear of producing criticality consequences on double batching. The problem of handling fuel units in arrays is discussed below.

## V. ALLOWABLE NUMBER AND SIZE OF UNMODERATED BUT FULLY REFLECTED MASSES

In a given area, the total allowable quantity of fuel material is a function of the weight of fuel in fuel units and the spacing of the fuel units. Table 2 shows the total allowable quantity of fuel (with an included safety factor of considerably more than three) for various sizes of fuel units (50 percent enriched uranium) and various spacings of these units. It is clear that the smaller the unit size and the greater the spacing of units, the greater is the total allowable quantity of fuel.

The maximum size of fuel is considered to be that quantity which could be doubled in size (by inadvertent double batching) without production of a critical mass. This maximum unit size was determined in the previous section to be 32 kg of Core-I fuel with a 50 percent uranium-235 enrichment. This results in a total allowable quantity of fuel of 830 kg (see Table 2), which is equivalent to 26 maximum-sized fuel units. However, the total quantity of fuel in the Fuel Cycle Facility will be restricted to 500 kg or sixteen 32-kg units. The required spacing of these fuel units is a center-to-center distance of 2 ft with a minimum of 8 in. of clear space between.

Table 2

ALLOWABLE QUANTITIES OF CORE-I FUEL (50 PERCENT $U^{235}$) AS FUNCTIONS OF SIZE AND SPACING OF FUEL UNITS[a]

| Center-to-center Spacing of Fuel Units (in.)[a] | Total Fuel Weight and Number of Fuel Units for Fuel Units Sizes[b] of | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 15 kg | | 20 kg | | 25 kg | | 32 kg | |
| | Fuel Wt (kg) | No. of Units | Fuel Wt (kg) | No. of Units | Fuel Wt (kg) | No. of Units | Fuel Wt (kg) | No. of Units |
| 12 | 310 | 20 | 250 | 12 | 210 | 8 | 175 | 5 |
| 15 | 510 | 34 | 410 | 20 | 350 | 14 | 290 | 9 |
| 18 | 770 | 51 | 620 | 31 | 525 | 21 | 435 | 13 |
| 21 | >1000 | >66 | 860 | 43 | 740 | 29 | 610 | 19 |
| 24 | >1000 | >66 | >1000 | >50 | 1000 | 40 | 830 | 26 |

[a]It is also necessary that there be 8 in. of clear space between fuel units.
[b]Data adapted from TID-7016, Figure 22, with a factor of safety greater than three.

According to TID-7016, p. 25, the "maximum unit" (or any unit size which is selected to be the maximum size) may consist of a group of smaller units in a single sealed container or distributed among several sealed containers. For fuel in the Fuel Cycle Facility, the sealed container restriction was removed since the possibility of water flooding may be ruled out.

The specification of 8 in. of open or clear space between units assures separation of units and is in accordance with information presented in the Nuclear Safety Guide which would allow a thick, close-fitting reflector around a cubic array of stored units (Figure 22, p. 26 of TID-7016, Rev. 1). This spacing criterion is met if the units are separated by a layer of water or concrete at least 8 in. in thickness.

In TID-7016, it is pointed out that relaxation of the customary double-batching safety factors is possible for storage of fuel under the explicit assumption that control of the individual units is more stringent in storage than in normal processing operations. Under storage conditions, the required center-to-center spacing of 32-kg fuel units is 12 in. with an included safety factor of two. However, for uniformity of rules, the 24-in. center-to-center spacing of fuel units will be required for fuel in both storage and process operations. This results in a factor of safety considerably larger than two.

These limits apply to fuel in process or storage in the Argon and Air Cells of the Fuel Cycle Facility. The fuel configurations listed on pp. 11 and 12 which are covered by these limitations are b, c, d, e, f, g, h, i, k, and q. The necessary fuel spacing and control of the sizes of fuel quantities will be achieved by the storage apparatus discussed in Section VIII, p. 22, and by administrative control of units in various stages of processing in predesignated areas in the passageway and cells. For instance, the passageway from the reactor to the Air Cell will be one area where not more than 1 unit (32 kg of fuel, 5 subassemblies) will be permitted exclusive of storage pits. The Air Cell will be divided into several areas, as will be the Argon Cell. The small transfer locks can also be one area, the large transfer lock another area.

In the case of uranium-235 storage (configuration p on p. 12), the uranium-235 will be received and stored in geometrically safe containers, which may hold up to 18 kg of fully enriched uranium. In subsequent handling, the mass limit will be 10 kg of fully enriched uranium as a unit, with a limit of 16 units on 2-ft centers in a cubic array and with a minimum of 8 in. of open space between units. The quantity of uranium-235 stored in the cells will be limited to one unit.

## VI. MODERATED CRITICAL MASSES

The minimum critical mass of uranium-235 is reduced drastically by optimum moderation. Hydrogen is one of the best moderators. Beryllium and carbon are also good moderators.

