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^{233}U JEZEBEL:
A BARE SPHERE OF URANIUM-233 METAL

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1.0 DETAILED DESCRIPTION

1.1 Overview of Experiment

In 1961, the ^{233}U Jezebel critical assembly was fabricated and operated at the Los Alamos Scientific Laboratory. There were actually three Jezebel assemblies built, one using Pu (4.5 at.% ^{240}Pu) and referred to as the ^{239}Pu Jezebel, one using Pu (20.1 at.% ^{240}Pu) and referred to as the ^{240}Pu Jezebel, and one using ^{233}U and referred to as the ^{233}U Jezebel. Only the ^{233}U Jezebel is described in this report. The ^{233}U Jezebel was an unreflected, or bare, ^{233}U metal critical assembly, nearly spherical in shape. The uranium was 98 at.% ^{233}U and was unalloyed. The ^{233}U Jezebel is considered to be acceptable for use as a benchmark critical experiment.

The ^{233}U Jezebel was successfully operated only from January 11 through August 9, 1961, during which time several critical experiments were performed, including a number of reactivity worth measurements.[a] After its last use in 1961, the ^{233}U Jezebel was disassembled and the material used for other purposes.

1.2 Description of Experimental Configuration

For criticality safety purposes, the nearly spherical mass was constructed in four major pieces, each of roughly the same mass, which were assembled to provide three-part subdivision for operational safety. All parts were nickel plated. The assembly was designed to be highly reproducible and to have minimum reflection, while retaining experimental flexibility. The following features ensured that these three design criteria were satisfied: (1) light but rigid framework and supports; (2) self-aligning of the three subdivisions by means of guide wires that supported the central section and a ball and socket support for the upper section, and (3) three uniform mass adjustment buttons, or plugs, to supplement the single control rod bar. A "glory hole" through the center of the assembly was provided for experimental reactivity worth measurements. Although there were no photographs taken of the ^{233}U Jezebel, the original experimenters stated that the ^{233}U Jezebel was virtually indistinguishable from the original ^{239}Pu

[a] U233 Jezebel Logbook, Pajarito Site, Los Alamos National Laboratory.

Jezebel.[a] Figure 1[b] shows the original Jezebel in its fully assembled configuration. Note the lightweight framework used to minimize the presence of neutron-reflecting material.

Figure 2 (Reference 1) shows the ^{233}U Jezebel with the control rod slot, glory hole, and mass-adjustment plugs. Two different configurations of the ^{233}U Jezebel were used in the basic critical experiments. Configuration A contained 16.556 kg uranium at an average density of 18.424 g/cm^3. The assembly was 25 cents supercritical with the three mass-adjustment plugs removed, the glory hole filled except for one 1.6 inch-long filler piece removed from the end, and the control rod fully inserted. Based on reactivity worth measurements and control rod calibrations, with all mass adjustment plugs in place, the glory hole completely filled, and the control rod fully inserted, the critical mass of the actual assembly would be 16.235 kg uranium at an average density of 18.424 g/cm^3. Configuration B contained 16.651 kg uranium at an average density of 18.424 g/cm^3. This configuration was 1 cent subcritical with all three mass adjustment plugs in place, a 0.5 in.-long cavity at the glory hole center, and the control rod fully inserted. Based on reactivity worth measurements and control rod calibrations, with the glory hole filled, the three mass adjustment plugs in place, and the control rod fully inserted, the critical mass would have been 16.269 kg uranium at a density of 18.424 g/cm^3.

From these two configurations (whose critical mass predictions differed by only 34 g uranium) the authors of Reference 1 used the mean value of the two masses to define the critical mass for the ^{233}U assembly (with the three mass adjustment plugs installed, the glory hole filled, and the control rod fully inserted) as 16,252 ± 17 g uranium at a density of 18.424 g/cm^3.

There has been no attempt to model the exact ^{233}U Jezebel assembly for calculational purposes. Instead, through careful analyses and experimental measurements by the Los Alamos experimenters, corrections were determined to convert the actual Jezebel configuration to an idealized bare sphere of homogeneous ^{233}U, which is amenable for calculation (Reference 1). A discussion of these corrections and the resulting idealized ^{233}U Jezebel benchmark model is provided in Section 3.1.

