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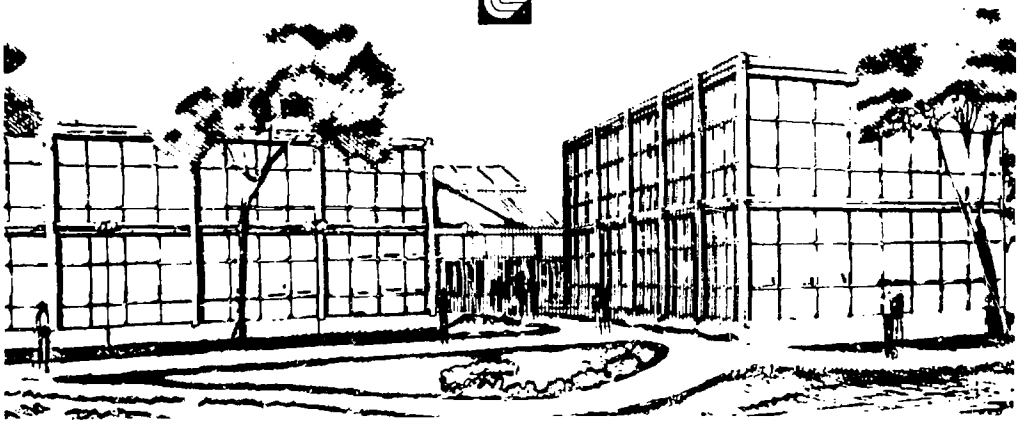

PRODUCTION OF EINSTEINIUM AND FERMIUM IN NUCLEAR EXPLOSIONS*

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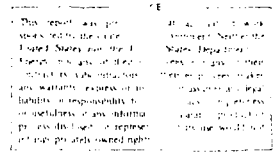

HISTORICAL BACKGROUND

Earlier papers in this symposium conveyed the excitement associated with the discovery of Es and Fm in debris from the Mike Event[1] (November 1952). It was with a similar feeling of excitement that teams of radiochemists from Lawrence Livermore Laboratory and Los Alamos Scientific Laboratory prepared to search for even heavier elements and new short-lived nuclides in the debris from large thermonuclear explosions scheduled for testing in 1954. A laboratory was set up on the island of Enewetak to facilitate the search for short-lived species.

When testing began in March 1954, samples of particulate debris were collected on filter papers immediately after each explosion by airplanes flown through the radioactive cloud. These samples were delivered as quickly as possible to radiochemical laboratories at Enewetak and in the United Stated for extraction of the heavy actinides. Throughout the study of the products from the megaton-range thermonuclear devices exploded in 1954 and 1956, we were disappointed to find that the yields of heavy nuclides were considerably lower than those from the Mike explosion. At that time, the heaviest species detected were the ^{255}Es - ^{255}Fm pair,

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nuclides already discovered in the MIKE debris. No evidence was found for the existence of elements heavier than Fm.

In the meantime, reactor production of Es and Fm was begun in 1952. Plutonium samples (napkin rings) were inserted into the highest reactor neutron flux available at the Materials Testing Reactor in Idaho. These irradiations resulted in the production of submicrogram amounts of Es and Fm, which were used for research studies in the period 1953-1960.

UNDERGROUND TESTS

Once again during the 1960s, when nuclear weapons testing was being conducted underground at the Nevada Test Site, attention was focused on production of very heavy elements in nuclear explosions. The AEC decided to design and test nuclear explosive devices that would produce heavy isotopes. This is accomplished by incorporating a ^{238}U target into the device so that it is exposed to an extremely intense neutron flux. In these devices, the neutrons are generated by the thermonuclear reaction $D+T \rightarrow n + {}^{4}He$. The ^{238}U target undergoes multiple neutron capture reactions while being exposed to a total fluence of approximately 10^{25} n/cm^2. This capture reaction phase is completed in less than a microsecond, before appreciable beta decay can occur. After the neutron capture phase, nuclides in each mass chain decay by beta emission, which continues until a beta-stable product is reached. These beta-stable products, or possibly a longer-lived beta emitter close to beta stability, are detected when the debris is examined; they provide evidence for the multistep process already described.

Although this method of heavy element production is effective, isolation of products is difficult. The nuclear device inevitably produces large amounts of energy, and in the process of dissipating this explosive

energy by melting and vaporizing rock, the reaction products are dispersed in an appreciable quantity of molten rock. In order to recover the heavy nuclides, it is necessary to drill down to a zone close to the initial device (which was typically 300 - 600 m below the surface of the Nevada desert) to obtain samples of the debris. Following recovery, the actinides are separated and purified.

The effort to design heavy-element producing devices was quite successful. A series of experiments were conducted, culminating in the most productive tests, Cyclamen[2] and Hutch[3], which were detonated in 1966 and 1969, repectively. Some of the experiments in this series are listed in Table 1. The exposure, or time-integrated neutron flux to which the target material was subjected, is a measure of how many multiple neutron capture reactions occurred. A value for this exposure was derived by fitting the observed mass-yield curve for a given device to relative yields calculated using a consistent set of capture cross sections for the uranium isotopes, masses 238 to 257. The high neutron exposure achieved in the Cyclamen and Hutch events led to greatly increased production of heavy products. The greatest success was obtained with ^{238}U targets. Various other heavy nuclides were tried as target materials, but did not provide any significant improvement over ^{238}U. For example, the target in the Tweed Event was mostly ^{242}Pu with a smaller amount of ^{237}Np. Although the device performed almost identically to the Par device, where an all-^{238}U target was used, the yields of heavier products from Tweed were substantially less. This effect was apparently due to greater fission losses in the first few members of the Pu capture chain. In the Cyclamen Event, a small amount of ^{243}Am was added to a ^{238}U target, but without effect. The observed yields of heavy nuclides could be explained as arising solely from capture in ^{238}U.

The production of heavy nuclides in the Cyclamen and Hutch Events is plotted in Fig. 1 in terms of total atoms produced during the nuclear explosion. Yields were measured experimentally for masses up to 255 and 257; no heavier species were identified. The lines in Fig. 1 connect points for calculated yields, which represent best fits to the experimental data. An odd-even fluctuation of these yields is evident; in the uranium isotope capture chain, the odd-mass members have larger cross sections for neutron capture and, hence, exhibit lower yields than for the even-mass neighboring isotopes. If one assumes a smooth trend in capture cross sections for heavier members of the capture chain, then predictions can be made for the yields of heavier, unobserved species beyond A = 257.

A direct comparison of production yields for the Hutch, Cyclamen, and Mike[4] events is shown in Fig. 2. A striking feature of this comparison is that a greater quantity of nuclides with mass > 250 was produced in the Hutch event than in the Mike explosion, in spite of the much larger explosive yield for Mike. For Cyclamen, the production of heavy nuclides was also very impressive when one considers that the yields of products with A = 250 to 257 in Cyclamen are only one order of magnitude lower than for Mike, while the total explosive yield was nearly three orders of magnitude lower.