When most elements are mixed with uranium-235, the minimum critical mass is increased, largely because of decreased uranium density. This is shown by TID-7016, Rev. 1, p. 23, Figure 19, in which allowance factors for mass limits of uranium-235 mixed homogeneously with other elements and compounds of other elements, are illustrated. The minimum critical mass is increased by mixing uranium-235 with elements of atomic numbers (Z) from 11 to 83 (sodium to bismuth). The minimum critical mass is also increased by mixing uranium-235 with carbon, nitrogen, oxygen, fluorine, and elements of atomic numbers 11 to 83 when there is at least one fissionable atom per 7 other atoms (e.g., UC, $UO_2$, $U_3O_8$, $UO_3$, $UO_2F_2$, $UF_4$, $UF_6$). Of the elements up to Z of 10, helium, nitrogen, oxygen, fluorine, and neon are normally gaseous and, therefore, would usually be present to an extent of less than seven atoms per atom of uranium unless present with uranium in a compound. Boron is a neutron absorber. This leaves hydrogen (and deuterium), beryllium, carbon, and possibly lithium as the only moderators which could reduce the minimum critical mass. Of these latter five, hydrogen from possible water leakage into the storage pits, graphite from crucibles, susceptors, etc., and beryllium as beryllia from crucibles might be present in the cells.

LAMS-2415 and TID-7016, Rev. 1, have various graphs which can be used for water solutions and slurries of uranium-235. These graphs show that the addition of water first increases the minimum critical mass slightly and then decreases it as more water moderator is added. The minimum critical mass occurs at hydrogen-to-$U^{235}$ ratios of around 400 to 1.

As in the case of hydrogen (water), the addition of graphite or beryllia as a moderator first increases the critical mass of $U^{235}$ and then decreases it. LAMS-2415, p. 31, Figure 18, shows this effect for bare spheres of homogeneous mixtures of fully enriched uranium with either graphite or beryllia (BeO). To decrease the critical mass of $U^{235}$, which is 48 kg for fully enriched $U^{235}$, back to 48 kg (after the initial increase) by addition of graphite would require about 2300 kg of graphite. To decrease it further to 16 kg would require about 3000 kg graphite or 470 kg beryllia (BeO). However, a maximum unit of Core-I fuel (32 kg of 50 percent enriched uranium) fully reflected with beryllia would be critical with about 340 kg of beryllia. With graphite, a 32-kg fuel unit could not be made critical by reflection. Process-size graphite or beryllia crucibles should weigh less than 100 kg each.

## VII. ALLOWABLE MASSES - MODERATED AND REFLECTED

### A. Carbon and Beryllia Moderators

In the previous section it was pointed out that hydrogen (water), carbon (graphite), and beryllia were the only effective moderators which might be introduced into the cells. In the case of graphite and beryllia, quantities of at least 3000 and 470 kg, respectively, thoroughly mixed with 32 kg of 50 percent enriched uranium, would be required for effective moderation. By limiting the total quantities of graphite and beryllia in the cells, the problem of possible moderation can be controlled. A moderator could conceivably consist of a mixture of beryllia and graphite, which would complement each other in moderation effect. Limitations on the total amounts of these will be effected in either of two ways:

a) The total quantity of graphite and beryllia in either cell will be limited to 600 and 300 kg, respectively (20 percent of that required for graphite alone plus 70 percent of that for beryllia alone). This will eliminate the need for administrative control of the graphite and beryllia in areas within the respective cells and is preferable to (b) below.

b) The total quantity of graphite and beryllia in any administratively controlled area in either cell will be limited to 600 and 300 kg, respectively. This will be required in the event the total quantity per cell cannot be limited as in (a).

Broken or scrap graphite or beryllia will not be allowed to accumulate in the cells and will be removed at the earliest possible moment consistent with efficient operation.

With the above limitation on the quantities of graphite and beryllia in the cell, the previously discussed limit of 32 kg of fuel will also apply to the following moderated or possibly inadvertently moderated fuel configurations (listed as n, r, s, and t on page 12):

1) Inadvertent mixtures of fuel with graphite or beryllia crucible pieces (n).

2) Skull oxide or uranium in the argon cell in halide flux, zinc and/or magnesium in tungsten, beryllia, or graphite crucibles in graphite secondaries or being transferred in small diameter transfer tubes (r).

3) Reclaimed uranium in cakes containing zinc and magnesium, being moved, stored, or retorted in tungsten, beryllia, ceramic, or graphite crucibles (s).

4) Uranium lost in waste halide flux, zinc, and/or magnesium wastes (t).

## B. Water Moderator

Remaining configurations which have not been discussed, particularly from the standpoint of the applicability of the 32-kg limit of fuel, are a, j, l, m, and o, listed on pages 11 and 12, which involve possible water moderation, and u and v which involve plutonium from blanket processing.

### 1. Subassemblies in Water-filled Coffin or Storage Pits (Configurations a and c)

Subassembly in Coffins. It is possible to put only one core subassembly into a coffin. The fuel in a core subassembly weighs 6.07 kg and consists of ninety-one 0.144-in.-diameter by 14.22-in.-long fuel pins surrounded by 0.006 in. of bonding sodium and 0.009 in. of cladding. The elements are spaced on a triangular lattice of 0.223 in. between centers. If water were to completely fill the coffin, the ratio of hydrogen to uranium-235 atoms of the array in the subassembly would be 3.75 for 50 percent enrichment and 2.0 for 93.5 percent enrichment. If it is assumed that the sodium and stainless steel are equivalent to their volumes in water (which they are not), the ratios would be 5.2 and 2.8, respectively. For homogeneous, water-moderated, 93.5 percent enriched uranium-water mixtures with water reflector, the minimum critical mass of uranium-235 for hydrogen-to-uranium-235 ($H/U^{235}$) ratios of 5.2, 2.8, and 0 are 18, 22, and 23 kg, respectively (LAMS-2415, p. 8). For arrays rather than homogeneous distributions, the critical mass is larger. As an example, an array of $\frac{1}{8}$-in. rods with 0.6-in. surface-to-surface spacings, for which $H/U^{235}$ is 52, has a critical mass of 6 kg as compared with 3 kg for homogeneous solutions. The critical mass for lattices of low enriched uranium (below 3 to 5 percent) may be less, however, than for homogeneous solutions.

