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Reviews for LLNL Fission Chain Yield Determination of Fission Spectrum Neutron Bombardment on Plutonium

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Introduction*:*
Accurate analytical and nuclear data are important to US national laboratories. Because the importance of these data to missions within Lawrence Livermore National Laboratory (LLNL) are well understood, our practice has been to periodically evaluate the nuclear data we use. New data has become available since the last analysis and a new evaluation is warranted.

This body of work represents the progress to date on the larger-scale issue of conducting an evaluation with a focus to determine the fission chain yields for ^{95}Zr, ^{99}Mo, ^{144}Ce and ^{147}Nd. Information was gathered from all sources possible including the literature, other laboratories, etc.

Our criteria were established to evaluate the body of work and establish whether we could use it in our evaluation. Uncertainties are paramount to this effort and were carefully considered. Examples of review topics include, but are not limited to: target manufacture, target isotopics, age of target prior to irradiation, neutron source/spectrum, irradiation information, chemistry and analysis details such as nuclear data, corrections for decay, etc.

Because the data set is rather small, one sentiment was to make every effort to keep data. If corrections were required efforts were made to assess the magnitude of those corrections and the corresponding effect on uncertainty.

All of these considerations were applied to create the preliminary results table below. This work will continue throughout the summer with final results expected in the fall.

We have reviewed nearly all of the available information on measured fission chain yields. Our next steps will involve incorporating data reported as relative measurements.

Preliminary results

Nuclide	Evaluated Fission Chain Yield	% Uncertainty*	Number of data points in evaluation
95Zr	4.73	3.0	5
99Mo	5.94	3.0	2
144Ce	3.69	3.0	5
147Nd	1.98	2.5	2

*Expressed as a percent of the larger of either the weighted standard deviation of the mean or the standard deviation of the average of the points

Document Reviews

Reference:	C.A. Anderson, "Fission product yields from fast (~1 MeV) neutron fission of Pu-239", LA-3383; UC-34 physics; TID-4500 (46th Ed.) 1965.
Location:	No location
Assemblies:	No Assemblies
Materials:	
Detection:	
Target Isotopics	
Experimental Details:	This is a Literature compilation (No evaluations). A lot of these numbers come from another book
Fission products:	89Sr, 89Sr, 95Zr, 97Zr, 99Mo, 103Ru, 103Ru, 106Ru, 109Pd, 111Ag, 112Pd, 132Te, 137Cs, 140Ba, 153Sm
Number of fissions:	
Amount of fissionable material;:	
Thermal fission yield:	
Error terms:	Data taken from the literature have sometimes uncertainties and sometimes none
Neutron spectra:	
Results ^{239}Pu(n,f)XX Cumulative:	See "FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne
Notes	• This paper is trying to justify a mirroring process for light masse fission chain yields • Do not use this data. We should use the data that are from experimental references. Most of the results are from other books that are not listing the origin of the results nor are they listing uncertainties
Concerns	

Fission Product Review Sheet

Reference	E. K. Bonyushkan, Yu. S. Zamyatnin, V. V. Spektor, V. V. Rachev, V. R. Negina, V. N. Zamyatnina, Soviet Atomic Energy, Vol. 10, p.10 (1961)
Measurement	$Y^{33,fis}$, $Y^{33,14}$, $Y^{49,fis}$ and $Y^{49,14}$ via beta counting of radiochemically separated samples
Location	No specific location identified
Assemblies	Fission spectra: ^{235}U breeding system without a moderator 14 MeV: D-T neutron generator
Material	120-150 mg foils of ^{233}U as U_3O_3 and ^{239}Pu as metal foils placed in hermetically sealed brass "cassettes" ~ 10mm in diameter
Detection	Beta counting of radiochemically of separated samples via a counter calibrated against a 4π-counter Fissions for ^{233}U fission spectra: small ionization fission chamber with ^{233}U. No details given. Fissions for ^{233}U 14 Mev Neutrons: neutron flux determined via associated particle detection with an alpha counter, fission cross section, and amount of material in foil Fission of ^{239}Pu: Fitting data to mass distribution and equating the integral of fit to 200% of the number of fissions.
Irradiation Details:	Irradiation time for both systems was 7-10 hours with total neutrons on target of ~$5x10^{14}$. No details on the number of samples irradiated or how exact specifications of those samples
Fission Products	In general ^{89}Sr, ^{99}Mo, ^{103}Ru, ^{106}Ru, ^{111}Ag, ^{115}Cd, ^{129m}Te, ^{132}Te, ^{136}Cs, ^{137}Cs, ^{140}Ba, and ^{141}Ce though not all isotopes were measured for all irradiations. Total 129 yield is inferred from ^{129m}Te measurement though no details cited.
Number of Fissions	Number of fission determined for 14 MeV of ^{233}U only for ^{140}Ba and ^{141}Ce measurement where samples were placed 48.5 mm from tritium target. All others determined relative to these isotopes, probably with foil irradiated much closer to tritium target or with higher fluxes making alpha counting difficult. For ^{239}Pu, measured fragments were used to determine mass distribution curve which was then normalized to 200%. Data was reflected between heavy and light mass peaks assuming a value of nubar of 3.2 for ^{239}Pu fission spectra. Only 27.5% of mass distribution measured directly. Also done for ^{233}U fission spectra as check for fission chamber measurements.
Amount of Fissionable material	120-150 mg samples stated but no details given on mass determination.

Chemical Separation	Fragments separated by the isotopic carrier method. Pu separated out by via precipitation of its peroxide from 3N hydrochloric acid with a preliminary removal of silver chloride. U separated out via extraction from 6N hydrochloric acid using a 15% solution of tributyl phosphate in benzene, also with preliminary removal of silver chloride. Separation of carriers and radiochemical purification done with the aid of techniques described in "handbooks on analytical chemistry and radiochemistry" (references listed). The final form of the carries for measurement were:$PbMoO_4$, RuO_2, AgCl, $Cd_2P_2O_7$, Te, Cs_2SO_4, $BaCrO_4$, CeO_2, and $SrSO_4$.		
Uncertainties	No discussion about uncertainties and contributions from various components. Uncertainties are listed with data and are generally around 10% for all irradiations, ^{233}U and ^{239}Pu with fission spectra and 14.5 MeV neutrons		
Neutron Spectra	No detail information describing energy spectrum for fission neutron. 14.5 MeV is from standard d-t generator		
Results ^{239}Pu (n,f) XX cumulative	Isotope	Fission Spectra	14.5 MeV
	^{99}Mo	5.9 ±0.6	4.16±0.40
	^{103}Ru	6.0±0.7	6.25±0.80
	^{106}Ru	4.8±0.6	4.16±0.5
	^{111}Ag	0.55±0.06	1.46±0.14
	^{115}Cd	0.09±0.01	1.23±0.10
	115_{tot}	0.095±0.010	1.30±0.11
	^{129m}Te	0.45±0.09	Not Listed
	129_{tot}	1.17	Not Listed
	^{132}Te	3.5±1.0	4.58±0.50
	^{137}Cs	Not Listed	5.1±0.8
	^{140}Ba	5.4±0.5	4.35±0.4
Concerns	1. Percentage errors listed are similar for all four irradiations, even though different methods were used to determine number of fissions. 2. How accurate is reflecting data between heavy and light mass fragment? 3. Given only ~25% percent of the 200% of the fission mass distribution is directly measured, how accurate is the number of fission determination?		

Uncertainty Check	Various components of uncertainty 1. Chemical Efficiency during separation – not discussed in detail. ~ 1% 2. Beta counting efficiency – limited discussion ~ 4% 3. Counting statistics – Not discussed explicitly but based on mass of samples and number of neutrons during irradiation this should be small, < 1% 4. Dead time – Not discussed but should be small correction that can be calculated with reasonable accuracy 5. Decay losses during irradiation and after irradiation – not discussed. Time between irradiation and counting not discussed. Half-lives used not discussed but should contribution due to uncertainty of half lives should be small 6. Half-life for converting count rate to number of atoms – Again half-lives used not discussed but should be small contribution 7. Fission determination: Extrapolation to full 100% of mass peak from measuring only 13% of all fragments. Given estimate in uncertainties above total number of measured fragment atoms is accurate to ~5%. Lowest mass fragment measured for Pu-239 is Mo-99, implying lower half of mass plot is an extrapolation. Also on true high side of heavy mass fragment with Ba-140 being heaviest fragment. Assume extrapolation region (40% of all masses) is only known to 20%, and interpolation region (50% of all masses) known to 10%, implies correction only known to about 10%. Now adding in 5% uncertainty for measured masses would imply about 12% uncertainty in number of fissions. Thus 12% uncertainty should be minimum uncertainty for this chain yield measurement.

Reference:	S. Cierjacks, Progress Report on Nuclear data research in the federal republic of Germany" 1974 – G. Cottone "Fast fission yields and α values of some nuclides" pp42-44, 1974
Location:	Rapsodie reactor
Assemblies:	Referenced to [A.R. Musgrove et al., "Prediction of unmeasured fission product yields", IAEA panel on FPND, Bologna (1973)]
Materials:	239Pu but no description of isotopics or chemical form
Detection:	Isotope mass dilution spectroscopy, and gamma counting
Target Isotopics	No description of target isotopics
Experimental Details:	Potentially this is referenced in [A.R. Musgrove et al., "Prediction of unmeasured fission product yields", IAEA panel on FPND, Bologna (1973)]
Fission products:	125-Sb, 131-Xe, 132-Xe, 133-Cs, 134-Xe, 135-Cs, 136-Xe, 137-Cs, 143-Nd, 144-Nd, 145-Nd, 146-Nd, 148-Nd, 150-Nd
Number of fissions:	• No description of irradiation time, number of fissions, and neutron flux • For the normalization process they used the Maeck methodology of summing the fission products and extrapolating or interpolating the missing yields
Amount of fissionable material;	No description of amount
Thermal fission yield:	No thermal irradiations were performed
Error terms:	No description of uncertainty treatment, uncertainties are listed
Neutron spectra:	The spectrum is only described by an α value of 0.134 ± 0.003
Results ^{239}Pu(n,f)XX Cumulative:	See "FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne
Notes	• This is an annual progress report, very short 2 page paper. Eventually Cottone published some results with the Kotch in 1981. • We should use the Kotch results and not this progress report
Concerns	• There is no description of the target isotopics or chemical form • There is no description of the nuclear data used (t1/2, Branching ratios, etc…) • There is no discussion of the efficiency curve for the gamma detectors • No description or reference for the chemistries • There is no discussion of uncertainty treatment • The uncertainties seem small given the uncertainties in efficiencies and nuclear data

Cuninghame and Willis, J. Inorg. Nucl. Chem. 39 (1977) 383-386

Fission Product Review Sheet

Reference: J. G. Cuninghame and H. H. Willis, "Absolute yields in the fission of ^{239}Pu by mono-energetic neutrons of energy 130-1700 keV", J. Inorg. Nucl. Chem. 39 (1977) 383-386

Location: 3 MeV Harwell van de Graaf (IBIS)

Assemblies: none

Materials: 2 g of Pu metal, ^{238}Pu 0.016%, ^{239}Pu 96.328%, ^{240}Pu 3.461%, ^{241}Pu 0.187%, ^{242}Pu 0.008%

Detection: Beta counters, gravimetric chemical yields

Experimental details: See Cuninghame et al., J. Inorg. Nucl. Chem. 36 (1973) 1453 for most of experimental details. Cd box around assembly, sealed in Ar gas bag. Target mounted as closely as possible to 0^0 relative to beam axis, 4 to 6 cm from neutron target. Neutrons energy determined kinematically from proton irradiation of either ^{3}H or ^{7}Li. Thick foil/thin foil technique, thick foil is 2 g Pu metal, thin foil is Pu deposit (same material) as salt on stainless steel plate. Flux monitoring during experiment with the "long counter" is only to ensure constant flux during irradiation, Number fissions thick foil calculated from fragments emitted by thin foil, etched tracks in Macrofol, scaled by mass. Macrofol response calibrated by ^{252}Cf source. Irradiations were 4 hours in length, chemistry followed by beta counting.

Fission products: ^{99}Mo, ^{111}Ag, ^{140}Ba, ^{147}Nd, ^{153}Sm, ^{156}Eu

Number of fissions: 5000 fission tracks in monitor foils on average.

Amount of fissionable material: 2 g Pu metal each irradiation, see above

Thermal fission yields: none

Error terms: Table given, major term from counting has to do with self attenuation of betas during counting, major term in quantification of fissions is number of tracks, some estimate of errors due to irradiation correction factors (see below) is given.

Neutron spectrum: in keV, 130+10-25; 300+10-28; 700+43-68; 900+48-73; 1300+33-70; and 1700+33-77

Results ^{239}Pu(nf,f)XX: (as quoted in paper)

Nuclide Fission chain yields in %, ^{239}Pu (n,f) (E in keV) (1st uncert is stat, 2nd uncert is stat + syst)

	E= 130	300	700
^{99}Mo	5.24 ± 1.7% ± 5.9%	5.42 ± 5.3% ± 7.7%	5.65 ± 5.7% ± 8.0%
^{111}Ag	0.29 ± 3.4% ± 6.6%	0.28 ± 14.3% ± 15.3%	0.32 ± 5.7% ± 6.4%
^{140}Ba	4.96 ± 2.6% ± 6.2%	5.22 ± 0.2% ± 5.6%	5.96 ± 11.1% ± 12.4%
^{147}Nd	2.19 ± 3.3% ± 6.4%	2.22 ± 1.8% ± 5.9%	2.46 ± 3.7% ± 6.7%
^{153}Sm	0.30 ± 10.0% ± 11.5%	0.33 ± 15.2% ± 16.2%	0.36 ± 13.9% ± 15.9%
^{156}Eu	---	---	---

	E = 900	1300	1700
^{99}Mo	5.58 ± 7.2% ± 9.1%	5.36 ± 5.2% ± 7.7%	5.61 ± 2.3% ± 6.1%
^{111}Ag	0.33 ± 6.1% ± 8.3%	0.36 ± 5.6% ± 7.9%	0.38 ± 2.6% ± 6.2%
^{140}Ba	5.34 ± 7.9% ± 9.7%	5.22 ± 4.4% ± 7.1%	5.42 ± 7.2% ± 9.1%
^{147}Nd	2.38 ± 2.5% ± 6.1%	2.25 ± 1.3% ± 5.8%	2.60 ± 5.8% ± 8.0%
^{153}Sm	0.35 ± 8.6% ± 10.2%	0.36 ± 13.9% ± 15.0%	0.36 ± 2.8% ± 6.2%
^{156}Eu	---	---	0.087 ± 1.1% ± 5.7%

Notes: Main point of paper has to do with trends of yields with energy; valley and wing yields increase with E, peak yields are relatively constant, as expected from Lisman(2). However, some of the trend needs to be removed due to different contributions of fission of ^{240}Pu as a function of energy.

