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ATOMICS INTERNATIONAL A Division of North American Aviation, Inc.		AI Memo 8810 TDR NO Rev. I	APPROVALS <i>Norman Ashley</i> <i>M.E. Remley</i>
TECHNICAL DATA RECORD		PAGE <u>1</u> OF <u>29</u>	
AUTHOR N. Ketzlach	DEPT & GROUP NO 779-20	DATE 8-28-63	
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TITLE Criticality Study, Five Per Cent U-235 Enriched Fuel Fabrication		S A NO 0102	RECOMMENDED FOR OUTSIDE DISTRIBUTION ☒ YES ☐ NO <i>M.E. Remley</i> SIGNATURE
		TWR	
PROGRAM HALLAM CORE II	SUBACCOUNT TITLE Engineering and Administration		
DISTRIBUTION USE AN ASTERISK (*) TO INDICATE THOSE WHO ARE TO RECEIVE COMPLETE COPIES	STATEMENT OF PROBLEM A request has been made to establish nuclear safety criteria for the fabrication, storage, and shipment of 5 per cent U-235 enriched fuel. The starting fuel materials are UO ₂ and U metal (required in melting operation for adjusting the fuel carbon content).		
R.L. Ashley * M.H. Binstock * T.E. Cartt * J.J. Droher * P.E. Fleming * W.H. Friske * D.W. Haught * R.B. Gordon * F.G. Gronemeyer * R.K. Holbrook * N. Ketzlach(2) * J.C. Lang * R.S. Lubomirski * K.L. Mattern * A.S. Melgun * H. Pearlman * A.R. Piccot * E.L. Reed * M.E. Remley * F.W. Schlapp * J.F. Soppet * P.L. Soske * S.J. Spiegel * J.F. Trevillyan * W.R. Vaughn * A.R. Yarrow * J.M. Young * R.M. Peterson * H. Rood *	ABSTRACT Nuclear safety criteria have been determined for all process steps involved in the fabrication of 5.0 per cent U-235 enriched UC fuel rods. Criteria are also presented for the storage and processing of the feedstock and all intermediate forms of the fuel to the finished product. This includes criteria for the shipment of the assembled fuel rods. Criteria, presented for large batch sizes, are based on container geometry control. This allows for safe batch sizes of 60 kg uranium in a single melting and casting operation. Suggestions are made for ensuring safety in the event of crucible rupture accompanied by water flooding. Taking into account the neutron poisoning of the steel support tubes in the fuel loading retort, seventy five rods are safe (75 per cent of calculated critical independent of spacing between rods or the degree of water flooding). Where safety is not controlled by container geometry or double batching is possible, safe limits are based on 45 per cent of critical under conditions of optimum water moderation and reflection. Recommendations for the design of a shipping container using foamglass as a packaging and neutron poison material are made. An array of such containers (with 16 rods/container) could not be made critical under any conditions of water flooding. The use of styrofoam, however, as used in earlier shipments would limit the maximum safe number of shipping boxes to seven.		

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INTRODUCTION

The fabrication of the UC fuel elements involves a number of processing steps: (1) receiving of UO_2 and metal, (2) conversion of the UO_2 to UC, (3) casting of UC fuel slugs, (4) fabrication of the long fuel rods, (5) packaging and shipment of the rods to the reactor site, (6) assembly of the rods into eight-rod clusters, and (7) storage of the fuel element clusters.

The fuel having a density of 13.6 gm/cm^3 is to contain 4.8 per cent carbon and 95.2 per cent total uranium.

METHOD OF ANALYSIS USED

Although the UC fuel of interest is 5.0 per cent U-235 and has a density of 13.6 gm/cm^3 , advantage is taken of earlier studies^(1,2) made for this type fuel of 4.9 per cent U-235 enrichment and having a density of 13.4 gm/cm^3 . Based on these studies the maximum safe geometries for the 5.0 per cent enriched fuel (at optimum fuel piece size, water moderation, and water reflection) are only about 1.0 per cent lower than that for the 4.9 per cent U-235 enriched fuel. The maximum safe batch size, on the other hand, (at optimum water moderation and reflection) for the 0.852-inch diameter slugs of interest is actually about 1.0 per cent greater than that for the 4.9 per cent U-235 enriched fuel having the same diameter. The conservatism of the method of calculation used in obtaining the safe criteria will be discussed further under "Discussion of Results" below.