The critical mass for water-moderated subassemblies is greater than 18 kg of uranium-235 (or greater than 36 kg of total fuel). Eighteen kilograms of uranium-235 corresponds to 6 subassemblies. Therefore, there would be a factor of safety of much greater than 2 for a subassembly of even fully enriched uranium in a water-filled coffin (configuration a on p. 11).

Subassemblies in Air Cell Storage Pits. The Air Cell storage pits are cooled by water circulated under negative pressure and are also equipped with bottom air-vent drains. To flood a pit with water would require an incredible combination of unusual circumstances, which are: a water leak, a failure of negative water pressure conditions, and blockage of the ventilation system. Therefore, water flooding of the Air Cell pits is not considered credible.

Since it would be possible, theoretically at least, to place 19 subassemblies (2.29 in. across hex flats) in an Air Cell storage pit (12 in. in diameter), the number of subassemblies which can be put into a storage pit will be limited to four* by divider racks (see Section VIII) which will make it impossible to put more than four subassemblies into a storage pit. This limitation of four subassemblies (24.3 kg of fuel) is one of two exceptions to the 32-kg limit allowed for core fuel in nearly all other configurations. (The other exception is the amount of fuel permissible in aqueous liquid wastes or evaporators.) A 32-kg limit or five subassemblies in the Air Cell storage pits would undoubtedly be safe, but such a limit would not have as great a factor of safety as has been built into the 32-kg limitation for the core fuel in other configurations.

Blanket subassemblies including subassembly parts may be stored in some of the pits. In this event it might be desirable to store as many partial subassemblies in a pit as possible. Since completed core subassemblies containing fuel in these pits might be accidentally substituted for blanket subassemblies the possibility of such an occurrence is considered below.

The core subassemblies are hexagonal (2.29 in. across flats) in cross section, and the contained fuel elements are 14.22 in. long. The volume of the fuel space is 70 cu in. (1145 cc). Since the fuel weighs 6.07 kg, the average density is 5.3 g/cm$^3$ (neglecting stainless steel) which

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*See footnote on p.7.

is 28.2 percent of the density of full-density fuel (18.8 g/cc). The allowance factor for this reduced density is 4.3 for a full reflector (TID-7016, Rev. 1, Figure 18, p. 22). Since the height-to-diameter ratio for subassemblies in a 12-in.-diameter pit would be 14.22/12 or 1.18, the shape allowance factor for a full reflector would be negligible (TID-7016, Rev. 1, Fig. 17). The minimum critical mass for a full reflector and no water in the storage pit and using the allowance factors of 4.3 for reduced density and 1.6 for 50 percent enrichment would be 314 kg (22.8 x 4.3 x 1.6 x 2).* There would be an additional allowance factor for the stainless steel, which gives an added safety factor. Therefore, even though 19 subassemblies or 115 kg of fuel could possibly be inadvertently put into a 12-in. pit, a critical mass would not thereby result.

2. Fuel Elements in Cleaning Solvent - (Configuration j)

It has been suggested that fuel elements be cleaned in the Air Cell with a halogenated carbon fluid. Neither of the proposed solvents, trichloroethylene or tetrachloroethylene, is equal to water as a moderator although carbon atoms are present. Since the use of water represents the worst condition, water will be considered as the moderator. This condition could occur by an inadvertent substitution of water for trichloroethylene.

As mentioned above, the minimum critical mass of $\frac{1}{8}$-in., 93 percent enriched uranium rods with a surface-to-surface spacing of 0.6 in. is 6 kg uranium-235 (LAMS-2415, p. 20). For 0.144-in.-diameter pins in fuel elements, the minimum critical mass would be larger. If the number of elements being cleaned at one time is limited to 91 (3.03 kg uranium-235), the minimum factor of safety would be about 2. Even 91 fully enriched uranium rods would be less than a critical mass. However, to avoid any possible accident at this point, a geometrically safe container for the cleaning fluid having a diameter less than 5 in. would be used and the number of elements per batch would be limited to 91 (LAMS-2415, p. 10, 11).

3. Skulls or Skull Oxide in Water-flooded Storage Pits (Configurations l and m).

The 32-kg limitation will also be applied to the storage of melt refining skulls or skull oxide in each storage pit. However, in the storage of skulls or skull oxide in the Argon Cell water-cooled pits, the possibility of particles dispersed in the water must be considered. When skull oxide is stored, it will be in the form of small particles. (Screen analyses of fission skull oxide indicate variable distributions of the particle sizes ranging from larger than 10 mesh to smaller than 325 mesh. When unoxidized skulls are stored, nitridation may result in the formation of small particles.)

*The actual dry critical mass for Core-I fuel in the EBR-II reactor was 228 kg of uranium-235 or about 496 kg of the 46 percent enriched uranium fuel.