SAMPLE RECOVERY

An important part of detecting new short-lived nuclides produced in these explosions is the time required for the sample recovery. In underground experiments, it is usually several days after the explosion before the first samples are available for chemical purification and counting. Since the capture products are distributed in the vaporized rock and must be recovered from 300 - 600 m below the surface, only a small

fraction of the total production is recovered for experimentation. The Cyclamen Event was an exception in that samples were recovered extremely rapidly; debris samples were in the laboratories within 24 h after the event. Thus, experimenters were able to make sensitive tests for the existence of heavy nuclides such as ^{259}Md and ^{261}Md, which are probably quite short-lived.

To further emphasize the effects of explosive yield in dispersing the products of a nuclear explosion, a view of the cloud produced following the Mike explosion is given in Fig. 3. Figure 4 shows a large hole in the atoll reef, perhaps 1000 m in diameter, produced by the Mike explosion. After it was discovered that airborne debris from Mike contained significant amounts of heavy nuclides, including the new elements Es and Fm, efforts were made to collect device debris and coral that had fallen to surface of islands in the atoll chain near the original site of the event.

The Hutch surface crater, shown in Fig. 5, is another manifestation of the energy generated during the explosion. This device was exploded 600 m below the surface of the ground at the Nevada Test Site. An underground explosion first produces a spherical cavity filled with vaporized rock. Sometime following the explosion, usually within minutes to hours, the roof of the spherical cavity falls in. This collapse continues until it reaches the surface and produces a crater. The drill rigs that were used to recover samples from the Hutch Event are seen in Fig. 5 located away from the crater edge. A slant drilling technique was used to reach the debris zone directly below the crater.

Having reviewed why sample recovery can be rather difficult, we can compare data for fractions of the device recovered from the Mike and Hutch Events (Table 2). The initial efforts to sample Hutch debris were very

effective; a 100-g rock sample, typical of the sample size processed at each of four laboratories, contained approximately an 8×10^{-10} fraction of the total Hutch debris. In comparison, early samples from the Mike explosion (aircraft filters) contained only a 4×10^{-14} fraction of that device. These recovery fractions, when combined with the mass yield data of Fig. 2, show that a much larger sample of heavy nuclides (1.3×10^{10} atoms with A = 253-255 before decay) was available for laboratory study 7 days after the Hutch explosion than was available from the early sampling of Mike debris.

After the heavy nuclide content of the initial samples from each event was demonstrated in the laboratory, efforts were made to recover additional samples. Chemical processing of nearly a ton of coral samples containing Mike debris resulted in the isolation of 1×10^{-12} of the device, a significant improvement in total atoms of heavy nuclides available for experimentation. The larger scale recovery of samples (Phase II recovery) from the Hutch device was completed 60 days after the explosion and resulted in the recovery of 500 kg of rock. However, the concentration of debris in this 500 kg was disappointingly low; the total fraction of the device debris in this batch was less than 4 times greater than was present in the initial recovery of 10 kg of rock. Thus, it was not judged worthwhile to process the rock from the Phase II recovery. The low concentration of device debris could be explained by the intrusion of water after the first samplings. Although the Hutch device was detonated below the water table, the extreme heat of the explosion drove the water away from the zone where debris was sampled. A few weeks after the explosion, water flowed back into the region and a normal water table was reestablished. Thus the Phase II recovery operations, which employed a new sampling technique involving under-reaming

of the existing hole and collection of the material in a bucket below the reamer, were ineffective apparently because the operation was performed under water. Developmental tests of this new recovery technique had been performed in a dry hole.

RAPID SAMPLE RECOVERY

A new rapid sample recovery technique was tried in the Anacostia and Kennebec Events[5] in order to avoid the lengthy delays associated with drilling to 300-m depths. In each case, the sampling system consisted of a 25-cm-diam vertical pipe leading from near the nuclear device up to four large holding tanks on the surface. The 230-m vertical section of pipe was filled with water containing a 50 wt% starch suspension to provide thixotropic properties to the fluid. The force of the explosion drove some device debris into this pipe. Debris entrained in the fluid mixture was carried to the surface where all of the fluid was collected in the holding tanks. The tanks were examined after the radioactivity had decayed. Between 10 and 40 kg of rock and device debris were found in the Anacostia tanks, while 360 kg of rock and device debris were collected in the Kennebec tanks. Analyses showed that the Pu concentrations in these rock samples were 25-33% of those found in the samples recovered by drilling. Thus, we see that these systems delivered experimentally useful quantities of device debris to the surface immediately following an explosion. In fact, the quantities of rock are comparable to those recovered in the initial Hutch drillback. Further development would be required to devise a system to separate rock and device debris from the large quantity of water-starch suspension and to manipulate the debris samples at early times when radioactivity is extremely high. Nevertheless, these demonstrations of a rapid sample-recovery technique are considered an important development

with regard to the ultimate usefulness of heavy-element production by use of thermonuclear explosions.

ODD-EVEN YIELD VARIATION

We have already seen that a typical mass-yield curve exhibits an odd-even variation of the total atoms versus mass number. This phenomenon was observed in the data from the Mike Event, as well as in more recent events. A new feature, observed first in the 1960s, was that the odd-even effect reversed somewhere in the vicinity of A = 250. Below A = 250, yields of the even-mass products are relatively higher than their odd-mass neighbors. Beyond A = 250, the effect is reversed. This behavior can be seen in the data for Cyclamen (Fig. 2) and for the Barbel Event[6] (Fig. 6). In order to explain this observation, Fields and Diamond[7] suggested that the heaviest products are produced in a capture chain with odd Z, e.g., Pa or Np, while the lighter masses are produced in the uranium capture chain. When multiple captures occur in an odd-Z element, the yields are reversed because the cross sections for capture by even-mass nuclides (which are nuclides with both an odd proton and an odd neutron) are larger than for their odd-mass neighbors. This explanation has been tested quantitatively by Ingley[8] and by Bell[9] and provides good agreement with the experimental data. In Fig. 6, one can see that the relative linearity of the experimental yield curve is due to the superposition of two curves, both somewhat concave downward, with the heaviest products being derived from capture in the Pa isotopes. Although no Pa existed in the original target, conversion of the target through $^{238}U(n,p)^{238}Pa$ reactions provides the starting material for the Pa capture chain. Two variables in the fitting procedure are the amount of ^{238}U surviving fast-neutron fission (N/N_o = 0.95×10^{-2}) and the conversion of ^{238}U to ^{238}Pa ($N/N_o = 1.6 \times 10^{-2}$).