The uranium feed stock to be handled may be U metal, UO_2 powder, or UC powder. For process steps involving these materials optimum fuel piece size and water moderation and reflection are considered when there is no control over these parameters. When fuel piece dimensions are fixed, the safe criteria will be based on the fuel size of interest but still under optimum conditions of water moderation and reflection. When safety of a given operation is based on container geometry, optimum water moderation and reflection will still be considered.

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The criticality conditions for water-flooded assemblies of fuel and water were made using S₄ (IBM cylindrical cell code for the calculation of thermal group constants), FORM (IBM code for calculation of fast-group constants, and AIM-5 (IBM code of a multigroup, one-dimensional diffusion equation) to determine critical dimensions of spheres and infinite cylinders containing fuel assemblies in water. These systems were considered to be water moderated and reflected by a 30 cm thick water reflector (equivalent to an infinite water reflection).

The FORM code contains the option of using or not using the Selengut-Goertzel approximation. For fuels of low enrichment studied using the Selengut-Goertzel approximation to define the neutron slowing down in water resulted in good agreement with experiment. Since it was felt that this agreement may have been fortuitous,⁽³⁾ the use of this approximation has been questioned in later studies. Not using the approximation results in higher calculated reactivities. This is conservative from a nuclear safety point of view. At the same time it is desirable not to be more conservative than necessary to establish a safe and economical operation. Therefore, calculations have been made⁽⁴⁾ for water lattices of 1/8-inch diameter highly enriched uranium fuel rods for comparison with experimental data. When the approximation was used in both the fuel core and in the water reflector, calculated critical masses were not less than experimental ones at all lattice spacings. Calculations were also made neither using the option in the core nor in the reflector as well as using it only in the reflector. Although smaller systems were calculated when the option was neither used in the core nor the reflector, the results were still conservative when compared with experiment when the approximation was used in the water reflector only. Therefore, the results used in the present study were based on using the approximation in the reflector only.

The neutron cross sections used are dependent on composition of the assembly and the ratio of water to fuel. They were calculated using

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TEMPEST (an IBM neutron thermalization code based upon the Wigner-Wilkins approximation for light moderators).

Material bucklings were calculated for various lattices of fuel in water from the critical sphere radii using 8 cm as the water-reflected extrapolation length. Critical cylinder diameters were calculated from these material bucklings for infinitely tall, water-reflected cylinders containing the fuel slugs or rods in water. The cross-sectional area of each critical cylinder multiplied by its corresponding concentration is the critical mass per unit length of cylinder. This in turn was used to calculate the maximum safe number of long fuel rods.

Critical, infinite-slab thicknesses are also calculated from material bucklings. For every fuel concentration there is a critical infinite-slab-thickness. The critical slab thickness multiplied by its corresponding concentration is the critical mass per unit area. When plotted as a function of concentration (water-to-fuel volume ratio), the critical mass per unit area goes through a minimum. Although safe, single plane arrays can be determined by this method, solid angle criteria have been generally used to evaluate safety of fuel arrays.

The same type analysis was made⁽⁶⁾ for styrofoam-filled steel shipping boxes containing a four-by-four rod array spaced on two-inch centers. The study made for 0.892-inch diameter rods of 4.9 per cent U-235 enriched fuel can be used for the 0.852-inch diameter rods of 5.0 per cent U-235 enrichment. Similarly, the results of the earlier study⁽¹⁾ for eight-rod element clusters can be used for the eight-rod element clusters (same spacing between rods).

