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Westinghouse Astronuclear Laboratory

REVIEW OF ASTROFUEL CRITICALITY LIMITS

FOR INCREASED FUEL LOADING

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October 1966

REVIEW OF ASTROFUEL CRITICALITY LIMITSFOR INCREASED FUEL LOADING

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1.0 INTRODUCTION

The criticality limits imposed on the various phases of NRX-A fuel fabrication at the Astrofuel facility are specified in Section II (Revision 0) of WANL-TME-621, "Criticality Hazards Control Procedures" for a maximum fuel loading of 500 mg U/cc. The effect on these limits of increasing the fuel loading in the fabrication process has been determined for those operations where the nuclear safety design is affected by fuel loading. Additional details on the fabrication process, the flow of material in the process, and the arrangement of equipment can be found in WANL-TME-621.

Reactivity calculations were made with the DTK transport code and the 16-group Hansen cross sections which include anisotropic hydrogen scattering. The applicability of these analytical tools to NERVA criticality calculations was demonstrated in prior studies on NERVA fuel lattices*. Except for the furnace fixtures, where a parametric study of the effect of fuel loading and coolant channel diameter on reactivity was accomplished, a fuel loading of 600 mg U/cc was used in the analysis. The results of this safety review are presented below under the following main headings: Furnace Fixtures, In-Process Handling, and Storage-Shipping Arrays.

As a result of the detailed analysis presented herein, it is concluded that the criticality limits and procedures currently in effect at Astrofuel are still applicable for a fuel loading of 550 mg U/cc** with the exception of the annular graphitizing fixture (Type II) which exceeds the maximum acceptable reactivity ($k = 0.9$) under flooded conditions. In order to extend the process to higher loadings and/or coolant channel diameters, it will be necessary to modify the criticality design of several fixtures - either by decreasing the batch size or by incorporating nuclear poison in the fixture assembly.

* WANL-TME-760, "Criticality of NRX-A Fuel Lattices", April 1964.

** This is maximum fuel loading contemplated at the time this work was in progress.

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It is intended that this document support changes in the Astrofuel Criticality Hazards Control Procedures (WANL-TME-621) which will be required if WAFF plans to increase the current fuel loading limit of 500 mg U/cc.

2.0 FURNACE FIXTURES

A parametric study was made of the effect of fuel loading (at constant coolant channel diameters of 0.115") and coolant channel diameter (at constant fuel loading of 500 mg U/cc) on the reactivity of each furnace fixture used at Astrofuel; the results of this study are summarized in Figures 1-9. For the induction furnaces, the graphite susceptors were specifically treated in the reflector region since this graphite-water configuration is slightly more reactive than a pure water reflector. The figures reveal that within the fuel coolant channel diameters of interest, the reactivity of the fixture assemblies increases as the size of the channel is increased. Reduction in the across-flats (AF) dimension in the course of the heat treating processes was taken into account.

The maximum reactivity of each furnace fixture when flooded with water was inferred from the appropriate figure and is listed below along with the assumptions used for each furnace configuration and for the fuel dimensions corresponding to the current NRX-A fabrication process. The fuel coolant channel diameter listed (.100 inches) is the largest size achieved during present fabrication operations. On the basis of these results, it is concluded that all furnaces may be safely operated with existing equipment for NRX-A fuel loadings that do not exceed 550 mg U/cc with the exception of the annular graphitizing fixture (Type II) which must be restricted to the current loading limit (500 mg U/cc) until a criticality design change is accomplished.

The nuclear safety implications of changing the process to a higher uranium loading and/or larger coolant channel diameters can be determined from the parametric curves.

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CURING FIXTURE - Figure 1

Furnace: Fixture is 7.75" high x 14" deep x 60" long consisting of five vertical layers of fuel elements. Each layer contains nine fuel elements, each of which is placed in a hexagonal cavity with an across-flats (AF) dimension of 0.826".

(Calculations performed on cylindricalized model with effective diameter of fuel region of 10.46 inches, surrounded by .587" graphite annulus).

Water reflector

45 fuel elements homogenized over fixture

Fuel: .100" coolant hole
.816" AF
550 mg U/cc
60" length

Reactivity: $k = 0.72$

BAKING FIXTURE (CYLINDRICAL) - Figure 2

Furnace: 13.5" O.D. fixture with .936" diameter holes
 B_4C rod (.7874" diameter) in center* with N (boron) = $.0544 \times 10^{24}$ at/cm³
Water reflector
69 fuel elements homogenized over fixture

Fuel: .100" coolant hole
.806" AF

* The center of the actual baking fixture is occupied by a steel support member and hence three poison rods located on a 7.25 inch diameter circle and 120° apart have been substituted for the central poison rod.