1.3 Description of Material Data

As detailed in Reference 1, the average composition of the ^{233}U is shown in Table 1.

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[a] Personal communications, Hugh C. Paxton and Gordon E. Hansen, 1993.

[b] Los Alamos National Laboratory Photo Negative 31643.

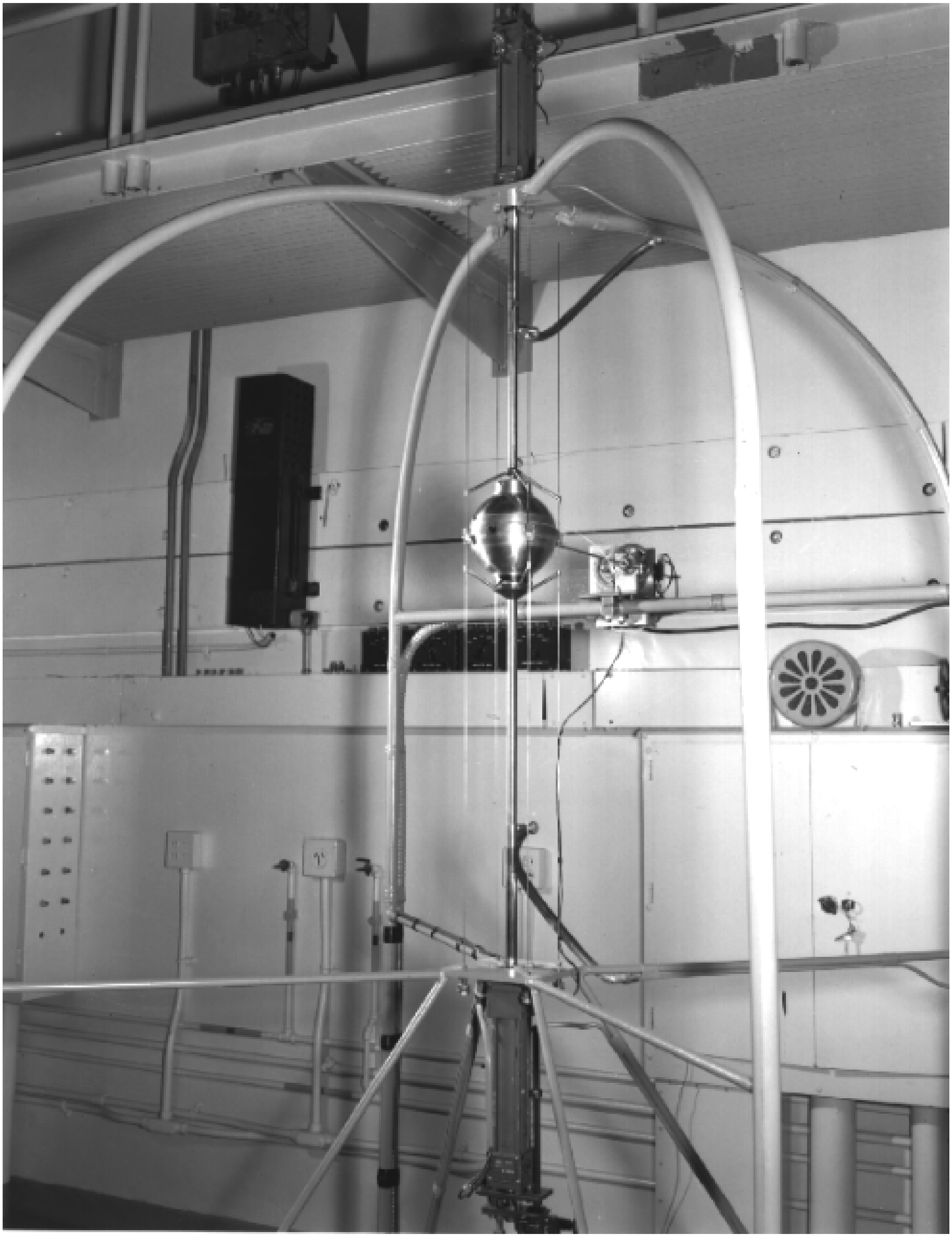

Figure 1. The Original Jezebel in its Assembled Configuration. The ^{233}U Jezebel was Essentially Identical in Appearance.