DISCUSSION OF RESULTS

Data will be presented (based on homogeneous mixtures of finely divided 5.0 per cent U-235 enriched metal-water mixtures) that can be used to establish safe batch sizes for UO_2 -water mixtures. The data are based on an earlier study⁽⁷⁾. Figure 1 is a plot of the maximum safe mass

Figure 1

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(45 per cent of critical) as a function of spherical container diameter for homogeneous mixtures of finely divided metal of this enrichment and water. The safe masses given in Figure 1 are at optimum water moderation and reflection. The maximum safe batch size approaches 790 gm contained U-235 as the container volume continues to increase. The maximum safe batch size continues to increase as the container volume decreases and approaches infinity as the safe container volume of 15.0 liters is reached. The safe volume of 15 liters is based on a sphere whose diameter is 85 per cent of critical. Therefore, the safe volume is 61 per cent of critical. The Nuclear Safety Guide⁽⁸⁾ recommends a safety factor of at least 1.3 on critical volume dimensions. That this analysis is conservative is indicated by the fact that the indicated safe limits for mass and volume according to the Guide are 800 gm U-235 and about 17 liters, respectively. From Figure 1 it is seen that the maximum safe mass of contained U-235 in homogeneous mixtures of 5.0 per cent U-235 metal and water is 2.33 kg in 18.93 liters (5.0 gallons). This container size has been singled out since it has been used in the past by suppliers for shipment to AI.

UC feed material is prepared by mixing UO_2 with carbon in the proper proportions and sintering in an induction furnace. The C/U-235 atomic ratio in the mixture is about 20. This adds no significant moderation to the system.

Criticality data will now be presented for 4.9 per cent U-235 enriched UC fuels at optimum water moderation and reflection. Figure 2 is a plot of the maximum safe batch size (45 per cent of calculated critical) as a function of fuel rod diameter and is independent of container geometry. It is seen that the maximum safe batch size approaches 800 gm contained U-235 as the fuel rod diameter approaches zero (homogeneous mixtures of finely divided UC and water). Obviously, as the length of the fuel slug becomes smaller and smaller it becomes increasingly non-conservative to base the maximum safe batch size on the true slug diameter. The equivalent fuel rod diameter that must be used to establish safe batch sizes for slugs of a particular diameter is a function

Figure 2

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of fuel composition, surface-to-volume and mass ratio, sphere size for which maximum safe batch sizes are calculated, etc.

That the surface-to-mass ratio of the fuel is a good basis for determining equivalent fuel piece sizes has already been shown.⁽¹⁰⁾ Figure 3 can be used to determine the equivalent rod diameter for fuel rods of all length-to-diameter ratios. This curve should be used only in determining equivalent fuel rod diameters needed to establish safe mass limits for fuels having an enrichment ≥ 5.0 per cent U-235. It can not be used for fuels of lower enrichment because the minimum critical masses for these latter fuels at first decrease with decreasing rod diameter, go through a minimum, and then increase with further reduction in fuel rod diameter.

Applying these criteria to 0.852-inch diameter slugs as a function of slug length, the maximum safe batch sizes (45 per cent of calculated critical at optimum water moderation and reflection) are plotted in Figure 4. As the slug length continues to increase the maximum safe batch size approaches 1.64 kg contained U-235. As it approaches zero (homogeneous mixtures with water), the maximum safe batch size approaches 0.80 kg contained U-235.

It is too conservative to base maximum safe batch sizes for long fuel rods on data developed for slugs in spherical geometry (Figure 2). The maximum safe mass per unit length fuel rod principle will be used for this purpose. Figure 5 is a plot of the maximum safe mass per unit length of rod as a function of fuel rod diameter (at optimum water moderation and reflection). These values are 45 per cent of critical.

Consider 0.852-inch diameter rods that are six-inches long and those that are 10 feet long. The six-inch length slugs have a length to diameter ratio of 7.0. Therefore, their equivalent diameter is 0.80 inches, and the corresponding safe batch size is 1.57 kg contained U-235 (44 slugs). On the other hand a single 10-foot long rod contains 0.71 kg U-235. Based on the spherical geometry the maximum safe number of

Figure 3

Figure 4

Figure 5

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such rods would only be two. From Figure 5, the maximum safe number is calculated to be 12. The 12 rods are safe independent of length, container geometry, spacing between rods, and the degree of water flooding.