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550 mg U/cc

60" length

Reactivity: $k = 0.81$

BAKING FIXTURE (ANNULAR) - Figure 3

Furnace: 16.5" O.D. x 9.0" I.D. fixture with .936" holes

Water reflector

90 fuel elements homogenized over fixture

Fuel: .100" coolant hole

.806" AF

550 mg U/cc

60" length

Reactivity: $k = .82$

GRAPHITIZING FIXTURE (I) - Figure 4

Furnace: 8" O.D. fixture with 0.914" diameter holes

Graphite-water reflector (furnace mockup)*

35 elements homogenized over fixture

Fuel: .100" coolant hole

.795" AF

550 mg U/cc loading

60" length

Reactivity: $k = 0.77$

*

Furnace susceptor region consists of 0.78 inches water, 1.0 inches graphite at 1.7 gm/cc, 2.50 inches graphite at 0.7 gm/cc and finally 8.0 inches of water.

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GRAPHITIZING FIXTURE (II) - Figure 5

Furnace: 17.5" O.D. by 8.23" I.D. with .914" diameter holes
Graphite-water reflector (furnace mockup)*
90 elements homogenized over fixture

Fuel: .100" coolant hole
.795" AF
550 mg U/cc
60" length

Reactivity: $k = 0.91$

GRAPHITIZING FIXTURE (III) - Figure 6

Furnace: 9" O.D. fixture with 1.062" diameter holes
Graphite-water reflector (furnace mockup)*
Fixture divided into 7 annular zones corresponding to the distribution of fuel along 3 concentric circular rings and the intervening layers of structural graphite between these annular fuel regions.
35 element capacity

Fuel: .100" coolant hole
.795" AF
550 mg U/cc loading
54" length

Reactivity: $k = .90$

* Furnace susceptor region consists of 0.78 inches water, 1.0 inches graphite at 1.7 gm/cc, 2.50 inches graphite at 0.7 gm/cc, and finally 8.0 inches of water.

LEACHING-COATING FIXTURE (I) - Figure 7

Furnace: 8.44" O.D. with 0.873" diameter holes
Graphite-water reflector (furnace mockup)*
35 elements homogenized over fixture

Fuel: .100" coolant hole
.754" AF
550 mg U/cc
54" length

Reactivity: $k = 0.89$

LEACHING-COATING FIXTURE (II) - Figure 8

Furnace: 9" O.D. with 1.062" holes
Graphite-water reflector (furnace mockup)*
35 elements homogenized over fixture

Fuel: .100" coolant hole
.754" AF
550 mg U/cc
54" length

Reactivity: $k = .90$

COATING FIXTURE (I) - Figure 9

Furnace: 8.44" O.D. fixture with 1.031" holes
Graphite-water reflector (furnace mockup)*
35 elements homogenized over fixture

*

Furnace susceptor region consists of 0.78 inches water, 1.0 inches graphite at 1.7 gm/cc, 2.50 inches graphite at 0.7 gm/cc, and finally 8.0 inches of water.

Fuel: .100" coolant hole
.754" AF
550 mg U/cc
54" length

Reactivity: $k = .88$

COATING FIXTURE (II)

Furnace: Open-well fixture with top and bottom support plates having maximum O.D. of approximately 7.25 inches and having a fuel capacity of 18 elements.

Fuel: .100" coolant hole
.754" AF
550 mg U/cc
54" length

Reactivity: In accordance with Figure 11, the minimum critical radius for a heterogeneous fuel array occurs at $H/U = 125$ and has been estimated to be 8.0 inches based on a material buckling $B_m^2 = .0195 \text{ cm}^{-2}$ and an associated reflector savings of 7.3 cm. The minimum critical number of elements in this heterogeneous array is approximately 40 elements, (Figure 10) which is about a factor of two (2) greater than the number of elements present in this particular fixture. In addition, the fuel is contained within a volume whose radius is less than the minimum critical dimension. It is therefore concluded that the open-well coating fixture is well subcritical for the above fuel specifications.

3.0 IN-PROCESS HANDLING

Criticality restrictions on the number of fuel elements that may be safely handled in a loose configuration are based on the minimum number of elements which can be made critical in a flooded and reflected lattice. The minimum number was previously* calculated to be 34 for elements with a 500 mg U/cc loading and was the basis for justifying 20 elements as a safe handling batch.