A set of calculated cross sections for neutron-rich uranium isotopes are available from the work of Truran and Cameron[10]. These cross sections are estimated from statistical model calculations and are normalized to the measured ^{238}U capture cross section (0.6 b) at 20 keV. Ingley[8] has fitted the mass-yield data from six underground nuclear explosions to produce a set of averaged experimental capture cross sections, which are compared with the calculated values of Cameron and Truran in Fig. 7. One can see the agreement with the calculated values is quite good. We also note that the lowest cross section occurs for ^{244}U, which presumably can be ascribed to the shell effect at 152 neutrons. For calculations of capture in a Pa chain shown in Fig. 6, Ingley[8] used a set of cross sections calculated by Truran[10].

Although extrapolation of the production curves for Cyclamen and Hutch suggest that detectable amounts of nuclides with A > 257 were produced, the radiochemistry teams could find no evidence for new nuclides beyond ^{257}Fm. We show some of the beta decay chains in Fig. 8, where the last nuclide listed is beta stable and is usually the nuclide that was measured quantitatively in these experiments. In the search for new species, the best chance for detection might have been in the mass chains 259 and 261, each of which would be expected to produce a detectable isotope of mendelevium. These odd-mass chains would be depleted less by spontaneous fission. From the Cyclamen experiment the following limits were set for ^{259}Md:

$t_{1/2}$ (SF) < 5 h or > 15 y

$t_{1/2}$ (α) > 30 y

and the corresponding limits for ^{259}Fm were:

$t_{1/2}$ (SF) < 5.5 h or > 7.5 y

$t_{1/2}$(α) > 30 y.[2]

From the Hutch experiments, the limits for ^{259}Md were:

$t_{1/2}(SF) < 12$ h or $> 1.25 \times 10^4$ y

$t_{1/2}(\alpha) > 1.25 \times 10^4$ y

and the corresponding limits for ^{259}Fm were:

$t_{1/2}(SF) < 12$ h

$t_{1/2}(\alpha) > 250$ y.[3]

In related experimental work, the nobelium, lawrencium, and element-104 fractions were examined for evidence (SF or alpha activity) of the presence of nuclides with $A \geq 261$. Again, no evidence for new species was found by any of four teams working at separate laboratories. Since that time, Hulet and co-workers[11] have used an accelerator to produce ^{259}Fm and ^{259}Md by charged-particle reactions. They demonstrated experimentally that these nuclides have extremely short half-lives for spontaneous fission (See Fig. 8). The nuclides ^{259}Fm and ^{259}Md are the most neutron-rich species that have been detected to date. Their extremely short half-lives are part of a trend toward rapid spontaneous-fission that is shown graphically in Fig. 9. We see that the trend to short half-lives is quite extreme at N = 158, 159; beyond this point, we do not know if this effect changes and if spontaneous fission half-lives become long enough to permit experimental detection of superheavy elements. There is one indication that the trend reverses, namely, the experimental results for isotopes of element 104 reported by Flerov and co-workers[13] and plotted as triangles in Fig. 9.

RESEARCH USING HUTCH-PRODUCED ^{257}Fm and ^{250}Cm

Although no new nuclides or new elements were detected in these underground experiments, significant amounts of certain rare and heavy

nuclides were produced in the explosion. Recovery of 10 kg of debris-rich rock and its subsequent chemical processing provided larger amounts of ^{257}Fm and ^{250}Cm for the experimentation than had been available in the past.[14] The Hutch detonation produced 6×10^{17} atoms of ^{257}Fm, of which 6×10^{9} atoms were recovered. This ^{257}Fm was used in a series of significant experiments by Hulet and co-workers[12,15] to discover an unexpectedly symmetric mode of fission accompanied by high kinetic energy release in the thermal-neutron induced fission of ^{257}Fm, to discover an new isotope, ^{258}Fm, which has a very short half-life for spontaneous fission (0.38 ms), and to determine more precise values for the decay characteristics and thermal fission cross section of ^{257}Fm.

Another rare isotope, ^{250}Cm, was also recovered from the Hutch debris. There was enough ^{250}Cm available to do neutron capture irradiations, which led to the production of a new isotope, 17-min ^{251}Cm. Sufficient data were obtained in the study by Lougheed, et al.[16] to produce a detailed level scheme of ^{251}Bk as shown in Fig. 10. The abundance of ^{250}Cm in the Hutch curium was 6.7 at.%. This high ^{250}Cm content is a significant feature of the Hutch curium fraction. Reactor production of heavy curium isotopes does not produce appreciable amounts of ^{250}Cm because its production depends upon competition between beta decay and neutron capture of 64-min ^{249}Cm, which has a thermal neutron capture cross section of 2.8^{b}. Even at the flux level of the HFIR (5×10^{15} n/cm^2-s), only 0.02% of the ^{249}Cm atoms undergo capture and are converted to ^{250}Cm.

FUTURE DIRECTIONS FOR HEAVY-ELEMENT SYNTHESIS

As a final topic, I wish to discuss the possible future exploitation of synthesis in nuclear explosions. If one considers the problem of generating

increased neutron fluxes in order to produce and detect nuclides beyond N = 158, a number of questions arise. For example: Where does the region of catastrophic rapid spontaneous fission, which dominates nuclear stability around N = 157, end? The shell model of the nucleus suggests that heavier nuclei will be stabilized because of the presence of closed shells in heavier regions, just as subshells occur at Z = 100 and N = 152 and major shell closings occur at Z = 82, N = 126. The current belief with respect to superheavy elements is that stabilization will occur near nucleon numbers, Z = 114 and N = 184. As a result, nuclides in this region might be long-lived enough to permit detection. However, at this time, theoretical predictions of spontaneous lifetimes for nuclides in the region Z > 100 and N > 158 are uncertain to several orders of magnitude. The Hutch and Cyclamen experiments provided opportunities to detect nuclides at heavier masses than 258; it appears that there was sufficient production of nuclides up to mass 263 to permit detection of their characteristic radiations within the limits stated. Our inability to detect new species in the mass range A = 258-263 was apparently due to the very short spontaneous fission half-lives for these nuclides.

The multiple-capture production path to superheavy nuclei requires extremely high neutron fluxes; it is a completely different approach than methods involving heavy-ion bombardment where one attempts to force rather massive projectiles to at least partially fuse with heavy target atoms. While the products from almost any heavy-ion reaction tend to be neutron deficient, our technique involves the absorption of many neutrons by a Z = 91 or 92 nucleus before any other reactions can occur. The relatively beta-stable product nuclei are approached from the direction of extreme neutron richness. Success depends upon how many very heavy atoms can be

produced in the multiple neutron-capture reactions, and how well these atoms survive during beta decay to a beta-stable product.