Cross sections for (n,f) in barns (approximate)

Energy (keV)	^{239}Pu(n,f)	^{240}Pu(n,f)
130	1.5	0.08
300	1.6	0.15
700	1.65	0.9
900	1.7	1.4
1300	1.85	1.5
1700	2.0	1.6

Concerns: Many corrections are applied to the data used to calculate the number of fissions in the chemistry foil: 1) A slightly different solid angle subtended by the chemistry target and thin target required a 8-11% correction; 2) Absorption of neutrons between the chemistry target and the thin target required a 2-3% correction. Thickness of the plutonium thin target attenuated the fission fragments relative to those leaving the ^{252}Cf calibration source, requiring a 2.7% correction (assumed to be the same as for ^{235}U experiments); and 4) the loss of ^{252}Cf events in Macrofol etching (25%) (this is higher by a factor of 4-5 from other track detectors that I've seen).

The chemistries described for Ag (an insoluble intermediate in solution) and Mo (no carrier exchange) are inadequate, and performance was not discussed in the paper. I estimate that background SF in each target is 1715 SF/minute from ^{240}Pu decay; for a target more than a few weeks old, the saturation level of all analytes is approached. From Laidler and Brown, J. Inorg. Nucl. Chem. 24 (1962)1485, the 240Pu SF FCY(^{147}Nd) is 1.22%, FCY(^{99}Mo) is 6.82% and FCY(^{140}Ba) is 5.99%;

resulting in a constant 21 dpm of ^{147}Nd, 117 dpm of ^{99}Mo, and 103 dpm of ^{140}Ba before the foil is irradiated. While SF will make tracks just like induced fissions, these activities are present before irradiation, in excess of what would be calculated from the track detector. While the induced component of the activity begins to decay at the end of irradiation, saturation keeps that component from SF alive until the separation from Pu is effected. There is not enough information in the paper to make a correction, but in the ^{235}U paper, it states that initial count rates for ^{99}Mo were a few hundred counts per minute. If we assume that the chemical separation took a short time relative to the half life of ^{99}Mo (or ^{147}Nd or ^{140}Ba), and that the beta counter efficiency was about 25% for all of these nuclides, as were the chemical yields, and that "a few hundred" is about 500, then spontaneous fission accounts for 1.4% of the ^{99}Mo yield, 5.8% of the ^{140}Ba yield, and 2.4% of the ^{147}Nd yield. As discussed, the Mo chemistry was not adequate and the data don't mean much, but if I correct the average value of FCY(^{147}Nd) from the table above (2.35%) and the average value of FCY(^{140}Ba) from the table (5.35%) downward by 2.4% and 5.8%, respectively, I get

Table, semi-empirically corrected fission chain yields for ^{147}Nd and ^{140}Ba (fast neutrons + Pu) from Cuninghame, compared with as-stated values from Myers

Nuclide	uncorrected Cuninghame	corrected Cuninghame	Myers
^{147}Nd	2.35%	2.29%	2.27(7)%
^{140}Ba	5.35%	5.04%	5.46(17)%

Reference:	W. Davies, "Absolute measurements of fission yields for 235-Uranium and 239-Plutonium in the Dounreay fast reactor", 13 Radiochimica Acta, Band 12, Heft 4 pp173-178, 1969
Location:	Dounreay fast reactor
Assemblies:	Dounreay fast reactor
Materials:	4 g of PuO2 in sealed stainless steel
Detection:	Isotope mass dilution spectroscopy, with gamma counting
Target Isotopics	238Pu: 0.0, 239Pu: 93.86 ± 0.12, 240Pu: 5.64 ± 0.09, 241Pu: 0.45 ± 0.06, 242Pu: 0.05 ± 0.05 (the uncertainties are a 95% confidence level)
Experimental Details:	• Isotope mass dilution spectroscopy for the stable elements • Chemical separation followed by gamma spec for ^{90}Sr, ^{137}Cs, ^{144}Ce • 18 month irradiation (1.6e15 n/cm2sec) only 9 month or real irradiation time • Corrections were done due to irradiation history • Dissolved between 4 to 8 months after irradiation • Stainless steel sealed was dissolved with the fission products • Description of chemical procedures and references • Multiple people preparing individual standards making multiple measurements • Mass spec measurements with mass bias measurements in between • Gamma detectors were calibrated by Amersham sources, Amersham claims 3% uncertainty •
Fission products:	^{90}Sr, ^{137}Cs, ^{144}Ce, ^{143,145,146,148,150}Nd
Number of fissions:	This was determined through a 5.55% ± 4.8% (this is % of %) burnup of 239Pu target
Amount of fissionable material;	4 g of PuO2
Thermal fission yield:	No thermal irradiation
Error terms:	• Fuel loss in the dissolution was 0.02% • Fission product loss was 0.4% • Largest uncertainty is from the measurement of the fuel burnup • The uncertainties ranged from 6-7% for a 95% confidence factor • The uncertainties in the results incorporate the statistical uncertainty in the multiple measurements • The 238U was a 0.04% content of the Pu target so a correction for 238U(n,g) to 239Pu was made (1.0004). This changed the burnup by 0.9% • half life corrections were made because of the irradiation was 2.5

	years after initial assay of target Pu atoms • Estimates of fission product burnup is less then 1%
Neutron spectra:	Fast reactor, neutron energies >2.23 MeV
Results ^{239}Pu(n,f)XX Cumulative:	See "FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne
Notes	• The uncertainties could be reduced by higher burnup rates
Concerns	• No errors listed for decay scheme of ^{90}Sr, ^{137}Cs, ^{144}Ce • This would mostly effect the 144Ce data • No nuclear data listed for these isotopes • Neutron spectrum is given in terms of energy range. It looks like a very hard spectrum • Burnup corrections are overall less then 1% however this is likely to be fission product specific

Fission Product Review Sheet

Reference:	R. P. Larsen, N. D. Dudey, R. R. Heinrich, R. D. Oldham, R. J. Armani, R. J. Popek, R. Gold, Nucl. Sci. and Eng. 54 (1974) 263-272
Location:	Argonne's Zero Power Reactor 3 (ZPR-3) (Critical Assembly), ^{235}U and ^{239}Pu also in Argonne Thermal Source Reactor
Assemblies:	60 – A mock-up of the 1970 configuration of EBR-II 61 – A mock-up of EBR-II with the ^{238}U blanket replaced by a Ni reflector
Materials:	gram amounts of ^{235}U, ^{238}U, and ^{239}Pu as thin metal foils, irradiated next to mica track detectors embedded with nanogram amounts of the fissionable materials (SSTR).
Detection:	GeLi detectors Fissions: Count the fission tracks in the Mica, divide by the 'optical efficiency factor', multiply by the weight ratio of the fissionable material in the foils and the SSTRs in the ZPR-3 experiments. In the ATSR experiments, the fissions were determined by assaying the foils for their ^{137}Cs content and dividing by the values from Lisman[1] et al. for the ^{137}Cs fractional fission yields. All samples were counted on the same detector and within the same time-frame.
Experimental Details – ZPR-3	Irradiation package – 2"x2"x0.327", ^{235}U & ^{239}Pu foils 1.75"x0.25"x0.030", ^{238}U foil 1.75"x0.25"x0.060", wrapped in Al to prevent loss of recoiling fission products. Each location had eight SSTRs, each set with two mica strips, 2"x0.375"x0.005", alternately stacked with two Pt strips of the same dimensions. Each strip of Pt contains four 0.25" depositions of fissionable material (99.999+% purity) at 0.5" intervals, spaced such that the assembled package had eight SSTRs spaced at 0.25" intervals along the length of the set. Amounts 10 – 50 ng for ^{235}U and ^{239}Pu, 0.2 to 2 μg for ^{238}U. (Paper ref. 4)
Fission Products	Each fissionable material strip was cut into seven 0.25"x0.25" pieces. Each piece weighed on an analytical balance. GeLi counting for a schedule over 128 days. Each section assayed a minimum of three times. Gamma standards from NBS, Amersham, and IAEA. Analyzed with BILE, a local version of GAMMANAL. Analysis done for ^{95}Zr, ^{95}Nb, ^{97}Zr, ^{97}Nb, ^{99}Mo, ^{103}Ru, ^{131}I, ^{140}Ba, ^{140}La. Specifically for ^{239}Pu fission, only ^{95}Zr, ^{97}Zr, ^{103}Ru, ^{131}I, and ^{140}Ba were reported.
Number of Fissions	HF etch the Mica, count tracks, two different observers. If δ tracks > 3%, both recount.
Amount of Fissionable material	^{235}U & ^{238}U in the SSTRs are determined by MS isotopic-dilution analysis. Each section was analyzed separately, completely dissolved with con HNO_3 / HCl, traced with ^{233}U. Pt separated by electrolysis into Hg from H_2SO_4 solution. ^{239}Pu determined by 2-π alpha proportional counting. ^{238}Pu content

[1] F. L. Lisman, R. M. Abernathy, W. J. Maeck, and R. E. Rein, Nucl. Sci. Eng. 42 (1970) 191

	< 0.001%, 238Pu alpha activity < 0.1% by alpha spec.
Thermal Fission Yields	Thermal neutron irradiations carried out on ^{235}U and ^{239}Pu foils, assayed by gamma spec along with the ZPR-3 foils. The number of fissions were determined by cooling the foils for 18 months, then assaying the ^{137}Cs content and using the FCY from ref. 1.
Error Terms	For fission product atoms per gram of material: 1. Counting statistics. 2. Calibration error. 3. Nuclear data (BR, $t_{1/2}$). 4. Attenuation in the foil. 5. Fissionable material weight in the foil. For the SSTRs: 1. Number of fission tracks. 2. Optical efficiency for converting the number of tracks to fission. 3. Mass of fissionable material.
Neutron Spectra	Values measured at thermal and 'Fast', where 'Fast' was at two energies, 293 and 442 keV, listed as ^{235}U Median Fission Energy. Crouch considered all values as 'Fast', at least that is the table where they ended up in his compilation.

Results ^{239}Pu (n,f) XX cumulative

^{235}U Median Fission Energy (keV)	^{95}Zr	^{97}Zr	^{103}Ru	^{131}I	^{140}Ba
446	---	---	7.03	4.01	5.19
442	4.78	(4.87)	7.11	4.08	5.31
293	4.76	(4.85)	7.01	4.14	5.26
Average	4.77	(4.86)	7.05	4.08	5.25
Unc.	3.5	3.0	3.1	3.1	2.9
Thermal	4.83	4.98	7.04	3.95	5.24

Notes	Thermal error terms are estimated to be equivalent to the evaluated Fast uncertainty. Results in () indicate interference in the gamma measurement from ^{239}Pu.
Concerns	4. Are the SSTR's and the fissile material foils seeing the same flux and spectrum? Probably, as there is less than 0.375" of Al between them, however they are on two sides of the Al plate placed into the experimental assembly. 5. A thought on a noted discrepancy with the ^{140}Ba values. There appears to be a relative effect of the irradiation time vs. ^{140}Ba yields. Namely, the longer the irradiation the higher the yield. Reaction rate ratios had been taken of X/^{140}Ba in a couple of paired experiments where the sole difference was the irradiation time, ~1 hour vs ~200 hours. For ^{95}Zr, the ratio was reported as 4.7% and 6.0% higher in two paired experiments. Other reaction rate ratios to other species showed no such effect. The authors offer no explanation.

Reference:	V. S. Prokopenko, V. Ya. Gabeskiriya, A. V. Inchagov, Yu. B. Novikov, V. M. Prokop'ev, V. V. Tikhomirov and A. P. Chetverikov, "Fission yields from 235U and 239Pu irradiation in the BOR-60 reactor", 1976 This is a translation of the original paper Atommoya Energiya, Vol 43 No. 1 pp59-60 Dec 24 1976
Location:	BOR-60 reactor Russia
Assemblies:	
Materials:	U-235 and Pu-239
Detection:	Isotope mass dilution spectroscopy, The fission chain yield is determined through the sum of 145+146Nd 5.56±0.12 for ^{239}Pu. This is a relative measurement of FCY to the 145+146Nd sum (5.56 ± 0.12% for 239Pu, 6.85 ± 0.2% for 235U)
Target Isotopics	No Pu isotopics were given
Experimental Details:	No description of the chemistries
Fission products:	135, 137, 140, 142, 143, 144 (Ce+Nd), 145, 146, 148, 150
Number of fissions:	• The fission chain yield is determined through the sum of 145+146Nd 5.56±0.12 for ^{239}Pu. This is a relative measurement of FCY to the 145+146Nd sum • The 145+146 mass chain yield was obtained from Lisman et al Nucl. Sci. Eng., 42 191(1970)
Amount of fissionable material;	Amount of target materials were not discussed
Thermal fission yield:	
Error terms:	Sparse discussion of error analysis
Neutron spectra:	• The initial argument was that the FCY in BOR-60 should be different then EBR-II because the spectrum was different. When they compare the FCY the differences are small for the isotopes they measured. • No description of the spectrum • No measurements of the spectrum are presented
Results ^{239}Pu(n,f)XX Cumulative:	See "FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne
Notes	• This is only good as a relative comparison to the Lisman paper because of the 145+146Nd fission determination • There is not enough details about these analyses to use this paper

Concerns	• Is the 145+146 really an insensitive sum • The uncertainty on the sum seems very small • The ratio of 145 between him and Maeck is 0.8. So there are significant differences in the 245 assessment between experiments • Due to the sparseness of data and the relative measurement of assuming the 145+146 sum, I suggest not using these results

Gindler-1983:

Executive summary

Abstract: Fission chain yields of 24 masses were determined for the fission of ^{239}Pu with monoenergetic neutrons of 0.17, 1.0, 2.0, 3.4, 4.5, 6.1, and 7.9 MeV, at the Argonne Fast Neutron Generator Facility. Fission product activities were measured by Ge(Li) γ-ray spectrometry of irradiated ^{239}Pu sample and by β counting of chemical separated fission products. The direct comparison is difficult for the current data set with those compiled for thermal, fission spectrum, and 14 MeV neutrons since the dependence of fission chain yield on neutron incident energy was not established.

Synopsis of LLNL assessment: The precise dependence of fission chain yields on the neutron incident energy was not determined for masses near peak fission yields due to the limited accuracy achieved in this work. Therefore, the direct comparison is not possible with the data compiled for thermal, fission spectrum and 14 MeV neutrons. For instance, the FCY's of ^{99}Mo are 6.29±0.42%, 6.03±0.40%, 6.30±0.44%, 6.21±0.42%, 6.36±0.44%, and 5.49±0.39% for E_n at 0.17, 1.0, 2.0, 3.4, 4.5, 7.9 MeV, respectively. The dependence of FCY on E_n is difficult to establish within 1σ (~7%).