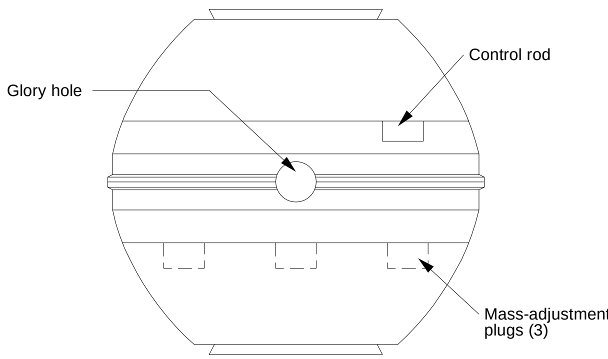

Figure 2. ^{233}U Jezebel Core, Showing Mass-Adjustment Plug Locations Used in Critical Experiment.

Table 1. Composition of the Uranium in ^{233}U Jezebel.

Isotope	Abundance, at.%
^{233}U	98.13
^{234}U	1.24
^{235}U	0.03
^{238}U	0.60

Impurities in the alloy constituted about 400 parts per million (ppm) as follows: carbon (160 ppm, atom density = 1.4780×10^{-5}), silicon (110 ppm, atom density = 4.3455×10^{-5}), and iron (70 ppm, atom density = 1.3907×10^{-5}), and others, not specified.

1.4 Supplemental Experimental Measurements

Although additional experimental measurements were performed with the ^{233}U Jezebel, the only known detailed documentation of these is in the U233 Jezebel Logbook at Pajarito Site at Los Alamos National Laboratory. However, several results of these experiments, including neutron spectral measurements, reactivity worth ratios, and leakage spectrum measurements, are found in a report issued by the Cross Section Evaluation Working Group (CSEWG) in 1994 (Reference 2). For completeness, the data from Reference 2 are repeated in Appendix C.

2.0 EVALUATION OF EXPERIMENTAL DATA

Although it would be difficult to determine the exact specifications of all of the parts and pieces that comprised the actual ^{233}U Jezebel reactor, the staff at Los Alamos determined an equivalent uniform, homogeneous spherical model that is well-defined and is entirely suitable and acceptable as a critical experiment benchmark. This work is described in Reference 1 and is summarized in Section 3.1 below.

3.0 BENCHMARK SPECIFICATIONS

3.1 Description of Model

In 1969, eight years after the original critical experiment was performed on the ^{233}U Jezebel nearly-spherical bare metal assembly, a re-evaluation of the critical specifications of the assembly was made to precisely establish the critical dimensions and masses of a uniform, homogeneous bare sphere of the fissile material used in the assembly (Reference 1). Experimental reactivity-worth measurements made on the original assembly and recorded in the logbook for the ^{233}U Jezebel were available for this re-evaluation. Additionally, measurements of the reactivity worth of the walls of the building were made by performing critical experiments on the Godiva bare ^{235}U reactor, both inside the building and outside the building on a tower. With this available information, it was possible to determine the critical mass of an idealized uniform, homogeneous sphere as accurately as dimensional fabrication tolerances and material composition assays would permit.

For the experimental configuration of the ^{233}U Jezebel critical assembly described in Section 1.2, the following corrections were applied. All Jezebel parts were nominally coated with 0.005-inch-thick nickel to prevent contamination. Although the nickel plating weights were known, the distribution of the plating was uncertain. Consequently, uniform thickness was assumed in apportioning the nickel between external and internal surfaces of the uranium pieces. Since planeness of mating surfaces could not be guaranteed, an average 0.001-inch gap between each of the three principal pairs of internal surfaces was assumed. Average densities were determined by adjusting measured material densities to allow for the nominal volume of internal nickel coating and voids. Voids remaining after correction for internal nickel were redistributed uniformly (with compensating surface-mass adjustment) so that values of average density were maintained. [Note that a restatement of the inverse-square relationship between density and bare critical mass is that a given mass increment is three times as effective when distributed uniformly (by a change in density) as it is when added to the surface] (Reference 1).