Larger numbers of such rods may be handled safely when encased in steel pipes.⁽¹¹⁾ An array of fuel rods, each enclosed in a steel pipe, is found in the fuel rod sodium bonding operation. The slugs are placed in a 20-mil thick 0.942-inch O.D. steel fuel tube. This tube in turn is located in an 83-mil thick 1-3/8-inch O.D. steel support tube. An array of these tubes containing fuel rods has been analyzed as a function of lattice spacing. For the purpose of this analysis the space between fuel and tube (normally filled with sodium) as well as between fuel tube and support tube and between support tubes was assumed to be filled with water. Such lattices would have the maximum reactivity as a function of spacing between fuel tubes. Figure 6 contains plots of the maximum safe number of such steel-encased fuel rods as a function of lattice spacing. Two curves are presented. The lower curve is based on 45 per cent of critical and must be used where double batching is possible. The upper curve is based on 75 per cent of critical where double batching is not possible. Such a condition might be considered where there are no more support tubes available in the assembly to accomodate more fuel tubes. Thus, if there are only 75 positions in which a single tube can physically be placed, it is not possible to add more fuel. The lattice spacing is given in terms of water-to-fuel volume ratio and also in terms of center-to-center distance between rods in a hexagonal lattice array. An added safety factor in the assembly under consideration is the fact that all the support tubes are located in two circular rows of a retort. Therefore, as many as 75 rods so loaded will be much less than 75 per cent of critical.

As mentioned earlier safety must be based on optimum piece size as well as water moderation and reflection when there is no control of fuel piece size. For the five per cent enriched U-235 fuel (UC) these safe parameters are 13.0 liters, 7.4 inches, and 2.6 inches, respectively for

Figure 6
MAXIMUM SAFE NUMBER OF RODS vs
LATTICE SPACING AND RATIO OF WATER-TO-FUEL VOLUME

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spheres, cylinders, and slabs.⁽¹⁾ The sphere volume is based on a safe radius whose dimension is 85 per cent of calculated critical. The safe cylinder and slab geometries were determined by a buckling conversion of the safe spheres to cylinders and slabs using 8 cm as the water-reflected extrapolation length. These compare with about 17 liters, 8.0 inches and 3.8 inches given in the Nuclear Safety Guide as safe for spheres, cylinders, and slabs containing 5.0 per cent U-235 enriched fuel and water. This is another example of the conservative approach used in the present nuclear safety analysis. Therefore, it is safe to use the UC criteria presented for both uranium metal as well as UO_2 when no other criteria are available. For containers of larger geometry, the maximum safe batch size is limiting. A crucible having a diameter of 10.5 inches and a depth of 18 inches has a volume of 25.5 liters. Based on Figure 1, the minimum critical mass in a sphere of this volume is 2.31 kg contained U-235. This compares with a critical mass of 1.78 kg contained U-235 for a 34 liter capacity container (see Figure 1).

It is planned to melt the UC for the slug casting operation in an arc furnace having a melting crucible of 7.4-liter capacity. This crucible is safe for all masses of U-235 even if water flooded. At the present time both the electrode and copper melting crucible are water cooled. Although thick copper reflection is more effective than water, it was indicated in the earlier study⁽²⁾ that if the copper reflector is no thicker than two inches (present design has a maximum copper thickness of 1 1/4 inches) and nuclear safety is based on infinite water reflection, the assembly will be safe.

Added safeguards must be considered to ensure safety in the event of rupture of the melting crucible with subsequent fuel spill out of it.

Consider a 60 kg uranium charge (3.0 kg contained U-235). This, of course, is safe inside the crucible. If it can all spill into an optimum configuration while water-flooded, it can be made critical. The minimum critical mass of five per cent U-235 enriched UC under these conditions is calculated to be 1.78 kg contained U-235. An obvious way of eliminating this prospect is to eliminate the source of water outside the crucible. One method of doing this is to incorporate a solenoid-operated dump valve in the furnace shell bottom that would automatically open when small quantities of water enter the bottom of this shell. The entire

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crucible charge can not be molten at one time with the cooling water passing through the crucible jacket. If the cooling water flow is stopped, the furnace charge could all be molten if the power remained on. However, the electrical power supply will not operate without cooling water. A system of interlocks has been incorporated in the furnace design that will automatically shut off the power if the water supply fails while melting and prevent the power supply from starting if the water fails before melting begins. It can be calculated (using Figure 1) that the fuel would have to distribute itself uniformly through a volume greater than 22 liters for criticality to occur with 60 kg of uranium (3.0 kg contained U-235).