LLNL full evaluation

I. Tabular summary

Reference	J.E. Gindler, L.E. Glendenin, D.J. Henderson, and J.W. Meadows, Phys. Rev. C 27, p.2058 (1983) ; relevant refs: PRC 17, 163 (1978), PRC 24, 2600 (1981)
Target material/isotopes	~ 210 mg Pu for each sample, Type I – ^{239}Pu: 99.955, ^{240}Pu :0.041, ^{241}Pu: 0.002, ^{242}Pu: 0.002 Type II – ^{239}Pu: 98.8, ^{240}Pu: 1.2
Detection	• γ-ray counting for Type I material • β counting for chemically separated fission product elements for Type II material
Experimental details	Irradiated for periods of 8 – 16 h. Aluminum container with the plutonium disk was attached to a low-mass fission chamber containing a thin, standardized deposit of ^{239}Pu to monitor the fission rate. The ^{239}Pu standard, obtained from the NBS, was deposited over a circular area 12.7 mm in diameter on a 0.13 mm thick platinum plate 19.1 mm in diameter. The fission chamber positioned ~ 3 cm from the neutron source.
Number of fissions	Fission rate typically were 4×10^4 /s; total fissions were on the order of 10^9.
Neutron spectra	• Argonne Fast Neutron Generator Facility • ^{7}Li(p,n) for E_n below 5 MeV

	• $^{2}H(d,n)$ for E_n above 5 MeV • Energy spread 2 – 8% for E_n > 0.17 MeV and 60% for E_n = 0.17 MeV

II. Data

The FCY's determined by either γ counting (γ) or β counting for radiochemically separated fission products (RC-β), are listed below in % of total fissions for ^{87,88}Kr, ^{91,92}Sr, ^{93}Y, ^{97}Zr, ^{99}Mo, ^{103,105}Ru, ^{109,112}Pd, ^{111}Ag, ^{115}Cd, ^{121,125}Sn, ^{127,129}Sb, ^{132,134}Te, ^{133,134,135}I, ^{135}Xe, ^{140}Ba, ^{142}La and ^{143}Ce.

Isotope	Meas. Tech.	0.17 MeV	1.0 MeV	2.0 MeV	4.5 MeV
^{87}Kr	γ	0.76±0.10	0.83±0.09	0.93±0.09	1.38±0.11
^{88}Kr	γ	1.13±0.10	1.16±0.09	1.42±0.10	1.61±0.12
^{91}Sr	γ	2.72±0.16	2.71±0.15	2.94±0.17	3.24±0.18
^{92}Sr	γ	3.05±0.38	3.00±0.38	3.36±0.42	3.70±0.46
^{93}Y	γ	4.16±0.40	4.43±0.42	4.86±0.46	5.41±0.56
^{97}Zr	γ	5.67±0.32	5.37±0.33	5.83±0.33	5.93±0.35
^{99}Mo	γ	6.29±0.42	6.03±0.40	6.30±0.44	6.36±0.44
^{103}Ru	γ	7.57±0.50	5.61±0.54	6.97±0.47	5.83±0.95
^{105}Ru	γ	6.03±0.55	5.44±0.43	5.49±0.38	5.53±0.41
^{109}Pd	RC-β	1.14±0.17	0.94±0.14	1.10±0.17	1.41±0.21
^{111}Ag	RC-β	0.25±0.04	0.24±0.04	0.28±0.04	0.63±0.09
^{112}Pd	RC-β	0.14±0.02		0.16±0.02	0.36±0.05
^{115}Cd	RC-β	0.027±0.004	0.036±0.005	0.050±0.008	
^{121}Sn	RC-β	0.032±0.005	0.044±0.007	0.048±0.007	0.13±0.02
^{125}Sn	RC-β	0.039±0.006	0.052±0.008	0.058±0.009	0.17±0.03
^{127}Sb	RC-β	0.34±0.05	0.37±0.06	0.35±0.05	0.77±0.12
^{129}Sb	γ, RC-β	1.18±0.24	1.20±0.24	1.27±0.25	1.65±0.33
^{132}Te	γ	5.52±0.38	5.11±0.35	5.33±0.51	5.37±0.56
^{133}I	γ	7.64±0.45	7.02±0.41	7.32±0.43	7.09±0.42
^{134}Te	γ	5.14±0.42	4.14±0.31	4.36±0.37	3.57±0.30
^{134}I	γ	2.92±1.16	3.31±0.95	2.46±1.32	4.15±0.92
^{135}I	γ	6.89±0.37	6.29±0.34	6.67±0.38	6.39±0.39
^{135}Xe	γ	0.85±0.37	0.92±0.34	0.73±0.61	1.58±0.54
^{140}Ba	γ	5.49±0.33	5.12±0.30	5.37±0.32	5.62±0.34
^{142}La	γ	4.88±0.41	4.49±0.37	4.92±0.44	5.00±0.40
^{143}Ce	γ	4.57±0.36	4.40±0.35	4.44±0.34	4.15±0.33
Summed Prob.		84.4	78.3	83.0	87.0

III. Experimental details

(See Section I)

IV. Data treatment

FCY's were determined by either high-resolution γ-ray spectroscopy of an irradiated Pu sample or β counting of a chemically separated fission product. The latter was applied for Type II sample to determine FCY's for masses near the symmetric fission region and the former for Type I sample for all other determinations. For β counting, the samples were counted in a calibrated low-background (0.5 counts/min) proportional counter equipped with an automatic sample changer. The radioactive purity of a sample was determined by following its decay over a period of several half-lives. Decay curves were analyzed to determine the observed counting rate (A_∞) at the end of irradiation for each fission product, which was corrected for chemical yield, counting efficiency, decay, genetic relationships, and degree of saturation during irradiation.

For γ counting, the irradiated samples were mounted on aluminum plates and placed in a computer-controlled sampler changer designed to give reproducible positioning of the samples. A 2.2 g/cm^2 steel absorber was placed between the sample and Ge(Li) detector to attenuate the ^{241}Am 59.5 keV γ ray. γ-ray spectra were recorded over a period of ~ 1 month to enhance statistical accuracy in the determination of the fission product activities. These activities as a function of time were analyzed to obtain the counting rate (A_∞) at the end of irradiation. Corrections were made for counting efficiency, counting loss due to the summing effect, branching ratios, genetic relationship, and the degree of saturation during the irradiation. Values of A_∞ are related to FCY's by the relationship

$$\text{FCY} = A_\infty \,/\, \text{fission rate},$$

where the fission rate was determined by counting the standard sample of ^{239}Pu in the fission chamber.

V. Uncertainties treatment

The accuracy of the methodology in determination of FCY's was estimated to be about 5%, equivalent of systematic error. The uncertainty for the absolute γ-ray efficiency was estimated to vary between 2 – 5% depending on the γ-ray energy. No individual uncertainty was addressed for chemical yield, β counting efficiency, and counting loss due to the summing effect. In general, uncertainties are in the range of 6 – 10% for peak fission yields (> 1%) by the γ measurement. Large uncertainties of about 15% are assigned to yields with masses near symmetric region by the β measurement.

VI. Unresolved questions in the assessments

A credible comparison of the current data with those compiled for thermal, fission spectrum, and 14 MeV neutrons, requires establishing the dependence of FCY on neutron incident energy. This dependence for masses near symmetric fission region is strong and thus was determined. However, the weak dependence for masses near peak fission yields is difficult to establish with sufficient accuracy from the current data. Therefore, the direct comparison is not possible for the current data set to the existing data with composite beams.

Fission Product Review Sheet

Reference	J.E. Gindler, L.E. Glendenin, D.J. Henderson, and J.W. Meadows, Phys. Rev. C 27, p.2058 (1983) ; relevant refs: PRC 17, 163 (1978), PRC 24, 2600 (1981)
Measurement	$Y^{49,mono}$ via 1. γ counting of irradiated samples and 2. β counting for radiochemically separated fission products
Location	Argonne Fast Neutron Generator Facility
Assemblies	Monoenergetic sources: $^{7}Li(p,n)$, $^{2}H(d,n)$; E_n = 0.17, 1.0, 2.0, 3.4, 4.5, 6.1, and 7.9 MeV
Material	Plutonium metal in a disk form with 12.7 mm diameter and 0.127 mm thick, sealed in a flat, thin-walled aluminum container. Two types of disk used in the irradiation. Type I with an enrichment of 99.955% of ^{239}Pu and 0.041% of ^{240}Pu. Type II with an enrichment of 98.8% of ^{239}Pu and 1.2% of ^{240}Pu. ^{241}Am presented in the disks in amount of ~ 10^9 dis/min (< 0.01 wt. %).
Detection	γ-ray counting for Type I material β counting of radiochemically separated fission products for Type II material
Irradiation Details:	Irradiated for periods of 8 – 16 h. Aluminum container with the plutonium disk was attached to a low-mass fission chamber containing a thin, standardized deposit of ^{239}Pu to monitor the fission rate. The ^{239}Pu standard, obtained from the NBS, was deposited over a circular area 12.7 mm in diameter on a 0.13 mm thick platinum plate 19.1 mm in diameter. It contains 99.1% ^{239}Pu and 0.883% ^{240}Pu. The fission chamber positioned ~ 3 cm from the neutron source.
Fission Products	$^{87,88}Kr$, $^{91,92}Sr$, ^{93}Y, ^{97}Zr, ^{99}Mo, $^{103,105}Ru$, $^{109,112}Pd$, ^{111}Ag, ^{115}Cd, $^{121,125}Sn$, $^{127,129}Sb$, $^{132,134}Te$, $^{133,134,135}I$, ^{135}Xe, ^{140}Ba, ^{142}La and ^{143}Ce.
Number of Fissions	Fission rate typically were 4×10^4 /s; total fissions were on the order of 10^9.
Amount of Fissionable material	~ 210 mg total mass for each sample.
Chemical Separation	Plutonium metal dissolved in concentrated hydrochloric acid containing ~ 10% concentrated nitric acid by volume. A hydrochloric acid solution of carriers for the elements of interest was added followed by a drop of bromine to affect the oxidation of antimony. Plutonium was removed by contacting this solution twice with nearly equal volumes of 0.2 formal weight HDEHP in xylene. Sulfur dioxide bubbled through the aqueous solution to reduce antimony. The fission products of Pd, Ag, Cd, Sn, and Sb were then separated.
Uncertainties	Uncertainties typically are in the range of 6 – 10% for peak fission yields (> 1%) by the γ measurement. Larger uncertainties of about 15% are assigned to yields with masses near symmetric fission region by the RC-β measurement, which refers to the β counting after chemical separation.
Neutron Spectra	The spread of neutron energy was 2 – 8% for E_n > 0.17 MeV and 60% for E_n = 0.17 MeV

Results ^{239}Pu (n,f)

Isotope	Meas. Tech.	0.17 MeV	1.0 MeV	2.0 MeV	4.5 MeV
^{87}Kr	γ	0.76±0.10	0.83±0.09	0.93±0.09	1.38±0.11
^{88}Kr	γ	1.13±0.10	1.16±0.09	1.42±0.10	1.61±0.12

XX cumulative	^{91}Sr	γ	2.72±0.16	2.71±0.15	2.94±0.17	3.24±0.18
	^{92}Sr	γ	3.05±0.38	3.00±0.38	3.36±0.42	3.70±0.46
	^{93}Y	γ	4.16±0.40	4.43±0.42	4.86±0.46	5.41±0.56
	^{97}Zr	γ	5.67±0.32	5.37±0.33	5.83±0.33	5.93±0.35
	^{99}Mo	γ	6.29±0.42	6.03±0.40	6.30±0.44	6.36±0.44
	^{103}Ru	γ	7.57±0.50	5.61±0.54	6.97±0.47	5.83±0.95
	^{105}Ru	γ	6.03±0.55	5.44±0.43	5.49±0.38	5.53±0.41
	^{109}Pd	RC-β	1.14±0.17	0.94±0.14	1.10±0.17	1.41±0.21
	^{111}Ag	RC-β	0.25±0.04	0.24±0.04	0.28±0.04	0.63±0.09
	^{112}Pd	RC-β	0.14±0.02		0.16±0.02	0.36±0.05
	^{115}Cd	RC-β	0.027±0.004	0.036±0.005	0.050±0.008	
	^{121}Sn	RC-β	0.032±0.005	0.044±0.007	0.048±0.007	0.13±0.02
	^{125}Sn	RC-β	0.039±0.006	0.052±0.008	0.058±0.009	0.17±0.03
	^{127}Sb	RC-β	0.34±0.05	0.37±0.06	0.35±0.05	0.77±0.12
	^{129}Sb	γ, RC-β	1.18±0.24	1.20±0.24	1.27±0.25	1.65±0.33
	^{132}Te	γ	5.52±0.38	5.11±0.35	5.33±0.51	5.37±0.56
	^{133}I	γ	7.64±0.45	7.02±0.41	7.32±0.43	7.09±0.42
	^{134}Te	γ	5.14±0.42	4.14±0.31	4.36±0.37	3.57±0.30
	^{134}I	γ	2.92±1.16	3.31±0.95	2.46±1.32	4.15±0.92
	^{135}I	γ	6.89±0.37	6.29±0.34	6.67±0.38	6.39±0.39
	^{135}Xe	γ	0.85±0.37	0.92±0.34	0.73±0.61	1.58±0.54
	^{140}Ba	γ	5.49±0.33	5.12±0.30	5.37±0.32	5.62±0.34
	^{142}La	γ	4.88±0.41	4.49±0.37	4.92±0.44	5.00±0.40
	^{143}Ce	γ	4.57±0.36	4.40±0.35	4.44±0.34	4.15±0.33
	Summed Prob.		84.4	78.3	83.0	87.0
Concerns	6. These were not precision measurements in general. The main focus of this paper was the yield of symmetric fission as a function of neutron incident energy. 7. This group did similar measurements on ^{235,238}U and ^{232}Th in addition to ^{239}Pu. The FCY of ^{147}Nd was reported for ^{235,238}U and the agreement with those of England & Ride is marginal assuming the yield dependence on neutron incident energy is negligible. No measurement was reported for the FCY of ^{147}Nd for ^{239}Pu. 8. The dependence of FCY, other than the region near symmetric fission, on the incident neutron energy can't be firmly established because of the limited accuracy. The direct comparison is difficult with other measurements using composite beams.					
Uncertainty Check	Various components of uncertainty 8. The uncertainty for the methodology in determination of FCY's was assessed to be about 5%. (systematic error) 9. The uncertainty for the absolute γ-ray efficiency was estimated to be 2 – 5 % depending on the γ-ray energy. 10. No individual uncertainty was addressed for chemical yield, β counting efficiency, and counting loss due to the summing effect.					