A tabulation of corrections in units of surface mass of uranium is given in Table 2.

Table 2. ^{233}U Jezebel Corrections to Obtain Idealized Sphere.

	Uranium Mass, kg
Critical Mass of Experimental Configuration (Density, g/cm^3)	16.252 (18.424)
Corrections:	
Asphericity	-0.044
Internal Ni & Homogenization	0.023
Equatorial Band	0.110
Polar Supports	0.108
External Ni	0.072
Framework	0.002
Building-wall Reflection	0.008
Air Reflection	0.004
Trace Impurities	0
Elevated Temperatures	0
Critical Mass of Homogeneous Sphere (Density, g/cm^3)	16.535 ± 0.4 wt.% (18.424)

Calculations using the ONEDANT code showed the external nickel to be equivalent to 60 g uranium using Hansen-Roach cross sections. Using ENDF/B-V 30-group cross sections, the calculated worth of the nickel is 70 g of ^{233}U alloy. Both values are in good agreement with the 72 g value in Table 2.

Based on the results for the configuration shown in Table 2, the recommended benchmark critical experiment model is an isolated, bare sphere of ^{233}U metal with a **critical mass = 16.535 ± 0.066 kg uranium at a density of 18.424 g/cm^3**.

3.2 Dimensions

A 16,535 g sphere of ^{233}U with a density of 18.424 g/cm^3 has a radius of 5.9838 cm.

3.3 Material Data

For the isotopic composition of the uranium shown in Table 1, the atom densities given in Table 3 are obtained.

Table 3. Atom Densities for the ^{233}U Jezebel Benchmark.

Nuclide	Atom Density, atoms/barn-cm
^{233}U	4.6712×10^{-2}
^{234}U	5.9026×10^{-4}
^{235}U	1.4281×10^{-5}
^{238}U	2.8561×10^{-4}

Calculations using the ONEDANT code, with both Hansen-Roach 16-group cross sections and 30-group ENDF/B-V cross sections, show that including the trace impurities listed in Section 1.3 increases k_{eff} by 0.0004. This corresponds to 23 g surface mass of uranium, an effect considerably larger than the 0 g shown in Table 2. Nevertheless, the calculated effect of the impurities is still well below the 66 g (0.4 wt. %) overall uncertainty in the critical mass reported by the experimenters. Thus, the impurities are omitted from the calculational benchmark material specifications shown in Table 3.

Similar calculations using the ONEDANT code, with both Hansen-Roach 16-group and ENDF/B-V 30-group cross sections, show that treating the ^{234}U as ^{238}U reduces the calculated k_{eff} by about 0.0037. Such a Δk is too large to warrant treating the ^{234}U in the metal as ^{238}U.

3.4 Temperature Data

The temperature of the benchmark uranium metal is nominal room temperature.

3.5 Experimental and Benchmark-Model k_{eff}

As described in Sections 1.2 and 3.1, specifications of the mass were adjusted to the critical mass with all mass-adjustment plugs installed, the glory hole filled, and the control rod inserted, and then further adjustments to the critical mass were made to convert the assembly to an idealized sphere. Thus, the "experimental" value of k_{eff} is 1.000 ± 0.001. The uncertainty in k_{eff}, as calculated with ONEDANT using both Hansen-Roach 16-group and ENDF/B-V 30-group cross sections, is due to the 66 g uncertainty in the critical mass.

4.0 RESULTS OF SAMPLE CALCULATIONS

Sample calculational results are shown in Table 4. Details of the calculations including code input listings are provided in Appendix A.

Because of the simplicity of the idealized benchmark ^{233}U Jezebel, a simple bare sphere of ^{233}U metal, it is ideally suited as a benchmark for virtually any of the computational codes in use today.