Another question is: Can samples be recovered rapidly and can new species in these samples be detected at short times following a nuclear explosion? We have already referred to experiments that demonstrated the feasibility of rapidly recovering samples that represent fractions of the device that are comparable to those recovered by drill-back techniques. Meldner, et al.[17] discussed the use of neutron counters to detect events with high neutron multiplicity ($\bar{\nu} > 5$) that are characteristic of the spontaneous fission of nuclei with A > 258. They conclude it would be feasible to record 10^3 events from the spontaneous fission of a mass-265 species in a device fraction of only 1×10^{-12} if the lifetime of this species is > 30 s. Other assumptions in their calculations are that one can design and field a thermonuclear device that subjects a ^{238}U target to a time-integrated neutron flux of about twice that obtained in the Hutch Event and that the resultant production of mass-265 atoms will be 10^{16} atoms.

It is possible that a successful effort to produce heavier elements may require a combination of high-flux multiple neutron capture (to produce a heavy, neutron-rich target material) and charged-particle bombardment with heavy ions. A proposed search for superheavy elements developed by Hulet, et al.[18] begins with the production of a large quantity of ^{250}Cm in a Hutch-like nuclear explosion in a natural salt formation. This nuclide would serve as target material for ^{238}U-ion bombardments. For a good experimental program, one needs about 100 μg (2.4×10^{17} atoms) of target material. If the device is exploded in a natural salt formation, the recovery of sufficient ^{250}Cm appears feasible.

There have been two nuclear explosions conducted in the U.S. in natural salt formation; these were the Salmon (1964) and Gnome (1961) Events. In Fig. 11, we see a schematic drawing of the cavity created by the Salmon explosion, in which a 5.3-kt device was detonated at a depth of 828 m. The energy released by the explosion melted and vaporized the surroundings, 90% NaCl, with the formation of a spherical cavity. As cooling progressed, molten salt on the walls of the cavity formed a puddle containing about 5400 metric tons of material at the bottom. As the puddle cooled, certain oxide and silicate minerals began to precipitate at temperatures of the order of 2000°C. Various radioactive elements that are somewhat refractory, for example, the actinides and the rare earths, were concentrated in the insoluble fraction, which was subsequently found to be principally $Ca_2Al_{0.6}Fe_{1.4}O_5$ and β-Ca_2SiO_4. These oxide-silicate minerals settled to the bottom of the molten salt puddle to form a highly radioactive zone of material whose specific activity was approximately 100 times that of the NaCl. Thus, most of the refractory device debris is contained in a shallow (1-m thick) lens consisting of about 50 metric tons of oxides.

Hulet, et al.[18] propose that following explosion of a Hutch-like device in a natural salt formation, and after the rather slow cooling of the molten salt and eventual solidification (perhaps requiring as much as 18 months), the actinide-rich ore be mined. Between 50 and 100 tons of this material would be chemically processed to yield perhaps as much as 250 to 500 μg ^{250}Cm. This very rare isotope would then serve as target material for heavy-ion bombardments with ^{238}U, and other projectiles in order to test this promising approach to the production of superheavy elements.

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Table 1. Underground nuclear explosions that have produced high neutron exposures.

Event name	Lab	Date	Exposure[a]	Target
Par	LLL	10/64	11	^{238}U
Barbel	LASL	10/64	11	^{238}U
Tweed	LLL	5/65	12	$^{242}Pu + {}^{237}Np$
Cyclamen	LASL	5/66	18	$^{238}U + {}^{243}Am$
Kankakee	LLL	6/66	12	^{238}U
Vulcan	LLL	6/66	12	^{238}U
Hutch	LLL	7/69	40	$^{238}U + {}^{232}Th$

[a]Equivalent 20 keV-time-integrated neutron flux (moles neutrons/cm^2).

Table 2. Comparison of sample recoveries for the Mike Event (a 10 000 kt atmospheric explosion) and the Hutch Event (an underground explosion in the range. 20-200 kt).

Sample description	Fraction of total device
Mike Event	
Initial samples - aircraft filters	4×10^{-14}
Later coral samples	100×10^{-14}
Hutch Event	
Phase I samples - T_0 + 7 days	
Total recovery - 10kg rock	30×10^{-9}
Most concentrated sample - 0.4kg rock	3×10^{-9}
Phase II samples - T_0 + 60 days	
Total recovery - 500kg rock	$< 120 \times 10^{-9}$

FIGURE CAPTIONS

Fig. 1. Mass yield curves in the Hutch and Cyclamen nuclear explosions. The solid lines are the result of calculational fits.

Fig. 2. Mass yield curves for the Hutch, Cyclamen, and Mike nuclear explosions.

Fig. 3. Mushroom cloud produced by the Mike explosion, Enewetak, November 1952.

Fig. 4. Crater in the Enewetak atoll reef produced by the Mike explosion; the Mike Crater is the large hole in the upper part of the picture.

Fig. 5. Surface crater at the Nevada Test Site produced by the Hutch explosion, July 1969.

Fig. 6. Mass yield curve from the Barbel nuclear explosion. Experimental data are shown as solid circles. Calculated yields from the ^{238}U capture chain are shown as a solid line; calculated yields from the ^{238}Pa capture chain are shown as a dashed line.

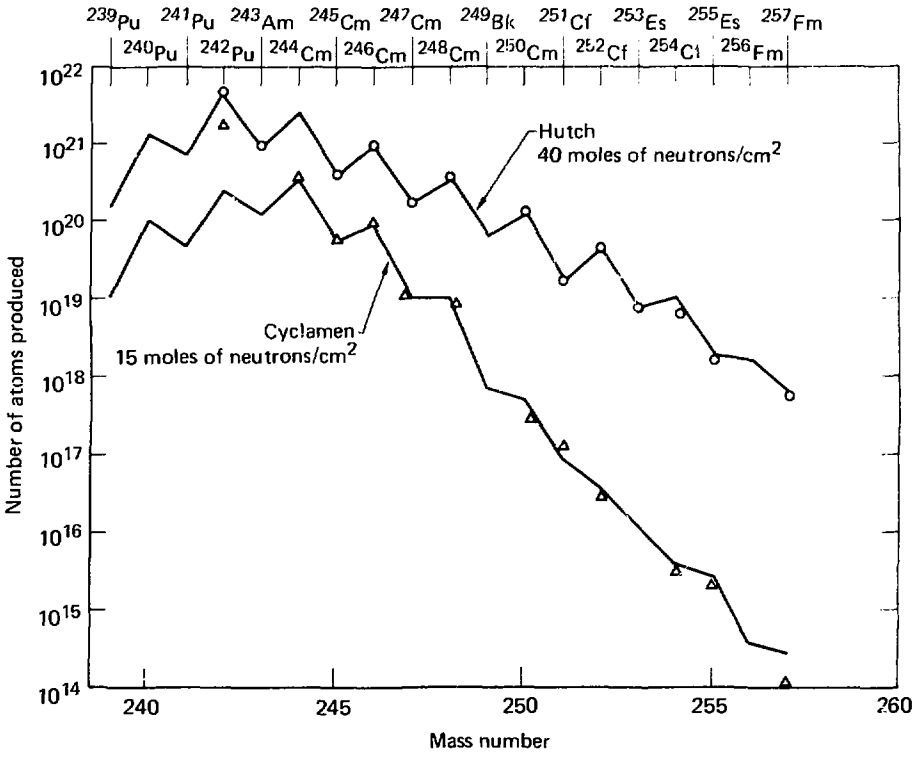
Fig. 7. Uranium isotope cross sections for 20-keV neutrons. The experimental values are an average from fitting data from the Anacosta, Par, Barbel, Kankakee, Vulcan, and Cyclamen Events.