It can be postulated that agitation of the water necessary for dispersal could, for example, be caused by boiling at the bottom due to self-heating. The criticality of finely dispersed particles in water can approach that of solutions. Since the storage pits are 12 in. in diameter and 10 ft long, and as much as 32 kg of skull oxide may be stored in each pit, they will not be geometrically safe for the worst assumed conditions of finely divided and dispersed oxide. Therefore, the oxide will be stored in approximately 1- to 3-kg lots in geometrically safe, closed containers which are 5 in. in diameter and 5 in. high. A description of these containers and racks in which the containers are to be stored is given in the next section (Section VIII).

If the melt refining skulls are kept in the melt refining crucibles, these will be stored in closed containers (see Section VIII) just large enough to hold the crucibles (which are $6\frac{3}{8}$ in. in diameter by $9\frac{1}{2}$ in. high). This is safe geometry which encompasses water flooding, since the crucible inside diameter is only $5\frac{1}{8}$ in., which is less than the minimum critical diameter for solutions (5.4 in. - LAMS-2415, p. 10) and since its volume is 2.9 liters, which is less than the minimum critical volume for 32 kg of 50% enriched $U^{235}$ fuel. The skull material will not be allowed to escape from a container.

In considering the storage of skull oxide in the storage pits without water flooding, it is noteworthy that self-heating rather than criticality may limit the quantity which can be stored in a pit. The top bulk density of fissium skull oxide is about 3.1 g/cm$^3$. The pits are about 30.5 cm in diameter by 305 cm long and have a gross volume of about 223,000 cm$^3$. They would hold about 690 kg of oxide each. If allowance factors of 3 for density (oxygen present) and of 3 for shape (cylindrical with height-to-diameter ratio of 10) are used, the calculated minimum critical mass would be 650 kg of oxide for a full reflector. The self-heating from one kilogram of skull oxide (from melt refining 10 kg of fuel) would be 2 kW (for fuel of 2 percent burnup and 15-day cooling).

4. Evaporator (Configuration o)

The high-activity liquid waste from the analytical caves will be absorbed in vermiculite without evaporation. This will minimize the hazard of fissionable material concentration.

The low-activity liquid wastes from the suspect tanks may be concentrated in the waste evaporator. Although there is little probability of the presence of enough fissionable material to be hazardous, from a criticality viewpoint, the liquid wastes, before evaporation, will be checked for fissionable material concentration. The total amount of fissionable material in all of the liquid wastes will be kept less than 200 g since the minimum critical quantity of plutonium in aqueous solution is only 510 g. This constitutes a very important exception to the 32-kg limit for core fuel in other configurations.

The waste solution tanks are used to store liquid wastes from the analytical laboratory caves, the wash water used in removing sodium from subassemblies, and perhaps solutions used in decontamination of equipment. There are no connections between the waste solution tanks and any fuel processing equipment or process operations.

5. Plutonium in Blanket Process (Configurations u and v)

The minimum critical mass of plutonium with reflector is 0.51 kg in solution and 5.6 kg in the alpha phase (7.6 kg in delta phase). The recommended quantities (TID-7016, Rev. 1, p. 10) are 0.22 kg in solution, 2.6 kg in the alpha, and 3.5 kg in the delta phases. Since the plutonium may be in any concentration during processing in the liquid metal system, the maximum quantity for a unit will be 2.6 kg. These units and the fuel units will not be placed closer than 2 ft between centers with at least 8 in. of clear space between. The maximum quantity of plutonium in the cells will be limited to 13 kg. The plutonium will not be stored in any of the pits without a special review of the problem.

## VIII. MECHANICAL DEVICES TO MAINTAIN SPACINGS OF FUEL IN STORAGE

Mechanical devices have been provided to maintain proper spacing of fuel materials in storage and to limit the quantities of fuel materials stored in the storage pits and in the argon cell. There are three categories of fuel storage:

1) Storage of fuel subassemblies in Air Cell pits.

2) Storage of ingots, skull oxide, and melt refining crucibles containing unoxidized skulls in storage pits in the argon cell.

3) Storage of ingots, skull oxide, and melt refining crucibles with contained skulls on racks in the argon cell.

Provisions, apparatus, and limitations which have been established for fuel stored in each of these categories are discussed below.

### A. Storage of Fuel Subassemblies in Air Cell Pits*

Certain designated Air Cell pits will be used for storage of fuel subassemblies. A maximum of four subassemblies will be stored in each pit. In those pits which are used for subassembly storage, racks are installed to limit the number of subassemblies to 4 per pit and to provide for air cooling of the subassemblies.

*See footnote on page 7.

Basically, a storage rack consists of four $3\frac{1}{2}$-in.-OD by 3.068-in.-ID steel pipes (nominal 3-in. schedule 40 pipe) mounted vertically and equally spaced on a $6\frac{3}{4}$-in. circle. Only one subassembly can be inserted into each pipe. The 4 pipes are about $8\frac{1}{2}$ ft long, and are provided with a bottom manifold which supports and admits cooling air to the pipes. A pipe to supply cooling air extends from the bottom manifold upwards out of the pit. The pipes are provided with a top spacer and can be removed from the pit as a rigid unit. At the ends of the pipes special sections are provided for centering the subassemblies. At the tops the pipes are enlarged to facilitate insertion of the subassemblies by manipulators.