Table 4.a. Sample Calculation Results (United States).

KENO (Hansen-Roach)	KENO (27-Group ENDF/B-IV)	MCNP (Continuous Energy ENDF/B-V)	ONEDANT (27-Group ENDF/B-IV)
1.0068 ± 0.0019	0.9625 ± 0.0012	0.9970 ± 0.0011	0.96

The calculations using the 27-group SCALE4 ENDF/B-IV cross sections significantly underpredict k_{eff}, as seen in Table 4. This underprediction is due to known deficiencies in the ^{233}U cross sections for this cross section library.[a]

Table 4.b. Sample Calculation Results (United Kingdom).[(a)]

MONK (UKNDL)
1.0011 ± 0.0011

(a) Results supplied by Nigel R. Smith of AEA Technology.

[a] Personal communications, L. M. Petrie and R. M. Westfall, Oak Ridge National Laboratory.

5.0 REFERENCES

1. G. E. Hansen and H. C. Paxton, "Reevaluated Critical Specifications of Some Los Alamos Fast-Neutron Systems," Los Alamos Scientific Laboratory report LA-4208, September 1969.

2. "ENDF-202 Cross Section Evaluation Working Group Benchmark Specifications," BNL 19302 (ENDF-202), Brookhaven National Laboratory, November 1974.

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 KENO Input Listings

Hansen-Roach 16-Group Cross Sections

The sample calculation with Hansen-Roach 16-group cross sections was run with 260 generations of 1000 histories per generation and the first 10 generations skipped for a total of 250,000 active histories. The data for metallic ^{233}U, ^{235}U, and ^{238}U (potential scatter $\leq$ 20 barns/atom for each) were used with isotropic (transport-corrected) scattering. The ^{234}U (ID 92400) data from the Mihalczo modification of ^{238}U was used for the ^{234}U.

KENO-V.a Input Listing for Table 4.a (16-Energy-Group Hansen-Roach Cross Sections).

```
U233 JEZEBEL 16.53 kg sphere at 18.42 g/cc HANSEN-ROACH
read param lib=41 gen=260 nsk=10 npg=1000 run=yes
end param
read mixt
mix=1 92301 .046712
        92856 2.8561-4
        92501 1.4281-5
        92400 5.9026-4
end mixt
read geom
sphere 1 1 5.9838
end geom
end data
end
```

27-Group ENDF/B-IV Cross Sections

The KENO V.a sample calculation with SCALE4 27-group ENDF/B-IV cross sections was run with 305 generations of 1500 histories per generation and the first 5 generations skipped for a total of 450,000 active histories.

KENO-V.a Input Listing for Table 4.a (27-Energy-Group SCALE4 Cross Sections).

```
=CSAS25
U233 JEZEBEL
27GROUPNDF4 INFHOMMEDIUM
U-233    1 0 4.6712-2 END
U-234    1 0 5.9026-4 END
U-235    1 0 1.4281-5 END
U-238    1 0 2.8561-4 END
END COMP
READ PARAMETERS
GEN=305  NPG=1500 NSK=5
END PARAMETERS
READ GEOM
UNIT 1
SPHERE     1  1  5.9838
END GEOM
END DATA
END
```

A.2 MCNP Input Listing

The MCNP sample calculation was run with 115 generations of 2500 histories per generation with the first 15 generations skipped for a total of 250,000 active histories.

MCNP Input Listing for Table 4.a.

```
K-EFF CALCULATION FOR U-233 JEZEBEL
1   1   0.04760215  -1 imp:n=l
2   0   1  imp:n=0

so 5.9838

ml  92233.50c  4.6712-2  92234.50c  5.9026-4  92235.50c  1.4281-5
   92238.50c 2.8561-4
kcode 2500  1.0  15  115
ksrc  0. 0. 0.
print
```

A.3 ONEDANT/TWODANT Input Listing

The ONEDANT sample calculations using SCALE4 27-group ENDF/B-IV cross sections used an S_{48} Gauss-Legendre quadrature, 200 mesh intervals (mesh width about 0.03 cm), and a convergence criterion of 1.0×10^{-4}.