Fig. 8. Beta decay chains for A = 251 to A = 264.

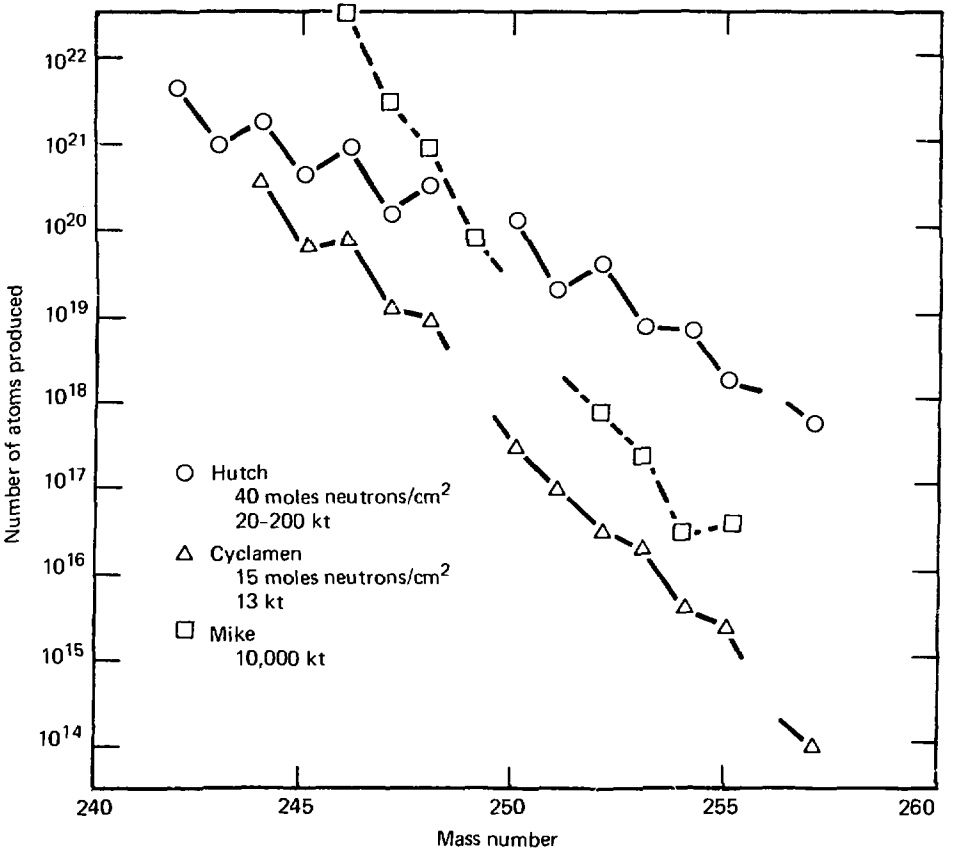
Fig. 9. Systematics of spontaneous fission half-lives.

Fig. 10. Beta decay scheme of ^{251}Cm, a nuclide that was produced by irradiating a sample of Hutch curium with neutrons.

Fig. 11. Schematic drawing of the cavity produced in molten salt by the Salmon explosion, detonated in October 1964 in Mississippi.


239Pu 241Pu 243Am 245Cm 247Cm 249Bk 251Cf 253Es 255Es 257Fm
240Pu 242Pu 244Cm 246Cm 248Cm 250Cm 252Cf 254Cf 256Fm
Hutch
40 moles of neutrons/cm2
Cyclamen
15 moles of neutrons/cm2
Number of atoms produced
Mass number
10^22
10^21
10^20
10^19
10^18
10^17
10^16
10^15
10^14
240
245
250
255
260

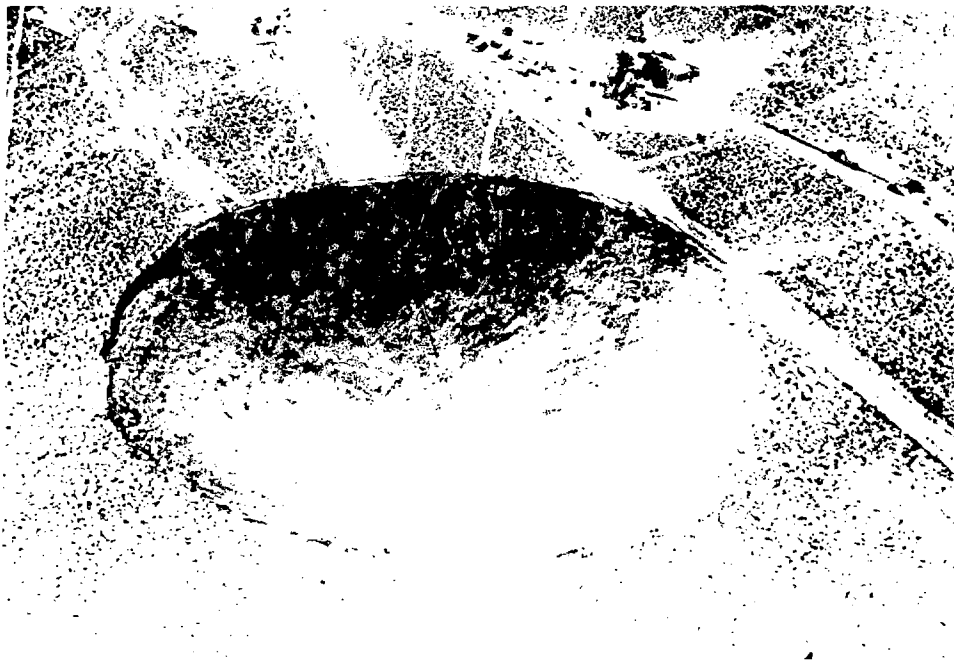
Hoff - Fig. 1


Number of atoms produced
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
240
245
250
255
260
Mass number
Hutch
40 moles neutrons/cm^2
20-200 kt
Cyclamen
15 moles neutrons/cm^2
13 kt
Mike
10,000 kt