The analysis has been repeated for NRX fuel with a 600 mg U/cc loading. The results which are summarized in Figure 10 reveal that thirty (30) fuel elements are the minimum critical quantity for this higher loading. It is therefore concluded that the reduction in the minimum number of elements in a lattice of 550 mg U/cc fuel is not significant enough to necessitate a change in the existing limit of twenty (20) elements for in-process handling.

4.0 STORAGE-SHIPPING ARRAYS

The nuclear safety design of Astrofuel and shipping arrays were reviewed for a fuel loading of 600 mg U/cc. Data used for this analysis include Figure 11, which contains the variation in material buckling with H/U ratio for NRX fuel lattices and Figure 12, which presents the maximum multiplication factor (k_{eff}) for infinite cylinders at optimum moderation.

In-Process Storage Array

Array: Four shelves in a vertical arrangement with a 12-inch edge-edge shelf spacing and effectively infinite in length. Each shelf may contain two fuel trays situated side-by-side (4.75" wide x 3.75" high) with a maximum spacing of 0.5 inches between them.

Fuel: Heterogeneous distribution of NRX design fuel elements with a 600 mg U/cc loading.

* WANL-TME-760, "Criticality of NRX-A Fuel Lattices", April 1964.

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Reactivity: The equivalent radius of the fuel contained in the two close-packed fuel trays on a shelf is 8.6 cm. Based on the calculated maximum value of the material buckling from Figure 11 for a moderated lattice of NRX fuel elements ($B_m^2 = .020 \text{ cm}^{-2}$) and a reflector savings of 7.3 cm, the minimum critical radius of an infinite reflected cylinder is 9.7 cm. The cylindrical dimension of the fuel contained in the trays is 13% smaller than the minimum critical dimension of a flooded and reflected system. Considering the slab configuration in which the fuel is actually arranged and the 0.5-inch spacing that may exist between trays, a geometric buckling of $B^2 = 0.0232 \text{ cm}^{-2}$ is obtained. Since this value exceeds the material buckling quoted above, a flooded and reflected shelf is sub-critical with this additional moderation provided between trays. It is estimated that the effective reduction in geometric buckling due to neutron interaction between shelves (8.25" edge-edge fuel spacing) is in the order of 1% and hence the spacing between shelves limits neutron interaction under fully flooded conditions to an acceptable level. Under drained conditions (water in coolant channels alone), the maximum solid angle intercepted by any shelf is $\bar{\Omega} = 3.0$ steradians. However, the maximum k_{eff} of a bare moderated cylinder having a radius of 8.6 cm is $k_g = 0.58$ (see Figure 12) which is the upper limit on reactivity imposed by the multiplication factor-solid angle criteria contained in TID-7016. Thus, the array is nuclear safe, even for an array of fully moderated and unreflected trays.

Scrap Containers

Container: Six inch (Sch. 40) pipe centered in a 55 gallon steel drum. Fuel material scrap is packaged in 1/2 gallon plastic wide-mouth bottles which have a 4.7 inch I.D.

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Fuel: Uranium-carbon material in powder form with a fuel loading of 600 mg U/cc ($C/U = 60$).

Reactivity: The maximum k_{eff} of an infinite 4.7" diameter cylinder of 600 mg U/cc ($C/U = 60$) fuel at optimum moderation and full reflection is shown in Figure 12 to be $k = 0.75$. Each individual scrap container is therefore safe under flooded conditions while a minimum water thickness of 16 inches between fuel as provided by the container design assures that there will be no significant interaction between containers. Arrangement of the scrap containers during shipment and storage has been specified such that the maximum solid angle of interaction is approximately 6.0 steradians. The maximum k_{eff} of an unreflected 4.7 inch diameter cylinder at optimum moderation is $k_e = 0.30$ which is the limit imposed on the reactivity of an individual unit by the TID-7016 solid angle criteria. Hence, the previously specified array of scrap containers is safe under completely flooded and unreflected conditions for 600 mg U/cc fuel even if the existing double-seal design were compromised.

Fuel Shipping Birdcage

Container: Sixteen suitcases (5" I.D.) arranged in a square lattice on 14-inch centers.

Fuel: Homogeneous distribution of fuel with $C/U-235 \approx 61$ (600 mg U/cc) in cylindrical geometry and infinite length.