Grundl et al., Nucl. Tech. 25 (1975) 237

Fission Product Review Sheet

Reference: J. A. Grundl, D. M. Gilliam, N. D. Dudey and R. J. Popek, "Measurement of absolute fission rates", Nucl. Tech. 25 (1975) 237-257

Location: Coupled Fast Reactivity Measurement Facility, Aerojet Nuclear Co.

Assemblies: Rogers et al., Nucl. Tech. 25 (1975)330

Materials: ^{239}Pu, ^{235}U, ^{238}U, ^{237}Np, and ^{234}U

Detection: Fission chamber and track detectors

Experimental details: Relative cross sections only, no fission-product yields. Three main focus areas, target quantification, track detector calibration, and fission chamber calibration. Since absolute fission basis is dependent on source characterization and detection of number of fissions, these are appropriate subjects. Source quantification and uniformity discussion is straightforward; see error terms, below. Use of small amount of separated ^{234}U to increase activity of mixed U isotopes is clever. Fission chamber is two independent fast ionization chambers, sharing a common ground. Thin actinide deposits face away from each other, in their respective chambers, platinum substrates in contact with the grounded cathode. Chambers are non-conducting and anodes are at edge of chamber to distribute electric field for charge collection. Minimal hydrogen in materials to avoid neutron downscatter. Chambers are not gas tight (flow conditions), so operate at ambient pressure. Fission fragments ionize gas, stop in walls of chamber. Charge-sensitive preamp is ~1 foot from detector – resolution issue. Two low-level discriminators to reject alpha pile up and define extrapolation to zero-pulse-height fissions. Thicker samples on cathode make the magnitude of extrapolation-to-zero larger. Intrinsic charge-collection time is 70 nsec (calculated); most observed dead time is electronic, 2-3 microsec. Dead time losses calculated from count rate and dead time. Absolute efficiency near 100%, but depends mainly on thickness of actinide deposits (see below). Track detectors, thin uniform deposit put in contact with mica; neutron irradiation, fission products damage mica and etching produces tracks that are visible with a microscope. Sources were plated so as to produce 10000 tracks in a 1" circle in an hour. Track shape has to do with entry angle of fragments into detector and/or thickness of source. Diamond-shaped tracks are source of discrepancy between analysts scanning micas. Efficiency of track detectors is found to be very close to unity, with a subjective uncertainty of 3%.

Fission products: none

Number of fissions: Variable, 0.8E10 to 12E10 n/sq cm sec

Amount of fissionable material: 5 – 200 micrograms/cm^2

Thermal fission yields: none

Error terms: Source atoms all related ultimately to mass and mass-spec isotope ratios through quantitative dilution, as are the radiation counter calibrations. Most measurements are multiple. Error is counting statistics and the propagated uncertainties on the various efficiencies, on order of 1%. Claim on mass of isotopes in thin deposit is 1.2 – 2.0% from standard deviations is consistent. For fission chamber measurements, if the count rate is < 5000/sec, the uncertainty on the dead time correction is 10%. The uncertainty on the extrapolation to zero calculation istaken to be 50%. Correction for absorption of fission fragments is 0.7% for a 100 ng/cm^2 deposit, with a 50% error bar. At thermal energies, there is a correction for neutrons absorbed in one chamber not available to the other; it is small. Scattering off the platinum backing requires an upward correction of 0.6% with a 50% error bar. For track detectors, the uncertainty on efficiency (1.025 x 2π) is about 3%, based on multiple determinations of multiple detectors by multiple observers, and taking into account the work in Nucl. Sci. Eng. 34 (1968)13. Claim is fission chamber measurement has 0.5% precision and 1.0% accuracy, and that track detectors have a similar precision but 3% absolute accuracy (see below).

Neutron spectrum: unknown

Results (nf,f)XX:

Nuclide	fission rate track det / fission rate fission chamber (should be 1.000), 1 sigma
^{235}U	1.027(17)
^{238}U	1.031(22)
^{239}Pu	1.018(21)
^{237}Np	1.026(23)

Notes: Technique of quantitative deposition is prone to failure, and the claimed uncertainty of 0.2% is certainly unbelievable except when held up by another form of analysis. Uniformity of deposits, particularly near edges, has always been questionable in these experiments. Preference of methane counting gas over P-10 due to neutron activation is interesting. Construction of the chamber makes assembly and disassembly easy, held by a friction clamp. Authors consider the fission chamber the primary technology and track detectors as backup technology.

Concerns: Fission chamber is much larger than that used in relevant measurements by ILRR and LANL (1" in diameter), so performance of smaller unit installed in a critical assembly is unsupported by this work. Insertion of chemistry foil in common ground of two ionization chambers (as in ILRR and LANL) might impact both conductivity and capacitance in unfavorable ways. Distance of preamp from detector in neutron field = spurious fissions? Origin of extrapolation-to-zero

algorithm is not clear. Corrections for the efficiency of both the fission chamber and the track detectors start out with the bald statement that they ought to be 100%, except for the calculated corrections. This is unsupported - the experimenters should have checked both with a ^{252}Cf source.

The authors assume that the efficiency of the track detectors and the fission chamber is about 100%, except for easily calculable correction factors. The efficiencies were not measured. The preference of the fission chamber to the fission track detector is not well supported. It would be difficult to evaluate either the efficiency of the counter or the uncertainty on that uncertainty.

Reference:	Katcoff S., "Fission-product yields from U, Th, and Pu'', Nucleonics (U.S.) Ceased publication; Journal Volume: Vol: 16, No. 24, 1958
Location:	Not applicable
Assemblies:	Not applicable
Materials:	
Detection:	
Target Isotopics	Not applicable
Experimental Details:	This is a compilation of published data
Fission products:	90Sr, 97Zr, 99Mo, 109Pd, 112Pd, 115Cd, 137Cs, 140Ba, 153Sm
Number of fissions:	Not applicable
Amount of fissionable material;	Not applicable
Thermal fission yield:	There is thermal data here but again this is a compilation but not an evaluation
Error terms:	No uncertainties are listed with this data
Neutron spectra:	
Results ^{239}Pu(n,f)XX Cumulative:	No used or listed
Notes	• Do not use this data. If we need to use this data we should use the references and we are assessing these references (e.g. Ford)

Concerns	• This data has a lot of approximately and no uncertainties listed
	• The data was compiled from several references.
	• The 239Pu data references:
	  • **Thermal:** H.R. Fiskel, R.H. Tomlinson, Can, J. Phys 37, 910-926 (1959) and K.Frize et al., in "proceedings of second International Conference on the peaceful uses of atomic Energy", Vol. 15 p 436, and M.P. Anikinia et al., and others
	  • **Fission spectrum:** G.P. Ford and C.W Stanley, AECD-3551 (1953) and some books

Reference:	Katcoff S., "Fission-product yields from neutron-induced fission '', Nucleonics (U.S.) Ceased publication; Journal Volume: Vol: 18, No. 11, 1960
Location:	Not applicable
Assemblies:	Not applicable
Materials:	
Detection:	
Target Isotopics	Not applicable
Experimental Details:	This is a revision of an earlier publication [Katcoff, Nucleonics 16 No. 4, 78 (1958)]
Fission products:	90Sr, 97Zr, 99Mo, 109Pd, 112Pd, 115Cd, 137Cs, 153Sm
Number of fissions:	Not applicable
Amount of fissionable material;	Not applicable
Thermal fission yield:	There is thermal data here but again this is a compilation but not an evaluation
Error terms:	No uncertainties are listed with this data
Neutron spectra:	
Results ^{239}Pu(n,f)XX Cumulative:	No used or listed
Notes	• Do not use this data. If we need to use this data we should use the references and we are assessing these references (e.g. Ford)

Concerns	• This data has a lot of approximately and no uncertainties listed
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	  • **Fission spectrum:** G.P. Ford and C.W Stanley, AECD-3551 (1953) and some books

Reference:	L. Koch, "Status Report of Fast Reactor Yields in the TACO Experiment", IAEA Second Advisory Group Meeting on Fission Product Nuclear Data, Petten, Netherlands (September 1977) L. Koch et al., "Cumulative Fast Reactor Fission Yields on ^{233}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am", Euro. App. Res. Rep. – Nuc. Sci. Tech., Vol 3, (1981) pp 1-22. L. Koch, Radiochim. Acta. Vol 29. (1981) pp 61-63.
Measurement	Absolute chain yields for many heavy mass fragments for ^{233}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am irradiated with fission spectrum neutrons
Location:	RAPSODIE fast reactor
Assemblies:	No Details given
Materials:	milligram amounts of ^{233}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am
Detection:	Fragment: Isotope dilution analysis for Xe and mass-spectrometry isotope dilution technique for Cs, Nd, Sm, Eu, and Gd. The measurement of Ba and Ce isotopes failed due to contamination of naturally occurring isotopes. Additionally, ^{125}Sb, ^{137}Cs, and ^{144}Ce were measured via gamma-spectroscopy of the dissolved sample. Fissions: Determined via equating total heavy mass peak to 100% of all fissions
Irradiation Detail	Target actinides were separated, deposited on pure Al foil, dried, rolled up and placed into separate stainless steel capsules having the same diameter as standard fuel pellets, but three times the height. All actinide samples were irradiated at up to a estimated total neutron fluence of 10^{23} n/cm^2 during 1970/71. No other details given.
Fission Products	^{131,132,134,136}Xe, ^{133,135}Cs, $^{143-146,148,150}$Nd, ^{149,151,152,154}Sm, ^{153}Eu were measured via mass spec. There is some question whether A=147 was measured directly or interpolated. See issues section below. Also ^{125}Sb, ^{137}Cs, and ^{144}Ce were measured via gamma spec. No details given about gamma spec measurements. Note, even though text states Gd was measured, no chain reported that would require Gd measurement.
Number of Fissions	Because of failure of Ba and Ce mass spec measurements only 65.5% of heavy mass fragment distribution measured directly for ^{239}Pu. For similar measurement by Maeck the percentage was 88%. The rest is interpolated by using thermal yields and/or recommended value of fission spectra yields. They estimate only a 0.7% error whether recommended fission spectra numbers are used or thermal numbers, but it is unclear whether this based solely on the ^{235}U case or is also true for ^{239}Pu.
Amount of Fissionable	No info other than milligram quantities

material						
Chemical Separations	For Xe gas released from target but contained in steel capsule, the capsule was opened under vacuum with a laser beam. The freed gas was mixed with a spike of natural Xe by cryopumping and analyzed by mass spectrometry. A similar procedure was used by for Xe gas liberated during the dissolving of the sample. The rest of the separations is only documented by Figure 1 of the reference which is included below.					
Error Terms	For ^{239}Pu, three separate "foils" were irradiated and each isotope was measured with three different assays from each foil, except for Xe for which only 1 assay was done. Standard deviations of the various measurements are reported but there is no other discussion or reporting of statistical or systematic errors in the analysis.					
Neutron Spectra	No detail given on spectra though ^{143}Nd/^{150}Nd ratio can be contrasted from the measurements reported and can be used as a measurement of average neutron energy. This value is consisted with other fast reactors measurement.					
Reported FCY ^{239}Pu fission spectra * Not Measured # Not reported in final report (1981) ** See Concerns	Mass	Yield w/ std	Mass	Yield w/ std	Mass	Yield w/ std
	125	0.097±6.9%	135	7.597±0.84%	145	2.970±1.01%
	126*	0.200±0.0%	136	7.057±0.66%	146	2.443±0.76%
	127*	0.477±1.85%	137	6.427±0.59%	147**	2.033±0.44%
	128*	0.817±1.08%	138*	5.557±1.04%	148	1.637±0.74%
	129*	1.507±2.31%	139*	5.473±1.26%	149	1.250±0.46%
	130*	2.523±2.13%	140*	5.317±1.31%	150	0.973±0.91%
	131	4.207±2.11%	141*	5.020±1.59%	151	0.799±1.59%
	132	5.730±1.52%	142*	4.683±2.14%	152	0.657±2.54%
	133	7.273±1.63%	143	4.273±0.83%	153#	0.47±6.4%
	134	7.830±2.01%	144	3.583±0.34%	154#	0.31±14%
Notes	In final report of 1981, results also compared to Maeck measurement. Agreement within ~2% is seen for measured masses 135-151, with the exception of 144 with a disagreement of 3.5%. The yield for this mass is based at least in part on a gamma spec measurement of ^{144}Ce for Koch, but from mass spec only for Maeck. The disagreement for mass 131-134 ranges from 3.6% to 8.6% with the Koch values always larger than the Maeck measurement.					

Concerns – Mass 147	There is conflicting indications in the references as to whether the yield for mass 147 was actually measured or interpolated. The text of the progress report of 1977 states that the yield for mass 147 was measured, but the table that lists the values lists with the same notation as for masses that were not measured. In the final report, there is not specific indication in the text or the data tables as to whether 147 was measured or not, the data tables also defines a Z for each mass yield. It is unclear how to interpret this value, but the Z assignment for masses that were clearly measured are for elements that were stated to be measured. While for masses that clearly were not measured, the Z assignment are for elements that were stated not to be measured. The Z assignment for mass 147 is for Pm, an element that was not stated to be measured.					
Concerns – Mass 137	There may be a 3% error in the mass 137 yield determination because Koch was unable to measure the Ba isotopes. Maeck determined the mass 137 yield by summing both ^{137}Cs and ^{137}Ba and by correcting for the half life of ^{137}Cs to account for decay of ^{137}Cs. Maeck stated agreement between the two method and used the sum of the two isotopes in his determination of the mass 137 yield. Koch was only measured ^{137}Cs, but he does compare his number to Maeck using reference ICP-1050-II. While all the Maeck number listed in Koch agree with ICP-1050-II, the mass 137 value does not. The number Koch lists as Maeck's value is 3% low compared to the value in ICP-1050-II but is in excellent agreement with Koch measurement. So is the number Koch compares to for mass 137 just Maeck's number without adding in the ^{137}Ba contribution. It should be noted that the mass 144 numbers, which also relies on gamma spec is also 3.6% low compared to Maeck.					
Concerns -- Uncertainties	There is a real question as to what uncertainty should be assigned to Koch's numbers. Following Maeck's analysis of the uncertainty on the number of fissions, and assigning an 8% error to the regions not measured by Koch, (Maeck assigned an 8% error for his unmeasured region of A=126-130), results in uncertainty on the number of fission of 1.26%. For Maeck, his total chain yield uncertainty was typically about 1.5% percent and his fission uncertainty was determined to be 0.8%, which implies 1.25% of his error due to other factors. Translating this to the Koch measurement implies a typical yield total uncertainty of 1.8%. But there is also a possible 0.2% in the fission determination because of not measuring ^{137}Ba. So it would appear a 2% uncertainty is the absolute lowest uncertainty to be applied. However, the disagreement between Koch and Maeck are much greater for the masses 131-134. Also, this cannot be applied to mass 144 since Koch measured ^{144}Ce via gamma spec and Maeck used mass spec. And for mass 147, there is still the issue as to whether this is a measured quantity. Recommendation: Unless further info can be uncovered, I would suggest assigning a 3% error for the isotopes measured by mass spec, a 5% error for the isotopes measured by gamma spec, and a 10% error for the isotopes that were interpolated, for which I would include ^{147}Nd. If the standard deviation is larger, than these numbers, I would use that value.					
Recommened FCY	Mass	Yield w/ std	Mass	Yield w/ std	Mass	Yield w/ std
	125	0.097±6.9%	135	7.597±3.0%	145	2.970±3.0%