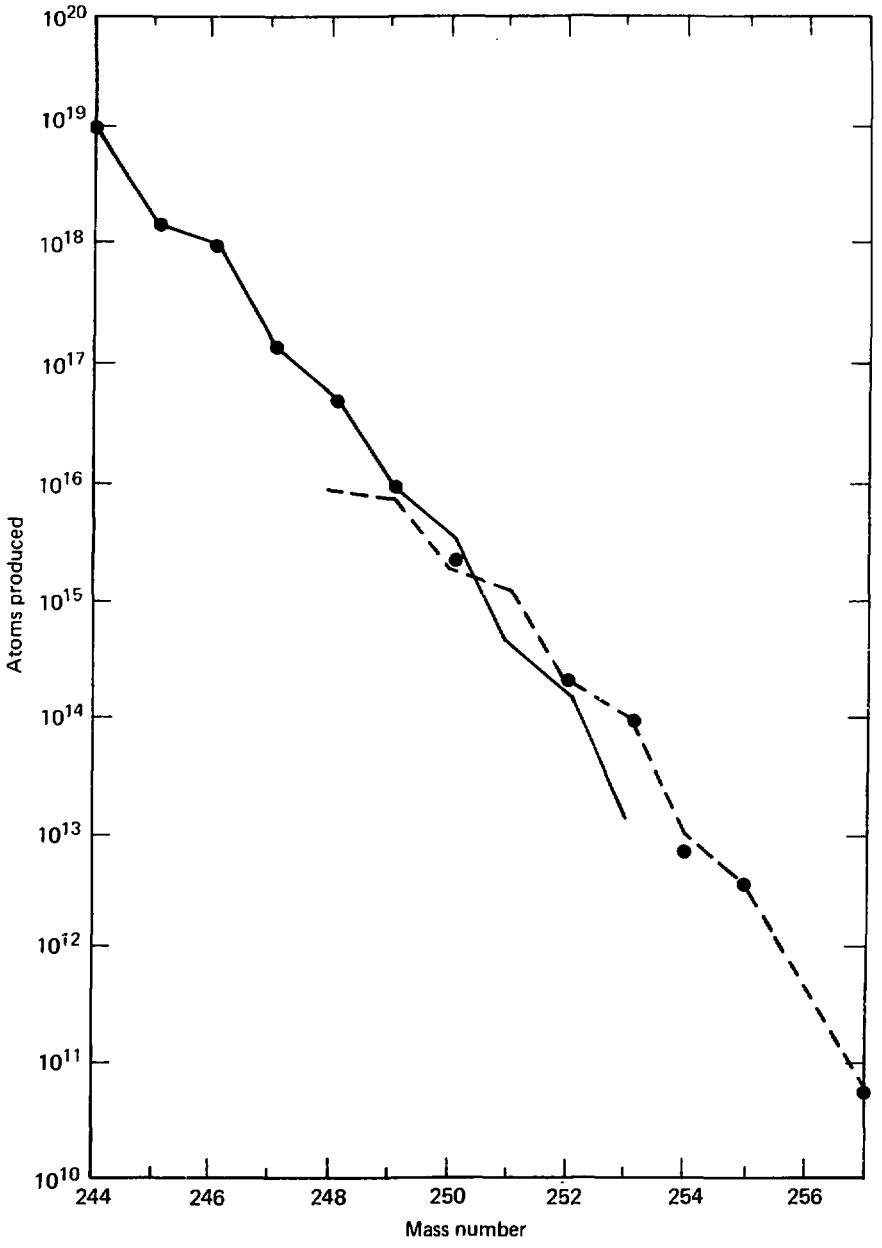
Hoff - Fig. 2

Hoff - Fig. 3

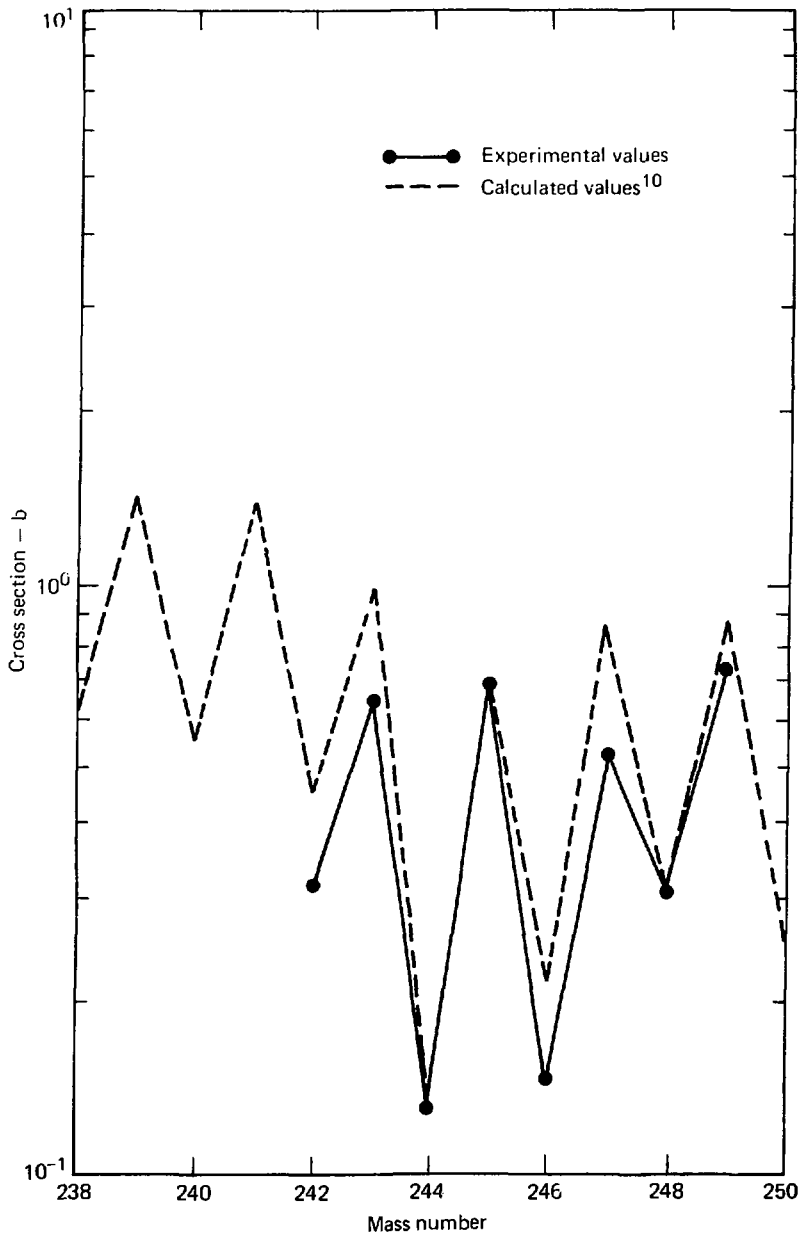
Hoff - Fig. 4



Hoft - Fig. 5


10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
Atoms produced
244
246
248
250
252
254
256
Mass number

Hoff - Fig. 6


10^1
10^0
10^{-1}
Cross section – b
Experimental values
Calculated values[10]
238
240
242
244
246
248
250
Mass number