B. Storage of Ingots, Skull Oxide, and Melt Refining Crucibles Containing Unoxidized Skulls in Storage Pits in the Argon Cell

Fuel ingots, skull oxide, and melt refining crucibles with skulls will be stored in the Argon Cell pits. For transportation and storage these items will be placed in individual containers which will hold only limited amounts of these materials. For storage the containers will be placed in individual carriers, which, in turn, will be placed on shelves of the pit racks. Per rack or pit, there are 9 shelves spaced vertically 13 in. apart. The storage rack, shelves, carriers, and containers are arranged such that only one container can be placed on each shelf.

Ingot Container. The ingot containers are constructed of 4-in. schedule 40 pipe and hold only one melt refining ingot each. The container is $5\frac{13}{16}$ in. deep and has an inside diameter of 4.026 in. It has a volume of 1.21 liters, and is provided with a lid and lifting handles for movement by manipulators. The melt refining ingots are rectangular in horizontal cross section, have rounded corners and edges, and taper from bottom to top. The bottom dimensions are 2.446 by 2.805 in., and the top dimensions for the maximum length of 5 in. are 2.734 by 3.093 in. The maximum weight per ingot is 10 kg. The container is geometrically safe for 50 percent enrichment for water flooding.

Skull Oxide Container. The skull oxide container is round in horizontal cross section and tapers from bottom to top. The bottom and top inside diameters are $4\frac{11}{16}$ and 5 in., respectively, and the inside height of the can is $5\frac{5}{8}$ in. The can has a volume of 1.7 liters, is constructed of zinc, and has a tight press-in lid. It will hold, if completely filled, about $5\frac{1}{2}$ kg of skull oxide; however, the normal charge would be the oxides from one skull or less than 2 kg, an amount which would fill the container to a depth of less than 2 in. This can has a volume smaller than the allowable volume for metal-water mixtures of any $U^{235}$ density up to 10 kg/liter, which is greater than the possible density of 50 percent enriched uranium. It also has a safe diameter and volume for solutions.

Crucible Container. The container for a melt refining crucible is constructed of stainless steel and has a diameter of $6\frac{1}{2}$ in. and a height of about 10 in. It holds one crucible which is $5\frac{1}{8}$ in. in inside diameter and $8\frac{1}{2}$ in. deep, and which has a volume of 2.86 liters. When used for the storage of a crucible with skull, it will be provided with a tight-fitting lid. The skull normally weighs less than 2 kg and is less than 2 in. high. The maximum possible skull would be an unpoured melt of 10 kg which would be less than 2 in. high in the crucible. The crucible has a safe volume for water-metal mixtures of up to 18 kg of 50 percent enriched $U^{235}$, and has a safe diameter and volume for solutions.

Storage Rack. A storage rack consists essentially of nine 10-in.-diameter by $\frac{1}{4}$-in.-thick shelf plates supported by three one-inch vertical rods welded to the periphery of the plates. The plates are spaced 13 in. apart (center distances), and the three rods are spaced about 90 degrees apart, which leaves one space of 180 degrees for loading of material onto the shelves. The rods are about 120 in. long and are supported from a 14-in.-diameter top plate which also serves as the cover for the 12-in.-diameter pit. The carriers for the ingot, oxide, and crucible cans consist of $8\frac{3}{4}$-in.-diameter by 4-in.-deep pans which have handles for a manipulator tool. Since the shelves are 13 in. apart vertically and since fuel ingots, skull oxide in the containers, and skulls or unpoured melts in crucibles are limited to 5, 2, and 2 in. of height, respectively, in containers, there will be a space clear of fuel of 8 in. or more between the fuel items.

## C. Storage of Ingots, Skull Oxide, and Melt Refining Crucibles with Contained Skulls on Racks in the Argon Cell

Fuel ingots, skull oxide, and melt refining crucibles with skulls will be stored in small quantities in the Argon Cell on the shelves of racks attached to the wall of the central control area. The ingots skull oxide and crucibles with skulls will be stored in the containers described in Section B above. Only one rack is attached per wall face between windows, and thus the racks are not adjacent to each other but are about 7 ft apart.

The racks are about 31 in. wide, 92 in. tall, and extend out from the wall about 18 in. The racks are provided with extensible supports for movable shelves. The supports can be extended a total of 16 in. The 27-in. by 15-in. shelves can be moved completely out of the rack on the extensible supports for loading or unloading. The shelves themselves can be removed from the supports.

The shelves on which fuel is stored are 24 in. apart vertically and are provided with spacers to limit the number of fuel containers per shelf. The amount of fuel per shelf will be limited to 32 kg.

## IX. POSSIBILITIES AND EFFECTS OF OVERBATCHING

In handling fuel through the various process steps the possibility and effects of over- or double-batching must be considered. Possibilities of overbatching fuel in the various fuel configurations listed on pp. 11 and 12 and measures taken to prevent overbatching are as follows:

a. One subassembly in the coffin

The coffin will hold only one subassembly.

b. Subassemblies in the open

Administrative control only is needed.

c. Storage of subassemblies in pits

Mechanical apparatus will be provided to limit the capacity of each pit used for fuel subassembly storage to four assemblies (see previous Section VIII).

d & i. Fuel elements in the cells

The fuel elements are normally handled in magazines of which the capacities are:

| | |
|---|---|
| Fuel element magazine for disassembled fuel elements | 25 elements |
| Refabricated fuel element-handling magazines: | |
| "A" magazine | 20 elements |
| "B" magazine | 50 elements |
| Subassembly loading magazine | 91 elements |

Double-batching would not result in exceeding the recommended limit of 32 kg of fuel.

e. Decanned fuel pins

The decanned fuel pins are normally placed in the chopped-pin charger from which they are charged into the melt refining crucible. The crucible is $5\frac{1}{8}$ in. in inside diameter and $8\frac{5}{8}$ in. deep, and has a volume of about 180 cu in. In the test work it was found difficult to charge more than about 10 kg of pins into the crucible. Double-batching, therefore, is not possible, and, even if it were, would result in a quantity of fuel less than the 32-kg limitation.