^{239}Pu fission spectra	126	0.200±10.0%	136	7.057±3.0%	146	2.443±3.0%
	127	0.477±10.0%	137	6.427±5.0%	147	2.033±10.0%
	128	0.817±10.0%	138	5.557±10.0%	148	1.637±3.0%
	129	1.507±10.0%	139	5.473±10.0%	149	1.250±3.0%
	130	2.523±10.0%	140	5.317±10.0%	150	0.973±3.0%
	131	4.207±3.0%	141	5.020±10.0%	151	0.799±3.0%
	132	5.730±3.0%	142	4.683±10.0%	152	0.657±3.0%
	133	7.273±3.0%	143	4.273±3.0%	153	0.47±6.4%
	134	7.830±3.0%	144	3.583±5.0%	154	0.31±14%

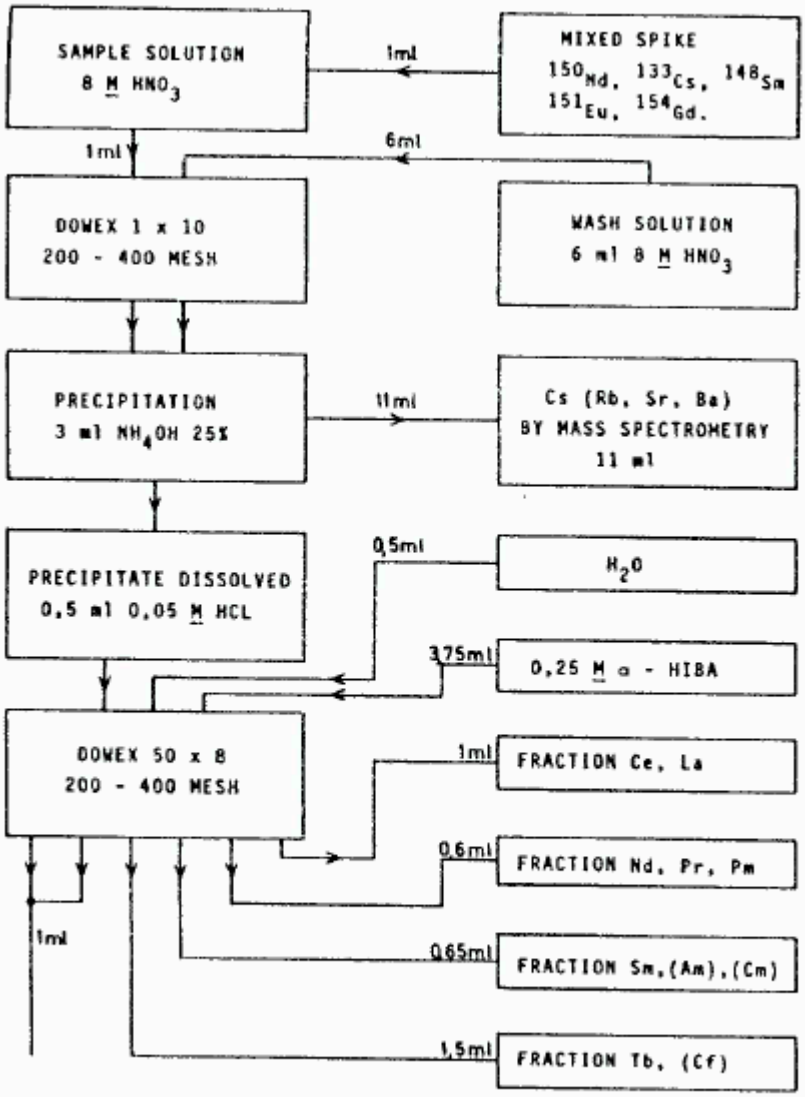

Fig. 1: Separation scheme for sample conditioning.

Laidler and Brown, J. Inorg. Nucl. Chem. 24 (1962) 1485

Fission Product Review Sheet

Reference: J. B. Laidler and F. Brown, "Mass distribution in the spontaneous fission of ^{240}Pu", J. Inorg. Nucl. Chem. 24 (1962) 1485-1492

Location: Aldermaston

Assemblies: none

Materials: Obtained from US AEC, 6.71 w% ^{239}Pu, 91.70 w% ^{240}Pu, 1.51 w% ^{241}Pu, 0.07 w% ^{242}Pu, amount determined during repeated purification from Am, followed by quantitative dilution and alpha counting.

Detection: beta counting with van Duuren shielded end-window counter, bkg 1.5 $\pm$ 0.5 cpm, calibration method in Nucleonics 17 (1959) 82.

Experimental details: Based on absolute SF rate and ingrown fission product concentrations. Carrier added, equilibrated, separated and discarded at a well-defined time – defines zero time for ingrowth. Ingrowth times from 1 day to several weeks. Carrier added, equilibrated, separated for counting. Attempted to approach saturation for each nuclide. Attempted chemical decon factors 1E11, which is probably adequate. Samples prepared by filtration. Radiochemical purity determined by following decay over several half lives.

Fission products: 15 isotopes A=89-147

Number of fissions: Unknown

Amount of fissionable material: Unknown, but described as "adequate"

Thermal fission yields: none

Error terms: Duplicate determinations, median values reported calculated by method of Dean and Dixon, Anal. Chem. 23 (1951) 636.

Neutron spectrum: Pure fission spectrum. Correction negligible for SF neutrons and (alpha,n) neutrons inducing fissions in ^{239}Pu and ^{241}Pu. Downscatter calc performed, correction for induced fissions < 0.2%

Results ^{240}Pu(nf,f)XX: as given in paper, uncert is 1 sigma on last digits

Nuclide	FCY, $^{239}Pu_{SF}$, in %
^{97}Zr	6.46(21)
^{99}Mo	6.82(7)
^{140}Ba	5.99(22)

^{141}Ce	6.02(39)
^{147}Nd	1.22(37)

Notes: SF half life determined to be 1.340(15)E11 years. Prompt neutrons assigned to be 2.2/fission (Phys. Rev. 100 (1955) 190). Data self consistent with mass reflection around A=118.9. These data have been reproduced, but the duplicate data have not been published, largely because they are the same within errors.

Concerns: Chemical separations are fine, but primitive – I worry about ^{241}Pu in beta counters (did they use absorbers?)

Reference:	Laurec, J., "Determination des rendements de fissions induites par un spectre de neutrons de fission dans le 239Pu et l' 235U pour les chaines 95, 144 et 147", CEA report, CEA/DE/RCP/DO -00058, Jan.1981
Location:	Prospero reactor
Assemblies:	Prospero reactor
Materials:	18 and 27 mg of PuO2
Detection:	Fissions were determined from measuring 99Mo, 103Ru, 132Te, 140Ba, 141Ce, and 143Ce and using their known Fission-chain-yields to get an average number of fissions. Gamma spec LEPS GeLi was used on one target and chemical separation and gamma spec (LEPS GeLi) was used on the second target.
Target Isotopics	238Pu: not listed, 239Pu: 97.3, 240Pu: 2.7, 241Pu: 0.06, 242Pu: not listed
Experimental Details:	• Two thick PuO2 targets were irradiated • One empty target was also irradiated simultaneously to the other two for background subtraction • Targets were sealed in Al holder • LEPS Ge(Li) detectors were used for fission product identification • Nuclear data used is given and has t1/2 and branching ratios • One target was counted over a period of several months. The 144Ce started to appear after 1 month • The targets were counted before and after irradiation to subtract the Pu background • The empty target activations were observed • Second target was gamma counted then dissolved and the 144Ce was chemically separated and then gamma counted again • Irradiations were 10^5 sec repeated 5 times • 1 mm thick Cd sheet was wrapped around thick target
Fission products:	• 99Mo, 103Ru, 132Te, 140Ba, 141Ce, and 143Ce for determining number of fissions • 95Zr, 144Ce, and 147Nd fission chain yields were calculated
Number of fissions:	~10^{15} neut/cm2 over the full irradiation on both targets
Amount of fissionable material;	• 18 to 27 mg for the thick foil of PuO2
Thermal fission yield:	• No thermal irradiation

Error terms:	• All uncertainties are 1 sigma
	• The uncertainty in the number of fissions is spelled out.
	  • It is the standard deviation from six fission products
	  • It is inappropriate to take the standard deviation of the mean since the fission chain yields are likely to have come from

	their own previous experiments so that the # of fissions is correlated to all of the fission chain yields used. • The uncertainties in each of the measurements are ~5% • It is explicitely stated that the uncertainties in nuclear data were not incorporated into these analyses
Neutron spectra:	• Critical assembly • Fission spectrum: how is it affected by the Cd sheet. • The Cd changes the low energy part of the fission spectrum. Form a description in the previous paper but not referenced here
Results ^{239}Pu(n,f)XX Cumulative:	See "FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne
Notes	• I recommend that the uncertainty should be at 6% for 95Zr, 144Ce, and 147Nd. The uncertainty listed in the final results is an average of the two samples that is less then the individual uncertainties. Although this would be correct both samples share the same methodology of determining the number of fissions that has a 4% uncertainty. It would be hard to argue that the overall uncertainty can be better then the determination of number of fissions.
Concerns	• No discussion of GeLi calibration. However, the GeLi detectors were calibrated using a round robin method with standard Amersham sources in the previous Laurec paper but it was not referenced here. • No discussion of calibration of counting geometry. However, the counting geometry was calibrated and fixed in the previous Laurec paper but it was not referenced here. • No discussion of chemical procedure for dissolution of target #2 or references • No discussion of Bateman correction for irradiation specifics. However, Bateman equations were developed for the changes during irradiation times in the previous Laurec paper but it was not referenced here. • They updated their half lives and branching ratios but not to modern values from 12.3 to 12.8 not 13.1. We will have to update these as well • They updated their 95Zr half live and changed their FCY for 95Zr • Some small changes in t1/2 and branching ratios are needed for the other isotopes. • No gamma fiting discussion. However, the background subtraction for the gamma peaks is a trapezoid in their previous paper but it was not referenced here. • MCNP calculations for the previous paper shown negligible effect from the Al and Cd around the target

	• No uncertainties are discussed from the gamma counting are shown. However, this was discussed in their previous paper but it was not referenced here. • In the previous paper the uncertainty in the GeLi detector efficiency was from 1.5 to 2% depending on the energy range. No discussion of these uncertainties is mentioned, nor is it incorporated into the overall uncertainty.

Reference:	Laurec, J., "Determination des rendements de fissions de 235U et 239Pu par une methode radiochimique", CEA report, DAM/DE/RDE/# 0686 DO 019, 1976
Location:	Saclay for thermal, Prospero and Caliban critical assemblies for fission spectrum
Assemblies:	Saclay for thermal, Prospero and Caliban critical assemblies for fission spectrum, there was a 14 MeV irradiation but I did not read through it.
Materials:	PuO2
Detection:	Fission chamber, chemistries and gamma spec GeLi
Target Isotopics	238Pu: not listed, 239Pu: 98.28, 240Pu: 1.68, 241Pu: .036, 242Pu: Not listed
Experimental Details:	• GeLi detectors were calibrated with standard Amersham sources • Nuclear data used is given and has t1/2 and branching ratios • Batman equations were developed for the changes during irradiation times • There is a description and a reference to their fission chamber • Target description between thin and thick foils • The thick foil is outside of the fission chamber with monitor foils to calibrate between the thin and thick foil location • 0.8 mm thick Cd sheet was wrapped around thick target and around the fission chamber • The thin target was on a Ti backing, the thick target was sandwiched in Al then Cd and then poly. • Multiple parametric studies on targets, fission chambers target location, neutron flux, counting time, and neutron generators • Studies on appropriate Cd thickness • Fission chamber detection efficiency studies.
Fission products:	95Zr, 97Zr, 99Mo, 103Ru, 105Rh, 131I, 132Te, 133I, 140Ba, 141Ce, 143Ce, 147Nd
Number of fissions:	10^4 fiss/sec, 20 hour irradiation, for 10^{10} to 10^{11} fissions on the thick target
Amount of fissionable material;	• Using mass spec and alpha spec for thin and thick foils • 0.4 to 4 mg/cm2 for the thick foil of PuO2 • 2.2 μg/cm2 for the thin foil of PuO2
Thermal fission yield:	• 239Pu thermal irradiation measured the following fission products: 95Zr, 97Zr, 99Mo, 103Ru, 131I, 132Te, 140Ba, 141Ce, 143Ce, 147Nd • The Q99 value is 0.968
Error terms:	• Every section has an error discussion and all uncertainties are 1 sigma • Errors for the ratio method for mass determination is discussed • Corrections for the fission chamber dead time (~2%) • Corrections for the fission chamber threshold (~1%)

	• Determination for fission fragment detection efficiency in the thin foil • Uncertainties associated with the different locations of the thin and thick foils • The uncertainty in the thick to thin mass has the largest uncertainty from 1.5 to 3.5% • Uncertainty in the GeLi detector efficiency was from 1.5 to 2% depending on the energy range • Discussions about gamma fitting and associated uncertainties

Neutron spectra:	• This was done at a critical assembly (no alpha values given)
	• There were studies with Cd thickness to find the optimum thickness to knock down the thermal component.
	• Fission spectrum: how is it affected by the Cd sheet.
	  • The Cd changes the low energy part of the fission spectrum. This is described in the paper.
	  • MCNP simulations were done to determine the effect on the fission spectrum

Results ^{239}Pu(n,f)XX Cumulative:	See "FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne
Notes	• There is more data in the 1981 paper
Concerns	• The branching ratio for 147Nd needs to be changed from 12.8 to 13.1 • Some small changes in t1/2 and branching ratios are needed for the other isotopes • The background subtraction for the gamma peaks is a trapezoid. It probably should be more like gammanal does it. • Is there a bias due to the poly around the thick source but not around the thin source • I did MCNP simulations and a 1 mm thick poly around the thick source has very little effect probably due to the 0.8 mm thick Cd sheet wrapped around the thick target and the same Cd sheet wrapped around the fission chamber • 240Pu content will have a background of all fission products at equilibrium and it maybe relevant due to the fact that only 10^{11} fissions were produced. However, the 240Pu content is only 1.6%. We will need to determine the magnitude of this effect. It will make the FCY to high. • No description nor reference for the chemistries used. • No description of geometry corrections for the gamma counting • I do not know if the results from the 1981 paper are new results or they are just the same as these results. When I ratio the results between the two publications the ratio is 1.000 for most including for the uncertainties. It would be surprising if these were independent results.