The use of a constant volume recirculation system (with heat exchanger) could also be used to minimize the quantity of water that could enter the furnace shell because of a cooling system leak. Still another method would be to replace the water with coolants that have poor moderating properties (i.e., liquid metals). The use of boral plates⁽¹⁾ (spaced on two-inch centers) could be used as an additional safety factor where water flooding can not be eliminated and it can not be shown that the system would be safe in the event of a simultaneous fuel and water leak. This latter method of ensuring safety may be applicable to the UC sintering operation where the sintering crucible is safe by geometry (even if water flooded) and it is not practical to incorporate a dump valve as described above. Another more obvious method of eliminating water flooding from an induction sintering furnace is to use solid copper or solid molybdenum coils instead of water-cooled copper coils. In the absence of water or other moderation it is not possible to make fuel systems, having a U-235 enrichment no greater than five per cent, critical.

The casting mold is made of graphite. The graphite reflector thickness is nowhere thicker than one inch. Since infinite water reflection is assumed, it is conservative to base nuclear safety on water reflection alone. It was shown earlier that the maximum safe number (45 per cent of calculated critical) of fuel slugs (0.852 inches diameter by 12 inches long) is 22 based on optimum lattice spacing, water flooding,

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and in spherical geometry. Therefore a graphite mold containing no more than this many slugs is safe. Maximum safe batches based on water flooding at optimum lattice spacing are conservative when applied to graphite moderated or graphite and water moderated systems. This is verified by criticality studies that have been made⁽¹²⁾ for mixtures of both heavy water and light water with uranium. The study indicated that although there are certain reactor sizes for which the critical mass for bare spheres of contained U-235 is smaller for mixes of D_2O , H_2O , and U-235, the minimum critical mass at optimum moderation is smaller with H_2O alone as the moderator than with moderator combinations of both D_2O and H_2O . This should also hold true in comparing minimum critical masses at optimum moderation for H_2O -moderated systems and H_2O -C-moderated systems. Namely, the minimum critical mass is smaller for the water-only moderated systems. However, for a particular mixture of water and uranium the critical mass may be smaller for this mixture when graphite has been added.

Beyond the melting and casting operation (excluding machining operations) there is control of fuel piece size (i.e. 0.852-inch diameter slugs and long rods). For all other operations nuclear safety must be based on optimum fuel piece size. From the data calculated as a function of fuel piece size, the maximum k_{∞} and minimum L^2 and τ have been determined as a function of water-to-fuel volume ratio for optimum piece size at each moderation. These terms have their usual meaning in reactor physics. The combination of these parameters, as indicated, result in maximum calculated reactivities (conservative from the standpoint of nuclear safety). Figure 7 contains a plot of the maximum k_{∞} at optimum fuel piece size as a function of water-to-fuel volume ratio. The dotted portions of the curve (for water-to-fuel volume ratios less than 2 and greater than 20) are conservative extrapolations of the calculated data. Figure 8 contains plots of the minimum L^2 and τ at optimum fuel piece size as a function of water-to-fuel volume ratio. Although the neutron age at the lower water-to-fuel volume ratios increases with decreasing moderation (solid portion of the curve), more conservative values were used at these lower water-to-fuel volume ratios (dotted portion of curve). A more detailed

Figure 7

Figure 8

MINIMUM NEUTRON AGE AND DIFFUSION LENGTH SQUARED vs WATER-TO-FUEL VOLUME RATIO
(OPTIMUM FUEL PIECE SIZE)

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analysis of neutron age as a function of moderation and rod diameter for fuels of this enrichment is required before the larger neutron ages can be used at the lower moderations.

Although Figures 7 and 8 have been used in connection with solid angle criteria to determine safety of arrays of fuel pieces, maximum safe mass/unit area data are presented for completeness of the study and also to serve as guide lines for single-plane arrays. Figure 9 is a plot of the maximum safe mass per unit area (45 per cent of calculated critical) as a function of fuel rod diameter for 4.9 per cent U-235 enriched UC fuels at optimum water moderation and reflection. This data can also be conservatively used for UO_2 fuels because of the greater uranium density of UC.