The pin charger has a bottom area of about 280 sq in. and a volume of about 500 cu in. The normal charge for the charger is about one subassembly or 6.07 kg of fuel pins. Thus, double-batching would result in only 12 kg, which is considerably less than the 32-kg limitation. The charger would probably not hold more than 28 kg of randomly oriented chopped pins.

f. Melt refined or remelt ingots

The ingots from melt refining or remelting operations will be charged to the injection casting crucibles. The injection casting crucible is 6 in. in inside diameter and $3\frac{1}{2}$ in. deep, and the remelt crucible would be about the same size or possibly the size of the melt refining crucible. The injection casting crucible would hold only about 28 kg of fuel even if solidly filled with no voids. Remelt ingots might be charged into a melt refining crucible. Even by using ingots and chopped pins it would be difficult to get more than 15 kg of fuel in the melt refining crucible.

g. Heels, shards, and pin rejects

This material would be charged to injection casting, remelting, or melt refining crucibles. The pin charger or similar container will be used to move and store the small pieces. The volume of this container or other containers used to move or store these pieces will be small enough to provide adequate safety in the event of double batching.

h. Injection cast pins

The pins will be contained in pallets or pans in maximum quantities of 160 or less pins (less than 16 kg per batch). Accidental double-batching of even 160 pins would not exceed the limit of 32 kg.

i. Fuel elements in magazines

This has already been considered under item d.

j. Fuel elements which may be cleaned in trichloroethylene

At some time in the future it may be desirable to clean fuel elements (one subassembly or 91 pins) in trichloroethylene. If this is done, good nuclear moderation would be possible by accidental substitution of water for the trichloroethylene cleaner. In the event that cleaning of fuel elements is done, the container in which the elements are immersed will be geometrically safe, i.e., less than 5 in. in diameter, for double-batching of the normal charge of 91 fuel pins or 6.07 kg of fuel.

k. Melt refining skulls in crucibles

The crucibles with skulls will be placed in containers large enough for only one crucible and in oxidation furnaces large enough for only one crucible. The skulls are expected to contain only about one kg of fuel. Even an unpoured charge of fuel would contain only 10 kg. Double-batching would not be harmful.

l. Melt refining skulls in crucibles in water-cooled pits in the Argon Cell

The crucibles with skulls will be placed in containers, each large enough to contain only one crucible. The pits will be provided with racks to produce proper crucible spacing (see Section VIII).

m. Skull oxide in Argon Cell in containers and/or in water-cooled pits

Ordinarily, the oxide from only one skull (about 1 kg of fuel) will be placed in one container. The pits will be provided with racks to effect proper container spacing (see Section VIII). The recommended quantities and spacings given in Section VIII allow a safety factor for accidental double-batching.

n. Inadvertent mixing of fuel and graphite and/or beryllia

This is very unlikely in appreciable quantities. A very large quantity of graphite or beryllia intimately mixed with the fuel is required for attainment of criticality. Criticality would not be closely approached within the limits established for these materials.

o. Waste liquid tanks and evaporators

The recommended limit of allowable fissionable material in all waste liquid is less than one-quarter of the minimum critical mass for $U^{235}$ and less than two-fifths of the minimum critical mass for plutonium. Therefore, a mistake in computing quantities by a factor of two would not result in a possible critical mass.

p. Uranium-235 storage and handling

The recommended limits allow a safety factor for double-batching.

q. New unirradiated fuel elements or assemblies

The recommended limits allow a safety factor for double-batching.

r. Skull oxide being processed

The skull oxide will be charged into crucibles in skull reclamation process furnaces. Batch quantities of 5 kg are anticipated. Even if batch quantities of 10 kg were used, double-batching would not exceed the recommended limit of 32 kg. The maximum bulk density of the skull oxide averages less than 3 $g/cm^3$. If the allowance factor of 2.5 for oxide in combination with the minimum critical mass for enriched uranium with full reflector (22.8 kg TID-7016, Rev. 1, p. 10, 23, 24) is used, it may be shown that the minimum critical mass for the skull oxide would be greater than 114 kg (22.8 x 2.5 x 2), which is over 20 times that of a normal batch size.

s. Reclaimed uranium fuel in cakes

Cakes of not more than 8 kg of uranium fuel are anticipated (two runs each with 5 kg of oxide). Double-batching would not exceed the recommended limit of 32 kg of fuel.

t. Uranium lost in waste streams of skull reclamation process

The total loss is expected to be not more than five percent of the fuel in the skull oxide charged. The allowance factor for dispersal of fuel in noneffective moderators is at least three, and would result in a large allowable quantity of fuel in these wastes. It is difficult, therefore, to envision a criticality problem for these wastes.

u. Plutonium in blanket material to the extent of about 1 percent

There is no possibility of an unmoderated critical mass; however, the recommended limit is 2.6 kg of plutonium as a unit.

v. Plutonium concentrates

It is anticipated that the batch quantity of plutonium in processing will be 1 kg or less. Double-batching would not exceed the recommended limit of 2.6 kg.