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Reactivity: The maximum k_{eff} for a single suitcase with optimum moderation and full reflection is shown in Figure 12 to be $k = 0.78$. Hence, an individual storage unit is safe under fully flooded conditions. The array of sixteen suitcases is also nuclear safe if fully-flooded since no significant neutron interaction exists with the 9" water spacing between suitcases. In the event of partially drained conditions wherein water is retained within the suitcase and the water between suitcases has drained off, nuclear interaction will occur between the moderated but unreflected suitcases. The total solid angle intercepted by the central suitcase is $\bar{\Omega} = 3.64$ steradians which limits the maximum k_{eff} of a moderated unreflected suitcase to $k_e = 0.52$. Since the reactivity of a bare suitcase has a maximum value of $k_e = 0.35$, the array is also safe under a drained condition.

Storage Vault

The nuclear safety design of the Astrofuel storage vault containing fuel beads and 500 mg U/cc fuel elements was presented in WANL-TME-687, "Nuclear Safety Design of the Astrofuel Vault Using Boral Spacers." To evaluate the safety of increasing the fuel loading to 600 mg U/cc, the same analytical models were employed except that the isotropic hydrogen cross sections used previously were replaced by the more accurate anisotropic set. Furthermore, a more realistic reflector savings ($\lambda = 9$ cm) based on experimental slab data was utilized in preference to the conservative value previously assumed ($\lambda = 10$ cm). The net result was a reduction in the multiplication factor.

Applying this revised analytical method to an array of 600 mg U/cc fuel, a multiplication factor $k_e = .81$ was obtained for a flooded and reflected shelf of fuel trays separated by boral spacers. Since the vertical edge-edge spacing between fuel trays in the array is in excess of 12 inches, the array of five shelves is nuclear safe under flooded conditions.

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The reactivity of the array under drained conditions has been shown to be so low in the previous analysis (WANL-TME-687) that the modest change in loading considered here does not have any safety significance.

For partially flooded conditions, the multiplication factor of a moderated, half-reflected shelf is $k_e = 0.60$. Even for the highly conservative assumption that fast neutron leakage $(1 - U_f)$ is unity, the multiplication factor of the array is acceptable ($k = 0.61$).

Hence, it is concluded that the Astrofuel vault is safe under all conditions of flooding for fuel loadings that do not exceed 600 mg U/cc.

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FIGURE 1
CURING FIXTURE (CYLINDRICALIZED)
10.5" EFFECTIVE DIAMETER - CAPACITY: 45 ELEMENTS

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FIGURE 2

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BAKING FIXTURE (CYLINDRICAL)

13.5" DIAMETER - 0.936" (DIAMETER) ELEMENT HOLES

CAPACITY: 70 ELEMENTS - B_4C ROD IN CENTRAL HOLE

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FIGURE 3

BAKING FIXTURE (ANNULAR)

16.5" O.D. x 9.0" I.D. - 0.936" (DIAMETER) ELEMENT HOLES

CAPACITY: 90 ELEMENTS

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FIGURE 4

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GRAPHITIZING FIXTURE (I)

8.0" DIAMETER - 0.914" (DIAMETER) ELEMENT HOLES

CAPACITY: 35 ELEMENTS

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FIGURE 5

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GRAPHITIZING FIXTURE (II)

17.50" DIAMETER WITH 8.229" (DIAMETER)

CENTER HOLE 0.914" (DIAMETER) ELEMENT HOLES - CAPACITY: 90 ELEMENTS

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FIGURE 6

GRAPHITIZING FIXTURE (III)

9.0" DIAMETER - 1.062" (DIAMETER) ELEMENT HOLES

CAPACITY: 35 ELEMENTS

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FIGURE 7

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COATING AND LEACHING FIXTURE (I)

8.44" DIAMETER - 0.873" (DIAMETER) ELEMENT HOLES

CAPACITY: 35 ELEMENTS

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FIGURE 8

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COATING AND LEACHING FIXTURE (II)

9.0" DIAMETER - 1.062" (DIAMETER) ELEMENT HOLES

CAPACITY: 35 ELEMENTS

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FIGURE 9

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COATING FIXTURE (I)

8.44" DIAMETER - 1.031" (DIAMETER) ELEMENT HOLES

CAPACITY: 35 ELEMENTS

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FIGURE 10
 H/U^{235}

CRITICAL NUMBER OF NRX-TYPE FUEL ELEMENTS IN
FLOODED AND REFLECTED LATTICES

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FIGURE 11
 VARIATION OF MATERIAL BUCKLING WITH H/U RATIO FOR
 HETEROGENOUS LATTICES OF NERVA FUEL

FIGURE 12

MAXIMUM k_{eff} FOR BARE AND REFLECTED INFINITE CYLINDERS LOADED WITH
600 mg U/cc FUEL AT OPTIMUM MODERATION