Reference:	Laurec, J., Adam, A., De Bruyne, T, "Determination des rendements de fissions induites par un spectre de neutrons de fission et des neutrons de 14.7 MeV dans 233U, 235U, 238U, 239Pu", CEA report, CEA-R-5147, 1981
Location:	Prospero reactor
Assemblies:	Prospero reactor
Materials:	PuO2
Detection:	Fission chamber, chemistries and gamma spec GeLi
Target Isotopics	238Pu: 0.0, 239Pu: 98.283, 240Pu: 1.681, 241Pu: .0363, 242Pu: 0.0
Experimental Details:	• GeLi detectors were calibrated using a round robin method with standard Amersham sources • Counting geometry was calibrated and fixed • Nuclear data used is given and has t1/2 and branching ratios • Batman equations were developed for the changes during irradiation times • There is a description and a reference to their fission chamber • Target description between thin and thick foils • The thick foil is outside of the fission chamber with monitor foils to calibrate between the thin and thick foil location • 0.8 mm thick Cd sheet was wrapped around thick target and around the fission chamber • the thin target was on a Ti backing, the thick target was sandwiched in Al then Cd and then poly.
Fission products:	95Zr, 97Zr, 99Mo-99Tc, 103Ru, 105Rh, 106Ru, 131I, 132Te, 133I, 136Cs, 140Ba, 141Ce, 143Ce, 144Ce, 147Nd
Number of fissions:	10^4 fiss/sec, 20 hour irradiation, for 10^{10} to 10^{11} fissions on the thick target
Amount of fissionable material;	• Using mass spec and alpha spec for thin and thick foils • ~1 mg/cm2 for the thick foil of PuO2 • 5.49 ± 0.03 μg/cm2 for the thin foil of PuO2
Thermal fission yield:	• 239Pu thermal irradiation measured the following fission products: 95Zr, 97Zr, 99Mo-99Tc, 103Ru, 105Rh, 131I, 132Te, 140Ba, 141Ce, 143Ce, 147Nd • The Q99 value is 0.967
Error terms:	• Every section has an error discussion and all uncertainties are 1 sigma • Errors for the ratio method for mass determination is discussed • Corrections for the fission chamber dead time (~4%) • Corrections for the fission chamber threshold (~1%) • Determination for fission fragment detection efficiency in the thin foil • Uncertainties associated with the different locations of the thin and thick foils

	• The uncertainty in the thick to thin mass has the largest uncertainty from 1.8 to 2.5% • Uncertainty in the GeLi detector efficiency was from 1.5 to 2% depending on the energy range • Discussions about gamma fitting and associated uncertainties • The systematic and statistical uncertainties were seperated
Neutron spectra:	• Fission spectrum: how is it affected by the Cd sheet. • The Cd changes the low energy part of the fission spectrum. This is described in the paper
Results ^{239}Pu(n,f)XX Cumulative:	See "FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne
Notes	•
Concerns	• The branching ratio for 147Nd needs to be changed from 12.3 to 13.1 • Some small changes in t1/2 and branching ratios are needed for the other isotopes • The background subtraction for the gamma peaks is a trapezoid. It probably should be more like gammanal does it. • Is there a bias due to the poly around the thick source but not around the thin source • I did MCNP simulations and a 1 mm thick poly around the thick source has very little effect probably due to the 0.8 mm thick Cd shee wrapped around the thick target and the same Cd sheet wrapped around the fission chamber • The statistical errors were added in quadrature and the systematic errors were added linearly. They should all be in quadrature if the comparison of the data is to external experiments. • In comparing the data internally they should only use the statistical components.

Lisman(1) et al., Nucl. Sci. & Eng. 42 (1970)191-214

Fission Product Review Sheet

Reference: F. L. Lisman, R. M. Abernathey, W. J. Maeck and J. E. Rein, "Fission yields of over 40 stable and long-lived fission products for thermal neutron fissioned ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu and fast reactor fissioned ^{235}U and ^{239}Pu", Nucl. Sci. & Eng. 42 (1970), 191-214

Location: Argonne's NaK-cooled EBR-1 (fast neutrons); MTR (thermal neutrons); both at the national reactor testing station

Assemblies: For thermal neutrons, light-water reactor, enriched U fuel; for fast neutrons, clad fuel containing plutonium

Materials: Thermal targets were high-purity oxides in Al cladding, mixed and pressed with 10% Al powder, 99.2% ^{239}Pu, 95.5% ^{241}Pu, 99.9% ^{233}U, 99.2% ^{235}U. Fast ^{235}U targets were 2% Zr, alloy clad in zircalloy; fast ^{239}Pu targets were 10% Al alloy clad in zircalloy.

Detection: Isotope dilution, chem. Sep and mass spec. There were a few gamma spec measurements that aren't described very well.

Experimental details: Thermal irradiation two ways for ^{233}U and ^{235}U, a mass balance experiment with destruction of uranium, and summing of fission fragments to 200% of fissions. Nuclides comprising 80% of the yield in the high hump were measured with an experimental uncertainty of ~1% on the ratio to A=148, unmeasured mass chains were estimated under guidance from previous literature values and given 20% error bars arbitrarily. Only the sum method was used for thermal ^{239}Pu and ^{241}Pu because of uncertainties on the amounts loaded in the targets. Corrections for neutron burn-in/burn-out made on all thermal measurements, based on previous cross section measurements; considered unimportant for fission spectrum irradiations. Samples cooled 0.5 to 3 years before dissolution. Agreement between methods for ^{233}U and ^{235}U, good to <2% so only sum to 200% method applied to fission-spectrum ^{239}Pu and ^{235}U systems. Long intermittent irradiations, 1 year for ^{239}Pu with a cooling time of 4 years and 5 years for ^{235}U with 4 years cooling. Yields ratioed to ^{148}Nd. Stable and radioactive species measured. Corrections for losses by radioactive decay during irradiation and cooling. For ^{239}Pu fast fission, 81% of high hump yield measured, with interpolation again comes to 2% uncertainty on absolute yields.

Fission products: 45 mass chains measured in fast irradiations, 43 chains measured in thermal irradiations, stable and long-lived fission products; value for A=147 extrapolated (20% error bar) and A=99 not measured.

Number of fissions: Fraction burn up is 0.07% fission of plutonium in fast neutron irradiation, 9.5E13 n/sq cm sec, 5.8E5 kWh integrated exposure; and 0.22% fission of uranium in fast neutron irradiation, 1.1e14 n/sq cm sec, 3.2E6 kWh integrated exposure. Thermal irradiation varied by capsule, from 8 to 36%.

Amount of fissionable material: Varied by capsule, thermal capsule 50-150 mg. "Fuel pins" for fast irradiations

Thermal fission yields: see below

Error terms: From the measurements, uncertainties associated with the fission yield values are ±2% based on relative standard of replicate measurements of $^{235}U_{th}$. Isotope ratios <1%, interpolated yields are probably at least as good as 20% based on interpolation of 81% to 100%, propagation to 2% on absolute yields is reasonable.

Neutron spectrum: 0.5 MeV medium neutron energy, EBR-1 spectrum not discussed, and amount of low-energy return not discussed; thermal irradiation is defined as resulting in a cadmium ratio for cobalt = 15.

Results $^{239}Pu(nf,f)XX$: FCY, uncert given in parens are 1 sigma on last digits

Mass chain	$^{235}U_{th}$ (mass bal)	$^{235}U_{th}$ (100% sum)	$^{239}Pu_{th}$ (100% sum)	$^{239}Pu_{fs}$ (100% Σ)
95	6.45(3)	6.51(12)	4.86(11)	4.78(9)
97	5.86(3)	5.92(11)	5.64(16)	5.47(10)
99	6.14(10)	6.24(12)	---	---
125	0.0291(33)[G]	---	0.116(14)	0.194(23)[G]
137	6.28(3)	6.32(11)	6.74(14)	6.58(11)[G]
140	6.31(3)	6.35(11)	5.61(12)	5.59(10)
141	5.50(34)[G]	5.53(35)[G]	---	5.28(106)[G]
144	5.42(2)	5.45(10)	3.78(8)	3.68(7)
147	2.12(4)	2.14(5)	2.15(8)	2.18(44)[E]

[G] gamma spec measurement
[E] extrapolated value (20% uncert)

Notes: The chemical separations performed seem reasonable, though there is not enough detail given to be certain. Results were compared with Davies, Radiochemica Acta 12 (4) (1969) 173. Overlap between mass balance and sum to 100% measurements for $^{235}U_{th}$ (given above) are adequate

Concerns: Transmutation during irradiation, no detail given beyond simple model, probably OK
Corrections for burn in / burn out from other work, based on simple cross section model normalized from $^{235}U_{th}$ results of this work to that of Farrar et al., Nucl. Phys. 34 (1962) 1367 and Can. J. Phys. 40 (1962)1017; authors claim most corrections are small, and that error propagation was performed properly even though the correction process is iterative. No burnup corrections were made for fission-spectrum irradiations – this is OK, based on Suyama and Mochizuki, Nucl. Sci. Tech. 42 (2005) 661.

There is the assumption made that wt loss of the uranium targets = fissions of ^{235}U in the mass balance experiments. Correction for yields beyond end member are not made, but are ≤0.3% in all cases. No irradiation history in fast-neutron irradiations. Gamma spec is not described, though ratio help with error control.

Lisman(2) et al., Nucl. Sci. & Eng. 42 (1970) 215-219.

Fission Product Review Sheet

Reference: F. L. Lisman, W. J. Maeck and J. E. Rein, "Determination of nuclear fuel burnup from fission product analysis" , Nucl. Sci. & Eng. 42, (1970) 215-219 (continuation of Lisman(1))

Location: Argonne's NaK-cooled EBR-1 (fast neutrons); MTR (thermal neutrons); both at the national reactor testing station

Assemblies: For thermal neutrons, light-water reactor, enriched uranium fuel; for fast neutrons, clad fuel containing plutonium

Materials: Thermal targets were high-purity oxides in Al cladding, mixed and pressed with 10% Al powder, 99.2% ^{239}Pu, 95.5% ^{241}Pu, 99.9% ^{233}U, 99.2% ^{235}U. Fast ^{235}U targets were 2% Zr, alloy clad in zircalloy; fast ^{239}Pu targets were 10% Al alloy clad in zircalloy.

Detection: Isotope dilution, chem. Sep and mass spec. There were a few gamma spec measurements that aren't described very well.

Experimental details: Data were taken from Lisman(1)

Fission products: 45 mass chains, stable and long-lived

Number of fissions: Given in Lisman(1), 0.07% fission of plutonium in fast neutron irradiation, 9.5E13 n/sq cm sec, 450^{0}C fuel temp, 5.8E5 kWh integrated exposure.

Amount of fissionable material: not given explicitly

Thermal fission yields: see below

Error terms: See discussion, Lisman(1)

Neutron spectrum: 0.5 MeV medium neutron energy, EBR-1 spectrum not discussed, and amount of low-energy return not discussed; thermal irradiation is defined as resulting in a cadmium ratio for cobalt = 15.

Results ^{239}Pu(nf,f)XX: See Lisman(1)

Notes: Authors present fast fission vs. thermal fission yields for 235U and 239Pu. The 235U and 239Pu distributions look similar, as they should. Biggest discrepancies from unity are for valley and wing nuclides. Data do not seem to support Cuninghame. In peak yields, most 1-sigma error bars overlap 1.0 yield ratio. Important for future experimental work: a small admixture of room return

neutrons in the experiments will not impact the measurement of our fission yield indicators.

Concerns: Some corrections to the thermal data for burn-in and burn-out are hard to quantify; see Lisman(1).

Reference:	W.J. Maeck, "Fast reactor fission yields for 239Pu and 241Pu", Allied chemical corporation, Idaho-Chemical Program. ICP-1050-II, 1977
Location:	EBR-II, INEL
Assemblies:	Fast breeder reactor, target were near center of the core
Materials:	U-233, U-235, U-238, Pu-239 The 239Pu target was: PuO_2
Target Isotopics	238Pu: 0.0, 239Pu: 99.10, 240Pu: 0.888, 241Pu: 0.014, 242Pu: 0.0
Detection:	Isotope mass dilution spectroscopy, counted 87.7% of the heavy mass chain and extrapolated or interpolated the rest of the heavy mass chain
Experimental Details:	• The Pu Oxide was mixed with Ni powder and sealed in Ni capsule • Irradiation was ~2 months, estimated flux was ~$8x10^{14}$ • Sample cooled for ~2 months • 4 samples were analyzed over a period of at least 1 year • The mass spec was calibrated and tested for impurities • Highly purified reagents • Noble gas traps were used and checked
Fission products:	Very large number of stable elements were measured and are listed in FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne.
Number of fissions:	~10^{19} fissions, constant irradiation. The absolute number of atoms from the 87.8% of the heavy mass chain were determined and the rest were interpolated or extrapolated to obtain the absolute number of fissions.
Amount of fissionable material;	~ 700 mg of PuO_2, the chemical procedures are spelled out for each of the mass chains that were measured.
Thermal fission yield:	Paper was published in 1981 from a thermal irradiation
Error terms:	• Statistical uncertainties from averaging of all the samples • Uncertainties from Extrapolation • Uncertainties from interpolations • Uncertainties were propagated for the number of fissions to 0.76% • I recommend increasing the uncertainty from 0.76% to 0.83% because the extrapolated mass should have uncertainties of 75% rather then 25% given the assumptions that were used
Neutron spectra:	• Average energy of ~400KeV • Neutron spectrum was determined using monitor capsules and calibrated GeLi detectors and a fitting code called SPECTRA [Ref: SC-RR-70-251, 1970]. • Maeck makes the comment that based on the 135CS abundance there is no evidence of significant thermal neutron component in the axial blanket position