## X. POSSIBILITY AND EFFECTS OF ACCIDENTAL FUEL ENRICHMENT

Uranium-235 will not be stored or stockpiled in the Air or Argon Cells. Since the amount to be added to compensate for 2 percent burnup and/or for melt refining skulls would be only about 200 to 600 g per melt refining or remelting charge of 10 kg, the possibility of introducing a full charge of fully enriched uranium should be remote.

The minimum critical mass of uranium-235 in fully enriched uranium (93 percent) with full reflector but without moderator is 22.8 kg. All normal charges or batches are considerably less in weight than the minimum critical mass of fully enriched uranium, as shown by the following list:

| | |
|---|---|
| Melt refining batch | 10 kg |
| Injection casting batch | $14\frac{1}{2}$ kg |
| Remelting batch | 10 kg |
| Skull oxidation | <10 kg |
| Pin processing | <$14\frac{1}{2}$ kg |
| Subassembly | 6.07 kg |
| Skull reclamation process batch | ~5 kg |

In the case of the storage pits, one fully enriched subassembly with three normal subassemblies or the skull oxide from one fully enriched melt refining charge along with the normal fuel oxide stored as recommended would be less than a critical mass.

## XI. REQUIREMENTS FOR CONTROL OF NUCLEAR CRITICALITY IN EBR-II FUEL CYCLE FACILITY

For purposes of recapitulation, the following summarizes the allowable limits of fuel, graphite, and beryllia in the EBR-II Fuel Cycle Facility. The allowable limits are stipulated as maximum-sized unit amounts of fuel, enriched uranium, and plutonium, and restrictions have been placed on the geometrical arrangements of the unit amounts.

### A. Fuel, Graphite, and Beryllia in Cells but Outside of Pits

The following limitations have been established with respect to handling of fuel, graphite, and beryllia in the Air and Argon Cells:

a) The maximum quantity of fuel to be handled as a unit is 32 kg.

b) The individual units of fuel will not be handled or placed at distances closer than 2 ft between centers and with less than 8 in. of clear space between units.

c) The total quantity of allowable fuel in the cells will be limited to 500 kg (including that in the pits). Thus, the maximum number of units in the cells will be less than sixteen.

d) The amount of graphite (or carbon) and beryllia in either cell (including locks) will be limited to 600 and 300 kg, respectively. Broken or scrap beryllia and graphite will not be allowed to accumulate in the cells.

e) Administrative procedures will be set up to insure adherence to the above limitations.

B. Fuel, Graphite, and Beryllia in Storage Pits

The following restrictions have been made with respect to storage of fuel and moderator materials in the storage pits:

a) No graphite or beryllia will be allowed in the storage pits, except for the trace amounts which might be present with fuel, melt refining skulls, or skull oxide.

b) The number of subassemblies in any storage pit in the air cell or passageway will be limited to four by mechanical and administrative control.*

c) The quantity of skull oxide in any one storage pit will be limited to a maximum of 32 kg. The skull oxide will be stored in cans which will not permit escape of fuel but which may not be water tight. A safe geometrical arrangement is insured, even in the event of water flooding, by use of cans with diameters of less than 5 in. and volumes of less than 3 liters.

d) The quantity of unoxidized skull present in crucibles stored in any one storage pit will be limited to a maximum of 32 kg of fuel. The crucibles will be individually stored in cans small enough to hold the crucibles in their original size. The cans may be permitted to flood with water but will not permit the escape of fuel.

e) Any metallic fuel stored in pits in the Argon Cell will be treated as if it were skull oxide unless it is stored as ingots in special containers (see Section VIII).

C. Fuel Outside Cells

Any fuel outside the cells would consist mainly of new fuel elements and subassemblies. Such fuel will be handled in maximum units of 32 kg of fuel with the spacing limits the same as that stipulated for handling of fuel inside the cells. A special storage area has been provided for fuel stored outside the cells.

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*See footnote on page 7.

D. Enriched Uranium-235

a) The maximum unit quantity for fully enriched $U^{235}$ (93 percent $U^{235}$) is 10 kg. An exception to this is fully enriched uranium that has been received in geometrically safe shipping containers.

b) As in the case of reactor fuel material, the individual units of fully enriched uranium will not be handled or placed at distances closer than 2 ft between centers or with less than 8 in. of clear space between units.

c) The fully enriched uranium-235 will not be stored in the cells. This eliminates the possibility of inadvertently preparing a batch of fuel pins from fully enriched $U^{235}$. Although sufficient allowance has been made so that inadvertent preparation of a single fully enriched batch would not result in a criticality incident, reactor operation with fully enriched fuel could be seriously affected.

d) Fully enriched $U^{235}$ will be stored in standard geometrically safe containers in a special storage area.

E. Plutonium Contained in Blanket Material and Concentrated in Blanket Processing Operations

The maximum plutonium for any unit quantity during or after processing will be limited to 2.6 kg. Units of this size will not be placed closer to each other or to fuel units than 2 ft between centers or with less than 8 in. of clear space between units. The maximum quantity of plutonium in the cell will be limited to five units (13 kg).

F. Waste Liquids

Aqueous waste liquids will be analyzed before concentration by evaporation. The total accumulation of fissionable material in all waste liquids will be limited to less than 200 g. Undoubtedly, these liquids would be processed to recover the fissionable material content long before the 200-g limit would be reached. Probably such liquids would be processed for recovery of the fissionable material content when this content reached about 10 g.