Hoff - Fig. 7

$^{251}Cm \xrightarrow[17\ m]{\beta^-} {}^{251}Bk \xrightarrow[57\ m]{\beta^-} {}^{251}Cf \xrightarrow[900\ y]{\alpha}$

$^{252}Cf \xrightarrow[2.6\ y]{SF}$

$^{253}Cf \xrightarrow[18\ d]{\beta^-}$ $^{253}Es \xrightarrow[20.5\ d]{\alpha}$

$^{254}Cf \xrightarrow[60.5\ d]{SF}$

$^{255}Cf \xrightarrow[1\ h]{\beta^-}$ $^{255}Es \xrightarrow[40\ d]{\beta^-}$ $^{255}Fm \xrightarrow[20\ h]{\alpha}$

$^{256}Es \xrightarrow[22\ m]{\beta^-}$ $^{256}Fm \xrightarrow[2.6\ h]{SF}$

$^{257}Fm \xrightarrow[101\ d]{SF}$

$^{258}Fm \xrightarrow[0.38\ ms]{SF}$

$^{259}Fm \xrightarrow[1.5\ s]{SF}$ $^{259}Md \xrightarrow[95\ m]{SF}$

^{260}Fm ?

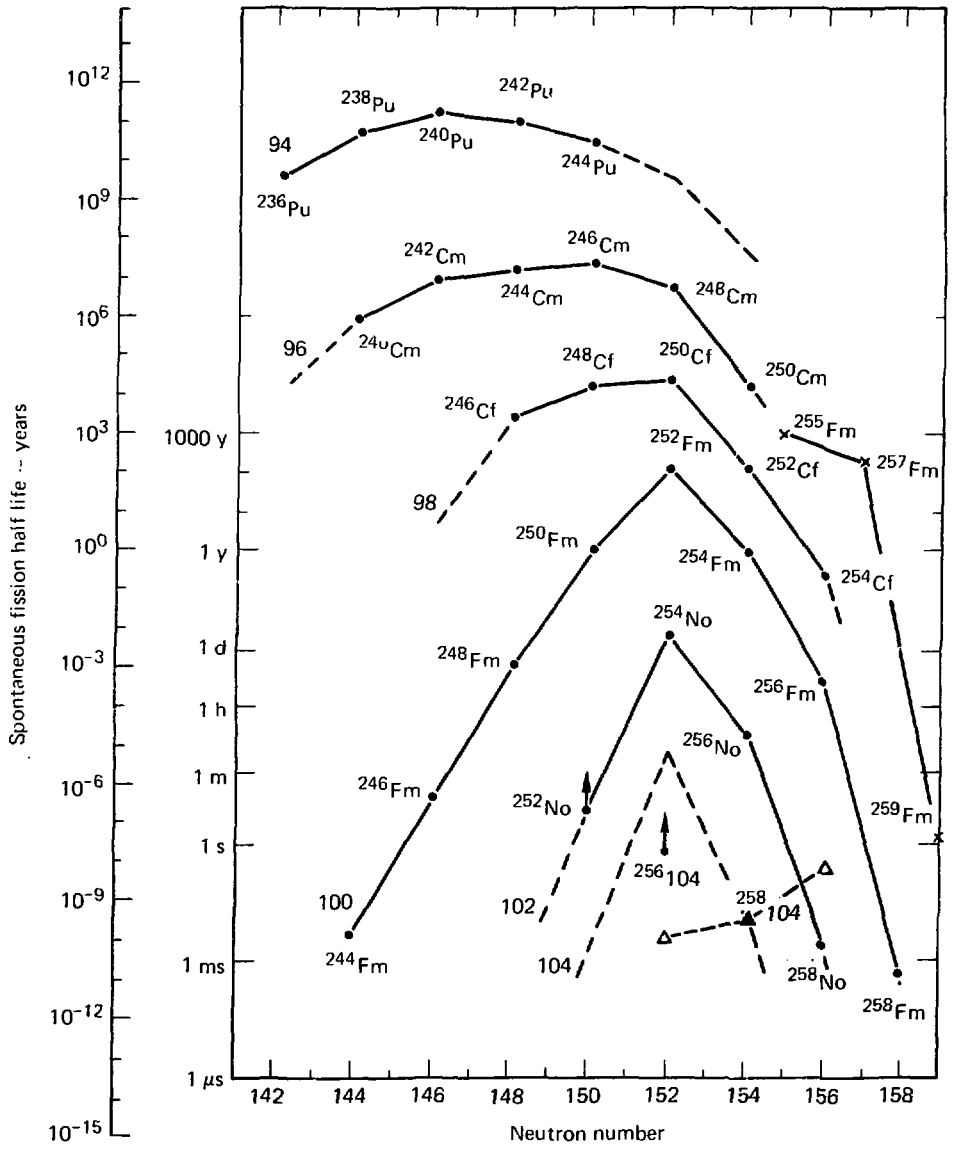
^{261}No ?

^{262}No ?

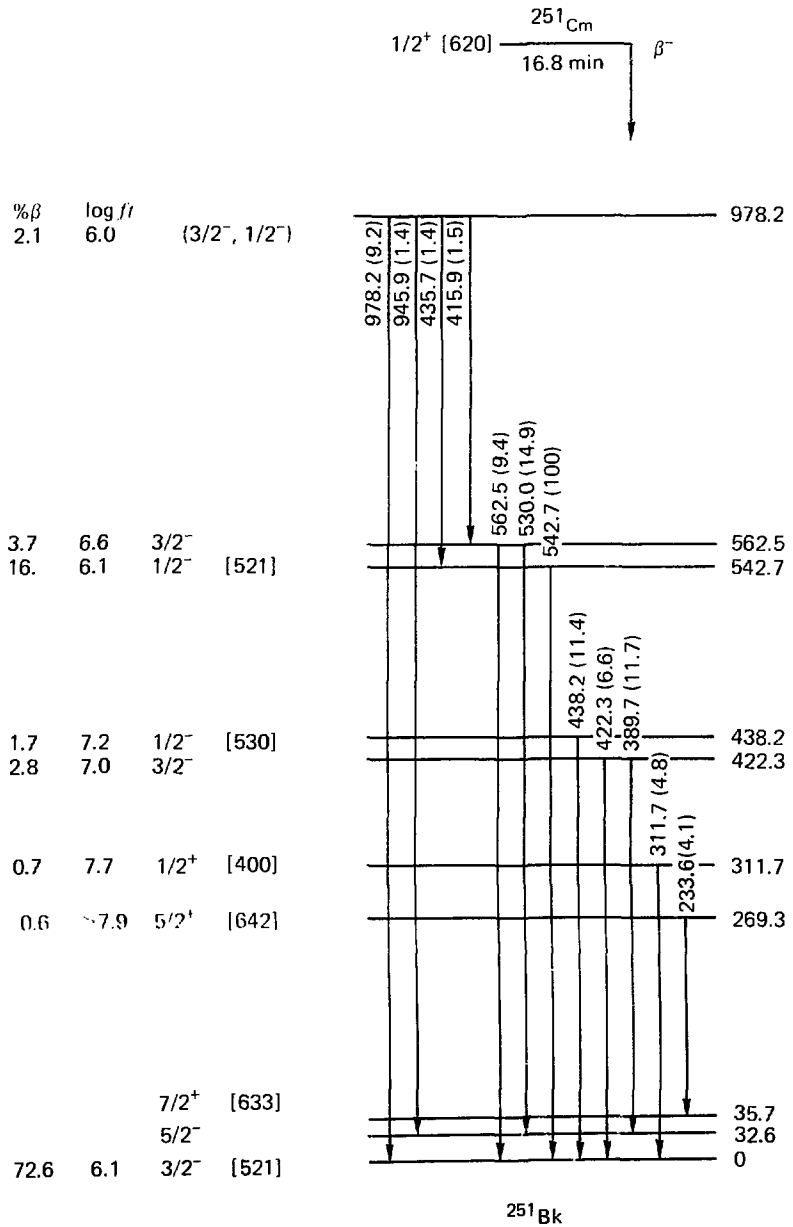
^{263}No ?