The first input file listed is the file used to generate the macroscopic 27-group cross sections from the SCALE4 code package.

ONEDANT Input Listing for Table 4.a.

```
=CSASI
U233 JEZEBEL
27GROUPNDF4 INFHOMMEDIUM
U-233 1 0 0.046712   END
U-234 1 0 5.9026-4   END
U-235 1 0 1.4281-5   END
U-238 1 0 2.8561-4   END
END COMP
END
```

```
          2
U-233 JEZEBEL ONEDANT SCALE 27 GRP CROSS SECTIONS
16.535 kg sphere at density 18.424 g/cc
/BLOCK 1
igeom=sph ngroup=27 isn=48 niso=1 mt=1 nzone=1 im=1 it=200 t
/BLOCK 2
xmesh=0.0 5.9838 xints=200 zones=1 t
/BLOCK 3
lib=xslib27
maxord=3 ihm=42 iht=3 ihs=16 ititl=1 ifido=2 i21pl=1 t
/BLOCK 4
matls=isos assign=matls t
/BLOCK 5
chi=.020   .195  .219  .126  .164  .172   .088   .014   .001   18z
ievt=1  isct=3   t
```

A.4 MONK6B Input Listings

Each MONK6B calculation using its standard UKNDL-based cross section library employed 1000 superhistories per stage and was run to achieve a precision of 0.0015. The results from two calculations using different random number seeds were averaged for each case to give a combined statistical precision of about 0.1%.

MONK Input Listing for Table 4.b.

```
* USDOE Benchmark  - U233-MET-FAST-001
* ============================ =====
* MONK6B Calculation
* JEZEBEL U233 Experiment - Bare uranium sphere
* Critical Mass = 16.535 kg
* Density = 18.424 g/cc

FISSION 1 4  NUCNAMES
* material 1 - U233 metal
CONC    U233 4.6712E-2  U234 5.9026E-4  U235 1.4281E-5  U238 2.8561E-4
CM

* part 1 - uranium sphere
NEST 1
SPHERE  1  5.9838

-1  100  1000  0 STDV 0.0015  -1

VOLUME
REGION 1  PART 1 /
END
```

APPENDIX B: ADDITIONAL ONEDANT RESULTS

A ONEDANT sample calculation of the ^{233}U Jezebel was made using Hansen-Roach 16-group cross sections for comparison, with the corresponding KENO calculations. The calculation used an S_{48} Gauss-Legendre quadrature, 60 mesh intervals (mesh width about 0.1 cm), and a convergence criterion of 1.0×10^{-5}. The data for metallic ^{233}U, ^{235}U, and ^{238}U (potential scatter $\leq$ 20 barns/atom for each) were used with isotropic (transport-corrected) scattering. The ^{234}U (ID 92400) data from the Mihalczo modification of ^{238}U was used for the ^{234}U. The calculated k_{eff} was 1.0041, which is statistically the same as that obtained with KENO (1.0068 ± 0.0019).

The input file for this ONEDANT calculation is shown below.

```
          4
U-233 JEZEBEL ONEDANT HANSEN-ROACH 167 ISOTOPE LIB
16,535 g U233 at density of 18.424 g/cc  SPHERE radius=5.9838 cm
98.13 at% 233; 1.24 at% 234; .03 at% 235; .60 at% 238
Mihalczo U-234
/
miniprt=y
igeom=sphere ngroup=16 niso=167 isn=048 mt=1 nzone=1 im=1 it=60 t
/
xmesh=0.0 5.9838 xints=60 zones=1 t
/
lib=bxslib libname=bxsl67 t
/
matls= U233 u232el .046712 u282el 2.8561-4 u252el 1.4281-5 u240R2 5.9026-4;
assign=matls t
/
chi= .204 .344 .168 .180 .090 .014 10z
ievt=1 epsi=1.0-5 norm=1 t
```

APPENDIX C: SUPPLEMENTAL EXPERIMENTAL MEASUREMENTS

Click here to view the Supplemental Experimental Measurements.