In the use of the solid angle criteria, the safety of an individual storage unit whether it be a single container or stack of containers was evaluated by assuming water flooding and an extrapolation length of 8 cm. In no case where there are no previously approved criteria will the allowable k_{eff} be greater than 0.9. For the calculation of k_{eff} for interaction purposes an extrapolation length of 4.5 cm will be used (bare systems). This is conservative. In describing the application of the solid angle method,⁽¹³⁾ the geometric buckling for fast neutrons was taken to be 2.5 cm; and for thermal neutrons, 0.36. In the present study 4.5 cm was used for both the thermal and fast groups. This effectively is equivalent to assuming a larger container size and hence less neutron leakage out of a storage unit (conservative from a nuclear safety point of view). The k_{eff} of a single storage unit as well as allowable solid angles will be presented for several geometry containers that are of interest to this study. To increase the applicability of these criteria the safety of the containers chosen are based on optimum fuel piece size for maximum reactivity. Safety of arrays of other containers can be similarly calculated using the above criteria.

Figure 9

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The following formulation was used in calculating k_{eff} from Figures 7 and 8.

$$k_{eff} = \frac{k_{\infty} e^{-B^2 \tau}}{1 + L^2 B^2}$$

B^2 is the geometric buckling.

Presently planned for use in the storage of the UC fuel materials and elements of the subject enrichment are 5.0-inch I.D. x 11-inch high containers (individually or stacked in columns), possibly one-gallon cans, and 5.5-inch I.D. cylinders no longer than 15 feet; the latter, for finished fuel rods. A tabulation of the calculated k_{eff} of each of these containers and those for the drying tray and melting crucible, filled with fuel (optimum fuel piece and independent of quantity), water moderated (optimum moderation) and water reflected is presented in Table I. The allowable solid angle, based on the bare k_{eff} , is taken from the referenced report.⁽⁸⁾

Table I

k_{eff} Individual Storage Units

<u>Container</u>	<u>water reflected</u>	<u>bare</u>	<u>Allowable solid angle (steradians)</u>
1-gallon	.708	.445	4.55
5" Dia. x 11"	.640	.348	5.52
5" Dia. x 22"	.696	.395	5.05
Column of gallon cans (108" tall)	.866	.615	2.85
Column of 5" Dia. cans (108" tall)	.732	.420	4.80
60 kg UC melt crucible	.84	.645	2.55
5.5" Dia. x ∞	.776	.486	4.14
5-gallon*		.80 ⁽¹⁴⁾	1.00
12" x 18" x 2" drying tray	.73	.55	3.50

*May be used by supplier for UO_2

The five-gallon cans (independent of the quantity of UO_2) may be stored

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in an infinite single-plane square lattice array in which the center-to-center distance between cans is at least 40 inches. A single row of such cans is safe when placed on 24-inch centers. Fifteen such cans on 40-inch centers in a three-plane array (1.00 steradians) may be safely stored. If only two such planes are involved (three rows of cans/plane), 33 cans may be safely stored. If these cans are placed in 55-gallon drums (one can/drum) an infinite single row of drums is safe. Obviously, a larger number of containers would be safe if the quantity per container were fixed at lower masses than the maximum allowable per container.

Although criteria have been established for the storage of UO_2 in five-gallon containers, the 5.0-inch diameter by 11 inches tall can will be the basic storage container. It is planned to store these containers in columns of containers (no taller than 108 inches). If stored in the SS Accountability Vault, they may be stored in two rows (infinitely long) of columns. The columns of 5.0-inch diameter cans are held in position by three $3/8$ " diameter cold rolled steel rods spaced at 120° . They are bolted to the tops and bottoms of steel shelves 36 inches apart. Three sections of these shelves make up the 108-inch column height. Two of the three rods are permanently bolted in place. The third one is bolted at one end to the top and bottom of a shelf. The other end of the rod is fixed in position by a bolt and wing nut to the shelf above. Removal of the bolt and wing nut allows the rod to be swung out so that a container can be removed from the column. The center-to-center spacing between rows is 20 inches and that between center-to-center of columns within a row is 27 inches. The solid angle of two such rows infinite in length is 2.57 steradians (4.8 steradians allowable in the Nuclear Safety Guide). Columns of one-gallon cans (108 inches tall) stored on the same spacing in two rows with this fuel would have a maximum solid angle of 3.49 steradians (maximum of 2.85 steradians are allowable). For the two-row column array of gallon cans to have a solid angle as low as 2.57 steradians, the center-to-center distance between columns within a row would have to be increased to 36 inches. The two-row arrays in the Vault will be at least eight feet (edge-edge) from an array of depleted or natural uranium which in turn is at least eight feet (edge-to-edge) from the next array of enriched material.