## XII. FUTURE CORE LOADINGS

It is anticipated that subsequent cores will be fabricated of plutonium with depleted or natural uranium as a diluent. The percentage of plutonium in such fuel will be less than the percentage of uranium-235 in the Core-I alloy (~50 percent) because of the greater reactivity of plutonium. If the plutonium fuel core size is the same as the Core-I size, the allowable mass for a unit of unmoderated but reflected fuel would be about the same as for the Core-I fuel, since the decreased concentration of the plutonium would compensate for its greater reactivity (LAMS-2415, p. 32). However, in the cases of possible effective moderation of the fuel, such as by water, the minimum critical mass would be considerably less. This would also be true in the event of accidental fuel enrichment.

Future cores may also consist of mixtures of plutonium and uranium-235 in natural or depleted uranium. The following from LAMS-2415, pp. 23 and 32, shows the critical masses of uranium-235 and plutonium for various volume fractions in uranium-238 with a thick ($7\frac{1}{2}$-in.) uranium reflector. The volume fraction of uranium-235 is based on a density of 18.8 g/cm$^3$ and that of plutonium on 14.2 g/cm$^3$, respectively:

| Volume Percent | Minimum Critical Mass, kg $U^{235}$ | Minimum Critical Mass, kg Plutonium |
|---|---|---|
| 100 | 15 | 6.5 |
| 90 | 16.5 | 7.1 |
| 80 | 18 | 7.8 |
| 70 | 19.5 | 8.7 |
| 60 | 22 | 9.9 |
| 50 | 25 | 11.4 |
| 40 | 30 | 13.7 |
| 30 | 36 | 17.2 |
| 20 | 50 | 24 |

Since one gram of plutonium-239 is equivalent to about 3 g of uranium-235, a fuel with 20 v/o (16 w/o) plutonium and 20 v/o (21 w/o) $U^{235}$ and 60 v/o $U^{238}$ would have a total critical mass of 45.6 kg of fuel (7.2 kg Pu and 9.9 kg $U^{235}$). For a full reflector corresponding to about 2 in. of uranium (or infinitely thick water), the critical mass would be about 65 kg of fuel, which is slightly less than that of 72 kg for the 50 percent $U^{235}$ fuel. On the same basis, a fuel of 35 v/o (29 w/o) plutonium in natural uranium would have a minimum critical mass of about 76 kg of fuel for a full reflector, while a fuel of 25 v/o (20 w/o) plutonium would have a minimum critical mass of about 115 kg of fuel. Thus, except for those instances in which water moderation is possible, batch sizes and spacing restrictions would be about the same as those established in this report for Core-I fuel.

If a larger reactor core were used with, say, only 25 percent uranium-235 enrichment in the fuel, larger unit masses could be used. TID-7016, Rev. 1, p. 24 shows an allowance factor of 2.5 for 25 percent enrichment. The "fully reflected" minimum critical mass would be 228 kg of fuel (22.8 x 2.5 x 4) and the recommended unit weight would be 100 kg of fuel (10 x 2.5 x 4).

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## XIV. BIBLIOGRAPHY

1. TID-7016, Rev. 1, Nuclear Safety Guide, revised by Subcommittee 8 of the American Standards Association. Sectional Committee N6, and Project 8 of the American Nuclear Society Standards Committee, Available from Office of Technical Services, Department of Commerce, Washington 25, D. C.

2. H. C. Paxton, Critical Data for Nuclear Safety Guidance, LAMS-2415 (Feb 1960).

3. H. C. Paxton and G. A. Graves, Critical Masses of Fissionable Metals as Basic Nuclear Safety Data, LA-1958 (April 1956).

4. H. C. Hoogterp, Critical Masses of Graphite-tamped Heterogeneous Oy-Graphite Systems, LA-1732 (May 1954).

5. H. C. Paxton, G. A. Linenberger, L. L. Lowry, R. N. Olcott, J. D. Orndoff, and J. E. Sattizahn, Bare Critical Assemblies of Oralloy at Intermediate Concentrations of $U^{235}$, LA-1671 (May 1954).

6. F. F. Hart, Safety Tests from Melting and Casting (Oralloy) (Uranium Isotopes), LA-1623 (Dec 1953).

7. E. C. Mallary, Oralloy Cylindrical Shape Factor and Critical Mass Measurements in Graphite, Paraffin, and Water Tampers, LA-1305 (Oct 27, 1951).

8. H. F. Henry, A. J. Mallett, C. E. Newlon, and W. A. Pryor, Criticality Data and Nuclear Safety Guide Applicable to the Oak Ridge Gaseous Diffusion Plant, K-1019 (5th Rev.) (May 22, 1959).

9. K-1380, Studies in Nuclear Safety, Lectures Presented at Nuclear Safety Training School Conducted by Union Carbide Nuclear Co., June 3-14, 1957, Oak Ridge Gaseous Diffusion Plant, Aug. 14, 1958.

10. ANL-5800, Reactor Physics Constants (1958).

11. J. C. Hesson, M. J. Feldman, and L. Burris, Description and Proposed Operation of the Fuel Cycle Facility for the Second Experimental Breeder Reactor EBR-II, ANL-6605 (April 1963).

12. D. C. Hampson, Preparation of Alloy for First Core Loading of EBR-II, ANL-6290 (Aug 1961).