	• The neutron spectra was checked against a fission spectrum and it is slightly softer (e.g. Big 10)
Results ^{239}Pu(n,f)XX Cumulative:	See "FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne
Notes	Maeck makes the comment that based on the 135CS abundance there is no evidence of significant
Concerns	1) What is the spectrum of EBR-II 2) Burnup of fission products during the irradiation 3) What is the effect between weapons grade and pure 239Pu 4) The 147Sm was corrected for long lived precursors but the equations are not shown
Resolved	1) Contacted D. MacKnight at Argon and he sent me a spectrum of EBR-II from the location of the irradiation. This spectrum is slightly softer but not by much. A comparison of the spectrum exist on my classified side 2) In a thermal irradiation, Maeck saw the 148Sm which is the destruction term of the 147Pm. He then added this amount back into the 147 mass chain. He would have seen this in the fission spectrum irradiation and would have also added it back in had he observed it. - I still have the concern that the 147Nd has a 10.98 day half life and could absorb a neutron and go to 148Nd which is stable and would not be observed as a destruction of the 147 mass chain. 3) Using Engl&Rider FCY I calculated a 0.5% effect on the number of fissions between the two types of Pu 4) Maeck was very careful and he makes the statement that the 147Sm was corrected for the 147Pm 2.623 y half life Background - Maek, et. al. measured the ^{147}Nd chain yield by quantifying the quasi-stable ^{147}Sm isotope by IDMS. Maek measured the ^{147}Sm concentration after a 58.833 day irradiation. The ^{147}Sm concentration was quantified at 83.333 and at about 1 year after irradiation, exact time not reported. The ^{147}Nd chain yield was calculated by a correction factor developed from the Bateman Equations describing radioactive decay to the end chain member ^{147}Sm. The measured ^{147}Sm concentration was not reported and approximations in the Bateman Equations were not described. The following corrections could have been performed: 4.1 Maek could have calculated the ^{147}Nd, ^{147}Pm, ^{147}Sm at the end of irradiation and appropriately calculated the decay and buildup of nuclides during radiation and in the subsequent decay period. The calculated ^{147}Sm / mass 147 chain yield at

	83.33 days is 6.75% in this case; and 23.96% at 1 year. This is the correct treatment. We note that in an EXCEL solution to the Bateman Equations at ~14 significant figures, there is a modest round off error that does not stabilize until the irradiation time approaches the ending irradiation period. We do not know the number of significant figures that Maek used in his calculations or the magnitude of numerical error introduced. 4.2 Maek could have calculated the ^{147}Nd, ^{147}Pm, ^{147}Sm at the end of irradiation but assumed (incorrectly) that since the ^{147}Nd half-life is short compared to is progeny, ^{147}Pm, the ^{147}Nd can be added to the ^{147}Pm at the start of decay, The reported ^{147}Nd chain yield would have been underestimated by 4.34% at 83.33 days and 0.98% at 1 year. This is possible given to the reported Nd-147 chain yield, but not likely. 4.3 Maek could have calculated the ^{147}Pm, and ^{147}Sm at the end of irradiation but assumed (incorrectly) that the 147 mass chain was all initially produced ^{147}Pm and decayed during irradiation to ^{147}Sm. The reported ^{147}Nd chain yield would have been overestimated by 13.33% at 83.33 days and 3.09% at 1 year. This is very unlikely due to Maek's the reported Nd-147 chain yield (it is within a few per cent of other reported measurements). 4.4 Maek could have assumed (incorrectly) that all of mass chain 147 was in ^{147}Pm at the end of irradiation and decayed over time to ^{147}Sm at the end of irradiation. The reported ^{147}Nd chain yield would have been underestimated by 15.92% at 83.33 days and 3.64% at 1 year. This is highly unlikely due to the reported Nd-147 chain yield.

Reference:	W.J. Maeck, "Fast reactor fission yields for U-233, U-235, U-238, Pu-239 and recommendations for the determination of burnup on FBR mixed Oxide Fuels: an interim project report", Allied chemical corporation, Idaho-Chemical Program. ICP-1050-I, 1975
Location:	EBR-II, INEL
Assemblies:	Fast breeder reactor, target were near center of the core
Materials:	U-233, U-235, U-238, Pu-239 The 239Pu target was: PuO_2
Target Isotopics	238Pu: 0.0, 239Pu: 99.10, 240Pu: 0.888, 241Pu: 0.014, 242Pu: 0.0
Detection:	Isotope mass dilution spectroscopy, counted 87.7% of the heavy mass chain and extrapolated or interpolated the rest of the heavy mass chain
Experimental Details:	• Irradiation was ~2 months • Sample cooled for ~2 months • 4 samples were analyzed over a period of at least 1 year • The mass spec was calibrated and tested for impurities • Highly purified reagents • Noble gas traps were used and checked
Fission products:	Very large number of stable elements were measured and are listed in FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne.
Number of fissions:	~10^{19} fissions, constant irradiation. The absolute number of atoms from the 87.8% of the heavy mass chain were determined and the rest were interpolated or extrapolated to obtain the absolute number of fissions.
Amount of fissionable material;	~ 700 mg of PuO_2, the chemical procedures are spelled out for each of the mass chains that were measured.
Thermal fission yield:	Paper was published in 1981 from a thermal irradiation
Error terms:	• Statistical uncertainties from averaging of all the samples • Uncertainties from Extrapolation • Uncertainties from interpolations
Neutron spectra:	• Average energy of ~400KeV • Neutron spectrum was determined using monitor capsules and calibrated GeLi detectors and a fitting code called SPECTRA [Ref: SC-RR-70-251, 1970]. • The neutron spectra was checked against a fission spectrum and it is slightly softer (e.g. Big 10)
Results ^{239}Pu(n,f)XX Cumulative:	See "FCY data.xls" file on the Mac desktop/FCY directory of Y. Dardenne
Notes	The results from this paper are superseded by the 1977 results

Concerns	5) What is the spectrum of EBR-II 6) Burnup of fission products during the irradiation 7) The 147Sm was corrected for long lived precursors but the equations are not shown 8) What is the effect between weapons grade and pure 239Pu
Resolved	5) Contacted D. MacKnight at Argon and he sent me a spectrum of EBR-II from the location of the irradiation. This spectrum is slightly softer but not by much. A comparison of the spectrum exist on my classified side 6) In a thermal irradiation, Maeck saw the 148Sm that is the destruction term of the 147Pm. He then added this amount back into the 147 mass chain. He would have seen this in the fission spectrum irradiation and would have also added it back in had he observed it. - I still have the concern that the 147Nd has a 10.98 day half-life and could absorb a neutron and go to 148Nd, which is stable and would not be observed as a destruction of the 147 mass chain. 7) Using Engl&Rider FCY I calculated a 0.5% effect on the number of fissions between the two types of Pu 8) Maeck was very careful and he makes the statement that the 147Sm was corrected for the 147Pm 2.623 y half life Background - Maek, et. al. measured the ^{147}Nd chain yield by quantifying the quasi-stable ^{147}Sm isotope by IDMS. Maek measured the ^{147}Sm concentration after a 58.833 day irradiation. The ^{147}Sm concentration was quantified at 83.333 and at about 1 year after irradiation, exact time not reported. The ^{147}Nd chain yield was calculated by a correction factor developed from the Bateman Equations describing radioactive decay to the end chain member ^{147}Sm. The measured ^{147}Sm concentration was not reported and approximations in the Bateman Equations were not described. The following corrections could have been performed: 4.1 Maek could have calculated the ^{147}Nd, ^{147}Pm, ^{147}Sm at the end of irradiation and appropriately calculated the decay and buildup of nuclides during radiation and in the subsequent decay period. The calculated ^{147}Sm / mass 147 chain yield at 83.33 days is 6.75% in this case; and 23.96% at 1 year. This is the correct treatment. We note that in an EXCEL solution to the Bateman Equations at ~14 significant figures, there is a modest round off error that does not stabilize until the irradiation time approaches

	the ending irradiation period. We do not know the number of significant figures that Maek used in his calculations or the magnitude of numerical error introduced. 4.2 Maek could have calculated the ^{147}Nd, ^{147}Pm, ^{147}Sm at the end of irradiation but assumed (incorrectly) that since the ^{147}Nd half-life is short compared to is progeny, ^{147}Pm, the ^{147}Nd can be added to the ^{147}Pm at the start of decay, The reported ^{147}Nd chain yield would have been underestimated by 4.34% at 83.33 days and 0.98% at 1 year. This is possible given to the reported Nd-147 chain yield, but not likely. 4.3 Maek could have calculated the ^{147}Pm, and ^{147}Sm at the end of irradiation but assumed (incorrectly) that the 147 mass chain was all initially produced ^{147}Pm and decayed during irradiation to ^{147}Sm. The reported ^{147}Nd chain yield would have been overestimated by 13.33% at 83.33 days and 3.09% at 1 year. This is very unlikely due to Maek's the reported Nd-147 chain yield (it is within a few per cent of other reported measurements). 4.4 Maek could have assumed (incorrectly) that all of mass chain 147 was in ^{147}Pm at the end of irradiation and decayed over time to ^{147}Sm at the end of irradiation. The reported ^{147}Nd chain yield would have been underestimated by 15.92% at 83.33 days and 3.64% at 1 year. This is highly unlikely due to the reported Nd-147 chain yield.

Myers et al., Phys. Rev. C18 (1978) 1700-1705

Fission Product Review Sheet

Reference: W. A. Myers, M. V. Kantelo, R. L. Osbourne, A. L. Prindle and D. R. Nethaway, "Fast neutron fission of ^{240}Pu", Phys. Rev. C18 (1978) 1700-1705.

Location: LANL FLATTOP plutonium critical assembly (natural uranium reflected)

Assemblies:

Materials: $^{240}PuO_2$ targets, 10-200 mg, encapsulated in Al, ^{238}Pu 0.017%, ^{239}Pu 0.67%, ^{240}Pu 98.41%, ^{241}Pu 0.53%, ^{242}Pu 0.37%. Enriched U-metal monitor foils, ^{234}U 1.0%, ^{235}U 93.2%, ^{236}U 0.67%, ^{238}U 5.2%. Pu targets were purified, precipitated and resintered before each run.

Detection: gamma counting and/or beta counting

Experimental details: Three 4-hour irradiations, $^{240}PuO_2$ targets sandwiched between ^{235}U metal foils, in Al can, in Cu can, shipped to LLNL and disassembled. ^{240}Pu targets counted in new cans, or dissolved and fractions counted. Corrections for decay during bombardment. Products measured relative to ^{99}Mo. Number of fissions in ^{240}Pu target from fissions induced in ^{235}U monitor foils, taking into account mass difference, isotopics, and cross section. Gamma-ray branching ratios from Gamanal library at that time (1978). Fission yields also calculated by forcing sum fissions in a hump to be 100%.

Fission products: 44 fission products, A=72-169

Number of fissions: Determined by ratio to ^{235}U monitor foils, proportionality constant = 0.825 $\pm$ 5%. Assembly is capable of generating 1E12 fis/hour /gram in ^{235}U.

Amount of fissionable material: Well quantified through volumetric dilution for each target.

Thermal fission yields: none

Error terms: 5% systematic error from $\sigma_f(^{240}Pu)/\sigma_f(^{235}U)$ – My estimate is that this is too small by factor 2. Gamma spec statistical uncertainties are 1% - also too low, I think. Probably 5% systematic on yields by forcing each hump to 100%. No error considered from irradiation conditions. Resultant error bar is 3%, from averaging two methods, each with a combined systematic error and random error of about 5% - this error analysis is pretty bad.

Neutron spectrum: plutonium fission spectrum

Results ^{239}Pu(nf,f)XX:
Yield of ^{99}Mo from mass balance and # fissions is 6.36(38)%
Yield of ^{99}Mo from sum mass distribution is 6.00(30)%

(as reported, all values given 3.0% relative undertainty, 1 sigma))

Nuclide	^{240}Pu FCY
^{95}Zr	4.49%
^{97}Zr	5.28%
^{99}Mo	6.18%
^{137}Cs	6.06%
^{140}Ba	5.46%
^{141}Ce	4.90%
^{144}Ce	3.97%
^{147}Nd	2.27%
^{156}Eu	.00172%

Notes: Radiochemistry procedures in Nethaway et al., Phys. Rev. C16 (1977) 1907; they seem adequate, though more detail could be given. Corrections for decay during irradiation were applied. Shipping delay to LLNL caused loss of all nuclides with half life less than 10 hours. Estimated contribution of ^{239}Pu in target is ~1% of fissions. Spontaneous fission contribution is probably unimportant as long as gamma measurements did not go on after several half lives on unseparated foils (corr < 0.05%)

Concerns: Error analysis is weak.
Extrapolation to fill in missing masses for sum-to-100% technique is not described.

Good enough to incorporate, particularly because it is only 6% of w.g. Pu.
Rajagopalan et al., Nucl. Sci. & Eng. 58 (1975) 414-419

Fission Product Review Sheet

Reference: M. Rajagopalan, H. S. Pruys, A. Gruetter, H. R. von Gunten, E. A. Hermes, R. Richmond, E. Roessler, A. Schmid and P. Wydler, "Mass yields in the fission of uranium 235 and plutonium 239 in the neutron spectrum of a gas-cooled fast reactor", Nucl. Sci. & Eng. 58 (1975) 414-419

Location: Wuerenlingen, Switzerland, Eidg. Institut fuer Reaktorforschung

Assemblies: Fast zone of zero-energy reactor (critical assembly) PROTEUS, simulating spectrum from a gas-cooled reactor (a plutonium assembly driven by uranium fast fissions); thermal neutrons from heavy water reactor DIORIT

Materials: Targets are 40 mg each of the oxide. $^{235}UO_2$ targets ^{234}U 1.6%, ^{235}U 97.5%, ^{236}U 0.08%, ^{238}U 0.8%. $^{239}PuO_2$ targets ^{239}Pu 92.1%, ^{240}Pu 7.4% ^{241}Pu 0.5%, ^{242}Pu not given. PuO2 target fired to only 450°C for ease of dissolution.

Detection: Ge(Li) detectors, whole targets and fractions following chem separations. Spectra processed with GASPAN code, IEEE transactions Nucl Sci NS-15 (2) (1968) 437. Since R-value technique used, nuclear data used is of less import (and not given); basis of R-values was Meek and Rider thermal ^{235}U yields, GE Vallecitos Report NEDO-12154-1 (1974). Quantification from identification and integration of strongest lines.

Experimental details: Several samples irradiated, with effort to make time between steps similar from target to target. U targets irradiated for 1 hour, Pu targets irradiated for 2 hours. For both, dissolution started 40 minutes after EOB. The chemical process used impacted Zr, Nb, Te and I, so these were determined from unseparated foils. The chemical yield was assumed to be 100% for other radionuclides (Sr, Y, Mo, Ru, Ba and rare earths) – this was proven by comparison with thermal irradiation of ^{235}U with and without chemical sep. U fractions started counting 80 minutes EOB, and were counted eight times over 10 days. Pu fractions started counting 4 hours EOB, and were counted six times over 10 days. Data were reported as R values on a ^{140}Ba basis. For ^{235}U, nuclides sufficient to measure 66% of high-mass peak were measured, so experimental data were extrapolated and interpolated, using guidance of Meek and Rider, with corrections for fission yield beyond end member; uncertainties associated with missing chains was 10-20%. Pu data not sufficient for similar treatment, so only R values are available.