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Columns of the 5.0-inch diameter cans are to be used for in-process storage. A two-row array of columns (18 inches center-to-center between columns in a row and 30 inches center-to-center between rows infinite in length) has a solid angle of 3.34 steradians (4.8 steradians allowable). A single row of such columns on 18-inch centers has a solid angle of 1.24 steradians. A combination of a one-row and two-row array (perpendicular to each other and separated by at least six feet) has a maximum solid angle of 3.70 steradians.

It may become desirable to transport the 5.0-inch by 11-inch tall cans in 55-gallon drums. Criteria will be presented for arrays of drums, each containing two cans on top of each other and centered in the drum. A two-plane infinite array of such drums is safe (4.8 steradians) and a three-plane array may have as many as 118 such drums (5.05 steradians, maximum allowable in packages 5.0 inches in diameter by 22 inches tall).

All work stations are at least three feet from each other as well as from single rows of in-process storage arrays. The in-process storage arrays (one-and two-row columns of 5.0-inch diameter cans on 18-inch centers within a row and 30 inches center-to-center between rows) have been discussed above. There is at least six feet between the two-row arrays and any work station. An infinite row of 5.0-inch diameter columns (18-center-to-center between columns in the row) at eight feet from another array and parallel to it adds 0.69 steradians to the array. From an infinite single row array of columns of gallon cans (at the same spacing between columns) eight feet distant 0.94 steradians are added.

It is planned that safe carts will be used for in-process transport of fuel. This cart will contain two shelves, each having provision for two cans. The cans will be spaced at least 12 inches edge-to-edge from each other and at least 6 inches from the edge of a can to the edge of the cart. The solid angle from the containers on this cart when passing within 12 inches (nearest distance of fuel on cart to fuel in array or at work station) adds 0.72 steradians to the interaction solid

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angle. This solid angle has been considered in evaluating safety of both work stations and storage areas. If there are no larger containers or no containers having fuel of greater reactivity than the 5.0 per cent enrichment, the SS Accountability Vault storage described above (two rows of columns @ 20 inches center-to-center between rows and 36 inches center-to-center within a row) may be spaced closer than that given. In fact two infinitely long rows (columns of 5.0-inch diameter cans) at 20-inch centers between rows and 18 inches center-to-center between columns within a row have a solid angle of only 3.92 steradians (safe for fuels of this enrichment). This two-row array is safe when eight feet distance for a similar, one-row array (4.61 steradians). However, there is not sufficient allowance for safe carts passing between such arrays. Therefore, only one row would be allowed on 18 inch centers between columns or the distance between columns would have to be increased in a two-row assembly.

Where the fuel at a given work station is not fixed by geometry of a container, the work station area (for solid angle calculations) was assumed to occupy a cross sectional area of two feet by two feet. These criteria are presented to illustrate the method in which the solid angle calculations are used in the analysis of fuel assemblies of this enrichment.

Another type array that will be discussed is that of shipping containers (10" x 10" cross-section) containing assembled fuel rods. Fuel rods of 0.892-inch diameter having an enrichment of 4.9 per cent U-235 have been shipped in styrofoam filled boxes. The boxes, made of steel, are 0.134 inches thick. Criticality conditions for assemblies of styrofoam-filled boxes, each containing a four by four array of rods (spaced on two-inch centers) were determined⁽⁶⁾ using the method described in an earlier report.⁽¹⁵⁾ The criticality conditions were calculated as a function of center-to-center distance between boxes (assuming water flooding between boxes). Since there are no experimental points to check the calculations for styrofoam-moderated systems, the calculated k_{∞} 's as a function of spacing between boxes were increased by 25 per

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cent. The maximum safe number of such boxes (45 per cent of calculated critical based on the larger k_{∞} 's) at optimum spacing between water-flooded boxes is seven. A single-plane, infinite array of boxes with 24-inch centers between boxes (boxes may be placed end-to-end in the long dimension) is safe.