^{264}No ?

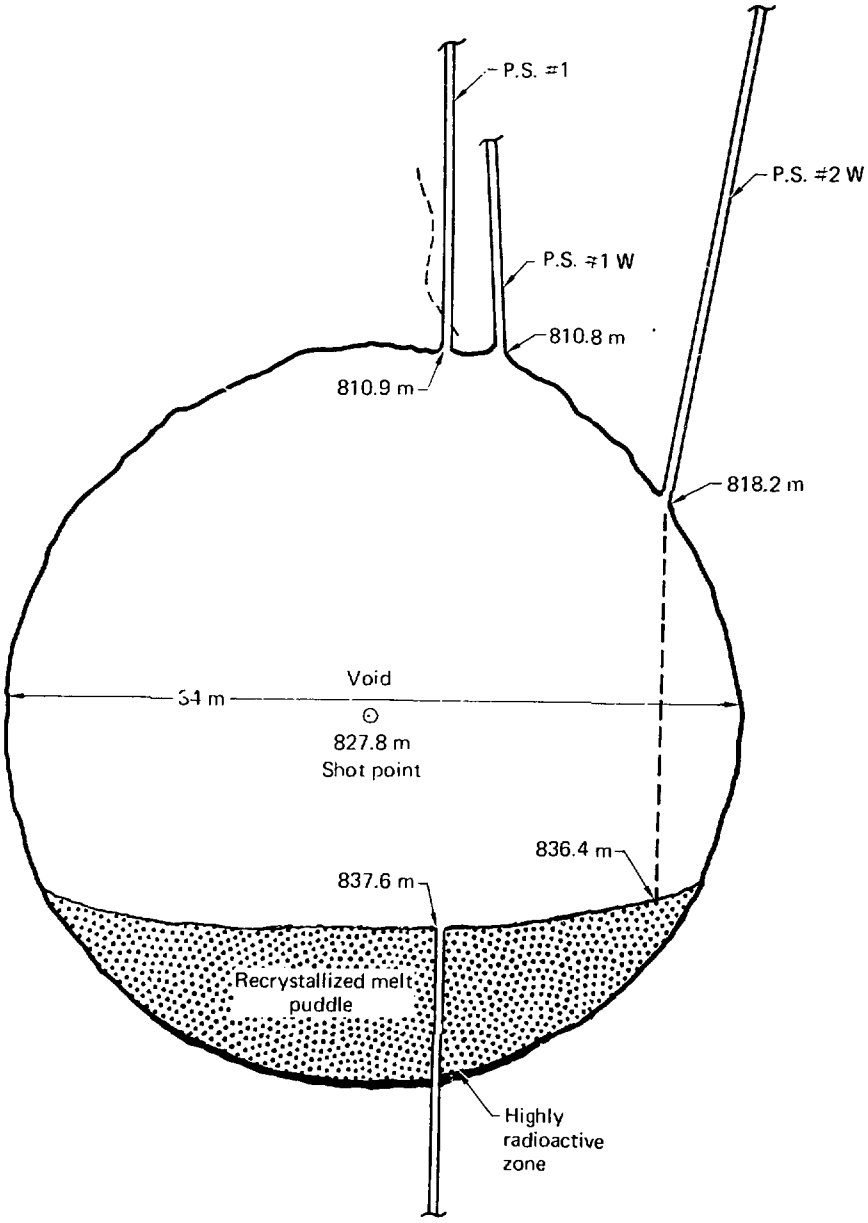
Hoff - Fig. 8


Spontaneous fission half life -- years
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
1000 y
1 y
1 d
1 h
1 m
1 s
1 ms
1 μs
142
144
146
148
150
152
154
156
158
Neutron number
94
96
98
100
102
104
^{236}Pu
^{238}Pu
^{240}Pu
^{242}Pu
^{244}Pu
^{240}Cm
^{242}Cm
^{244}Cm
^{246}Cm
^{248}Cm
^{246}Cf
^{248}Cf
^{250}Cf
^{250}Cm
^{252}Cf
^{254}Cf
^{255}Fm
^{257}Fm
^{259}Fm
^{244}Fm
^{246}Fm
^{248}Fm
^{250}Fm
^{252}Fm
^{254}Fm
^{256}Fm
^{252}No
^{254}No
^{256}No
^{256}104
^{258}104
^{258}No
^{258}Fm

Hoff - Fig. 9


251Cm
1/2+ [620]
16.8 min
β−
%β
log ft
2.1
6.0
(3/2−, 1/2−)
978.2
978.2 (9.2)
945.9 (1.4)
435.7 (1.4)
415.9 (1.5)
562.5 (9.4)
530.0 (14.9)
542.7 (100)
3.7
6.6
3/2−
562.5
16.
6.1
1/2−
[521]
542.7
438.2 (11.4)
422.3 (6.6)
389.7 (11.7)
1.7
7.2
1/2−
[530]
438.2
2.8
7.0
3/2−
422.3
311.7 (4.8)
233.6(4.1)
0.7
7.7
1/2+
[400]
311.7
0.6
~7.9
5/2+
[642]
269.3
7/2+
[633]
35.7
5/2−
32.6
72.6
6.1
3/2−
[521]
0
251Bk

Hoff - Fig. 10


P.S. #1
P.S. #2 W
P.S. #1 W
810.8 m
810.9 m
818.2 m
Void
34 m
827.8 m
Shot point
836.4 m
837.6 m
Recrystallized melt puddle
Highly radioactive zone

Hoff - Fig. 11