In the present study nuclear safety of such boxes, replacing the styro-foam by foamglass, was evaluated. Foamglass (a borosilicate glass) was recommended and tested in a proposed uranium container.⁽¹⁶⁾ The boron content of borosilicate glasses used, in the form of Raschig rings, to evaluate nuclear safety of aqueous uranyl nitrate solutions⁽¹⁷⁾ varied from 0.5 to 5.7 per cent boron by weight. In the present study it was assumed that the foamglass had a density of 0.141 gm/cm³ and a boron content of 1.6 per cent by weight.⁽¹⁸⁾ Figure 10 is a plot of the calculated k_{∞} 's (increased by 25 per cent above theoretical to cover uncertainties in the applicability of the method of calculations used) as a function of the center-to-center distance between boxes of water-flooded assemblies. It is indicated from this curve that an infinite array of such boxes (16 rods/box) could not be made critical independent of the degree of water flooding or the distance between boxes. By definition⁽¹⁹⁾ the poison incorporated in the foamglass as used in this study may be considered as a homogeneous poison. It was shown in an earlier theoretical study⁽²⁰⁾ that a homogeneous mixture of uranium oxide (three per cent U-235 enrichment), boron, and water could make such a system subcritical for all uranium concentrations. In fact the critical atomic ratio (maximum $k_{\infty} = 1.00$) of B/U-238 is 0.0135. Preliminary experiments in the PCTR at Hanford had indicated that for an H/U-238 atomic ratio of 3.5 the k_{∞} was equal to unity for a B/U-238 atomic ratio of 0.0102. The theoretical study indicated a k_{∞} of about 0.97 for such a system.

In a later study⁽²¹⁾ made for homogeneous systems of UO₂ (five per cent U-235 enrichment), water, and boron, the theoretical minimum B/U-238 atomic ratio for $k_{\infty} = 1.00$ was found to be 0.0283. The B/U-238 atomic ratio in the proposed foamglass-filled shipping box is 0.024 (0.45 equals B/U-235 atomic ratio). Although this is slightly less B than that theoretically calculated for optimum conditions in the UO₂-B-H₂O systems, it is a realistic safe value: (1) the UC fuel rods are

Figure 10

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lumped, (2) the two-inch centers between rods is not optimum, and (3) there is no void space within a shipping box for water to get between rods. Moreover, in an informal report⁽²²⁾, it was suggested that for uranium having an enrichment no greater than five per cent, an infinite number of packages should be safe provided the minimum B/U-235 atomic ratio was at least 0.48. The B/U-235 content of 0.45 in the shipping container being studied is therefore a very reasonable concentration to make an infinite array safe.

Upon unpacking the shipping boxes, the elements are assembled into eight rod clusters. In the fuel fabrication area, and possibly at the cluster assembly area, the fuel rods may be temporarily stored in 5.5-inch I.D. tubes. Based on Table I eight such tubes in three rows spaced on 18-inch centers, are safe independent of the number of fuel rods within tubes or the degree of water flooding. Eighteen such tubes are safe in a two-row assembly with 18 inches between tube centers within a row as well as between rows.

The rods are to be assembled into eight-rod clusters which are to be placed in 4.20-inch I.D. process tubes. In an earlier study⁽¹⁾ it was shown that two such clusters are safe (less than 45 per cent of critical) independent of spacing between clusters or the degree of water flooding. It was also shown in the same study that an array of these clusters spaced on the Hallam fuel storage pit lattice spacing is safe independent of the degree of water flooding.

Safety of arrays of these clusters in assembly areas have also been calculated using solid angle criteria. Because the maximum k_{eff} (0.65 for the reflected case and 0.32 for the bare case) for an individual cluster was based on a 4.2-inch diameter tube and the fuel material considered was optimum piece size at optimum moderation, safety of these tubes apply to all forms of UC fuel having enrichments no greater than 5.0 per cent U-235. A two dimensional array of such tubes or element clusters are safe (maximum of 31 assemblies) with an 18-inch center-to-center distance between rows of tubes as well as between tubes within a row. A two-row assembly of tubes (independent of the length of the rows) is safe with the same spacing between tubes or clusters.

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