Fission products:

Number of fissions: flux is 3E9 n/sq cm-sec, background from SF of ^{240}Pu is < 0.01%

Amount of fissionable material: 40 mg oxide each target

Thermal fission yields: Meek and Rider thermal ^{235}U yields, GE Vallecitos Report NEDO-12154-1 (1974)

Error terms: Statistical errors on R values, interpolated values given 10-20% error. Meek and Rider thermal ^{235}U uncertainties accepted as is, final R-values inflated by 1.5% when calculating FCYs because of use of Meek and Rider (not described very well – check).

Neutron spectrum: two spectra used in experiments for fast neutrons, but very little difference, meant to simulate gas-cooled reactor spectrum, median energy is 0.18 MeV,

Results $^{239}Pu(nf,f)XX$: uncert values are 1-sigma on last digits

Nuclide	$^{235}U_{th}$, Meek&Rider	$^{235}U_{fs}$(FCY, %)	$^{239}Pu_{fs}$ (^{140}Ba R-values)
^{95}Zr	6.46	6.49(19)	1.057(36)
^{97}Zr	5.96	6.05(13)	1.068(17)
^{99}Mo	6.13	6.23(13)	1.169(23)
^{140}Ba	6.32	6.29(13)	1.000
^{141}Ce	5.89	5.56(18)	1.139(20)
^{147}Nd	2.28	2.28(13)	0.989(21)

Notes: If England and Rider ^{140}Ba yield for Pu-fast is accepted, then FCY(^{147}Nd)= 1.90 $\pm$ 8.7%; FCY(^{99}Mo) = 6.04 $\pm$ 3.8%; FCY(^{95}Zr) = 5.75 $\pm$ 5.6%.

Concerns: Basis of R-values is ^{235}U thermal from Meek and Rider, so if nuclear data is disparate with Meek and Rider "average", there may be a problem – no way to evaluate, but extra 1.5% term is added to cover (?). Chemistry is OK, and corrections for loss are appropriate relative to unseparated foils

Good enough to incorporate

Evaluation of paper by A. V. Sorokina et al. (1971)

W. Younes

1st July 2009

1 Summary

In the paper by Sorokina et al. [1] The authors have counted fission events for reactor-spectrum irradiations of solutions of ^{239}Pu and ^{241}Pu by a track-counting method in mica detectors. Preparations of Cerium, Molybdenum and Barium were extracted by chemical means, and their β activities were measured. Yields of ^{99}Mo, ^{140}Ba, and ^{141,144}Ce were deduced from the measurements. In addition, the yields of other isotopes, which had been measured relative to the ^{144}Ce yield in previous work [2, 3], were turned into absolute yields (these include yields for ^{147}Nd and ^{155,156}Eu, which are of interest to this panel).

2 Experimental details

2.1 Samples

Solutions of ^{239}Pu and ^{241}Pu in nitric acid were prepared and used in the experiment. The isotopic composition of the ^{239}Pu solution is not given. For the ^{241}Pu solution, the paper only mentions that 4-7% of the total fissions are from ^{239}Pu. A drop of each solution was applied to natural-mica detector disks. The size and concentration of the drops is not given, but the maximum possible mass of the drops given the experimental conditions is 70 mg. An aluminum-foil beaker containing targets of gold, mica detectors with the Pu solutions, a mica detector with nitric-acid solution alone, and mica partitions was irradiated in a reactor neutron flux.

2.2 Neutron source

The samples were irradiated in the reactor at the A. F. Ioffe Physicotechnical Institute in St. Petersburg, Russia. The length of irradiation is not specified, etching of the mica detectors took place 2-3 weeks after irradiation. The neutron flux is not explicitly given, but the cadmium ratio for gold was measured at 4.26 during the irradiation.

2.3 Detectors

The natural-mica disks on which the Pu solutions were deposited served as detectors to directly extract the number of fissions by counting tracks in the material. Activities of preparations of Ce, Mo, and Ba, separated by ion-exchange methods from the irradiated Pu solutions were counted in a propane flow-through 4π β counter.

3 Data analysis

3.1 Fission counts

The total number of fissions was determined by track counting in the mica detectors. The detection efficiency of the mica was calibrated using ^{252}Cf, whose spontaneous fissions were also measured in an argon-filled ionization grid chamber. An efficiency of 96.7% with a standard deviation of 0.62% was obtained from 10 separate measurements. A background count from uranium naturally present in the mica was estimated at 5-7% of total counts. A background from the nitric-acid solution alone was determined to be 1.5-3.0% of the total number of tracks. Systematic uncertainties in the counting method were estimated at less than 1.5% by comparing counts obtained by two co-workers. The actual number of fissions is not given in the paper.

3.2 Product yields

The β activities of separated products of ^{99}Mo, ^{140}Ba, and ^{141,144}Ce were measured and used to determine absolute cumulative yields. In all cases, the effect of predecessors was taken into account using the formalism in [3]. The ^{140}Ba yield only appears to have been measured for the ^{241}Pu fission (with the contribution from ^{239}Pu subtracted using a ^{140}Ba yield taken from [4]), at equilibrium with ^{140}La.

In addition, yields measured by the same group relative to the ^{144}Ce yield in previous work [2, 3], were converted to absolute yields in the Sorokina paper [1] using their measured ^{144}Ce yield.

4 Results

The results of ^{239}Pu(n, f) yields of interest are summarized in table 1.

Product	Cumulative yield
^{99}Mo	$(6.17 \pm 0.19)\%$
^{144}Ce	$(3.85 \pm 0.09)\%$
^{147}Nd	$(2.13 \pm 0.09)\%$ (*)
^{155}Eu	$(0.171 \pm 0.019)\%$ (*)
^{156}Eu	$(0.124 \pm 0.005)\%$ (*)

Table 1: ^{239}Pu(n, f) Fission yields of interest deduced in the Sorokina paper [1]. The yields marked with "(*)" were measured relative to the^{144}Ce yield in previous work and turned into absolute yields in the Sorokina paper.

5 Concerns

In evaluating the paper the following questions and concerns can be raised:

- Some subjectivity is involved in counting tracks in the mica detectors. The authors have attempted to quantify a systematic uncertainty associated with that process by comparing counts obtained by two co-workers. Is this an accurate estimate of this uncertainty? If the co-workers were similarly trained in this task and used similar criteria to identify tracks, can the counts be considered independent?
- Is the chemical extraction of the products near-100% efficient? There is no mention in the text of any loss of material during this process.
- How reliable is the correction made for contribution from predecessors? Since the irradiation time is not given, it is impossible to gauge the accuracy of this correction.
- What was the efficiency of the grid chamber used to calibrate the mica detectors? This quantity is not specified in the text.

References

[1] A. V. Sorokina, N. V. Skovorodkin, S. S. Bugorkov, A. S. Krivokhatskii, and K. A. Petrzhak, Atomic Energy **31**, 99 (1971).

[2] N. V. Skovorodkin, A. V. Sorokina, S. S. Bugorkov, A. S. Krivokhatskii, and K. A. Petrzhak, Soviet Radiochemistry **12**, 453 (1970).

[3] N. V. Skovorodkin, A. V. Sorokina, S. S. Bugorkov, A. S. Krivokhatskii, and K. A. Petrzhak, Soviet Radiochemistry **12**, 458 (1970).

[4] H. Fickel and R. Tomlinson, Can. J. Phys. **37**, 926 (1959).

Yurova et al., Atomnaya Energiya 47 (1979) 26-28

Fission Product Review Sheet

Reference: L. N. Yurova, A. V. Bushuev, V. N. Ozerkov, V. V. Chachin, A. V. Zvonarev, Yu. G. Liforov, Yu. V. Koleganov, V. V. Miller and O. V. Gorbatyuk, "Yields of some fragments from fission of ^{235}U, ^{238}U, and ^{239}Pu by neutron from spectrum of BR-1 fast reactor", Atomnaya Energiya 47 (1979) 26-28

Location: BR-1 fast reactor, Pu fueled

Assemblies: 1-liter core, metallic Pu in stainless steel cladding, maximum neutron flux density 1E10 n/sq cm sec. Added graphite thermal column.

Materials: 90% ^{239}Pu oxide powder, 90% ^{235}U oxide powder

Detection: Gamma spec with Ge(Li), no nuclear data given as formalism is through simplified R-value method, $r = Y_f(A)/Y_t(A)$, whole sample counting (?)

Experimental details: Spectra taken from 8 hours to 6 days EOB, ten to twelve counts. Formalism is pseudo R-value (fast production Pu/ slow production Pu). Track detector results from thin foil scaled up to chemistry foil by relative masses for # fissions induced. Track detectors (polished glass disks, 1 mg/cm^2 recoiling layer) did not accumulate more than 2000 tracks. Gamma-ray count rate in Ge(Li) detector limited to 5000 cps. Pseudo R-value converted to fast FCY using evaluated slow FCY from Walker.

Fission products: 14 fission products measured

Number of fissions:

Amount of fissionable material: 3 mm diameter Al tube, 15 mm long

Thermal fission yields: basis of pseudo R-value translation to fast FCYs, came from Walker (see below). Measured thermal from thermal column is part of pseudo R and is not given separately.

Error terms: Measurement of gamma photons and construction of ratio was better than 1%, statistical; over whole data set, 1.3%; Counting of tracks; Position difference between chemistry foils and track detector (as much as 2 mm), doesn't exceed 1% correction. Error taken from Walker for thermal is propagated with ratio to give uncert on fast FCYs. Perturbation of flux by insertion of sample < 0.5%.

Neutron spectrum: BR-1 fast not described in paper, graphite thermal column not described in paper

Results ^{239}Pu(nf,f)XX: (as given, 1 sigma uncert on last digits)

Nuclide	^{235}U(n_{fs},f)	^{239}Pu(n_{fs},f)	^{238}U(n_{fs},f)
^{95}Zr	6.24(33)	4.91(17)	---
^{97}Zr	6.36(16)	5.85(15)	5.70(23)
^{99}Mo	6.40(12)	6.52(21)	7.17(17)
^{140}Ba	6.23(13)	5.84(16)	6.13(13)
^{143}Ce	5.61(11)	4.46(10)	4.81(12)
^{147}Nd	2.16(10)	2.05(10)	---

Notes: Compared with W. Walker in Proceedings of the panel on fission product nuclear data, Bologna, Nov. 26-30, 1973, review paper 11a, an evaluation of thermal neutron data. Correction for ^{240}Pu content < 1.5%.

Concerns: Basis of FCY is Walker evaluation, including propagated errors.
Write up is not very detailed, but there is more detail in the original Russian than in the translation. Experimental details not complete, no info on quantification of target, no discussion of thermal irradiation corrections (like blackness).

Use with some reservation.

Fission Product Review Sheet

Reference	L. N. Yurova, A. V. Bushuev, V. N. Ozerkov, V. V. Chachin, A. V. Zvonarev, Yu. G. Liforov, Yu. V. Koleganov, V. V. Miller, and O. V. Gorbatyuk Soviet Atomic Energy, Vol. 47, p.528 (1970)
Measurement	$Y^{25,fis}/Y^{25,th}$, $Y^{28,fis}/Y^{25,th}$, and $Y^{49,fis}/Y^{49,th}$ via gamma counting of irradiated samples
Location	BR-l fast reactor
Assemblies	~1 liter volume filled with rods of metallic plutonium canned in stainless steel. The reactor had a graphite thermal column measuring approximately 1m x 1m x 1m.
Material	Foils of Plutonium and Uranium enriched to 90% ^{235}U fabricated from UO_2 or plutonium metal and covered on both ends by 10 micron thick Al foil. The specimens were placed in a cylindrical aluminum capsule of 3 mm diameter, 15 mm height and thickness of 0.5 mm.
Detection	Ge(Li) detector was used on irradiated samples. The Ge(Li) detector was determined to have 1.69 keV resolution at 1333 keV. Specimens were first counted about 8 hours after irradiation and for 4-6 days thereafter. Each specimen was counted 10-12 times, with the total count rate of less than 5000 kHz, and a resolving time of 25 microseconds.
Irradiation Details:	The reactor flux in the center of the core was ~10^{10} n/cm^2/s. Irradiation time not specified, though irradiation time of several hours seems consistent with information presented
Fission Products	^{91}Y, ^{95}Zr, ^{95}Nb, ^{97}Zr, ^{97}Nb, ^{99}Mo, ^{103}Ru, ^{106}Ru, ^{131}I, ^{132}Te, ^{133}I, ^{135}Xe, ^{140}La, ^{143}Ce, and ^{147}Nd were measured.
Number of Fissions	The ratio of the numbers of fission for fission spectra neutrons to thermal neutrons was determined by the relative ratio of counts in track detectors. Each track detector was a polished glass disk 7mm in diameter and 1mm thickness. These track detectors with an actinide layer were placed in the aluminum capsule containing the target specimen. Track detectors were alternated between reactor core and thermal column to determine the ratio of the masses in actinide layer for two detectors. With the ratio and the ratio of the masses of the two specimens, the fission ratio can be determined. Each track detector pair was used for 18-20 measurements. Reactor power and irradiation time was chosen so that the number of tracks in the glass did not exceed $2x10^3$. Each track detector was counted several times by several operators
Amount of Fissionable material	Specimens were ~1mg/cm^2 thick. Though no mass determination info is stated, corrections for the fission activity due to ^{238}U and ^{240}Pu are stated to be 1.016 and 1.015, respectively.
Chemical Separation	No chemical separation done to irradiated samples.

Uncertainties	There are several statements indicated that the presence of the aluminum capsule does not alter the neutron flux. It is stated that this correction is estimated to be less than 0.5% and experimentally verified to be less than 1%, though no details given on the estimate or the experiment. The statistical error for determination of the ratio of the gamma intensities between fission spectra irradiation and thermal irradiation is stated to be less than 1%. Systematic errors should be very small since this is ratio measurement of the same gamma line. The accuracy of the fission ratio is stated to be 1.3% by looking for the 18-20 measurements for each pair of track detectors. Uncertainty on fission spectra chain yields mostly due to uncertainty of thermal chain yields.					
Neutron Spectra	No detail information describing energy spectrum for fission neutron.					
Results ^{239}Pu (n,f) XX cumulative	Isotope	Y^{fis}/Y^{th}	Y^{th} (Yurova)	Y^{fis} (Yurova)	Y^{th} (E&R)	Y^{fis} (Y^{th} E&R)
	^{91}Y	1.081±0.022	2.54 ±0.05	2.75±.08	2.486±0.025	2.687±0.061
	^{95}Zr	0.98±0.03	5.01 ±0.08	4.91±0.17	4.818±0.067	4.722±0.159
	^{95}Nb	0.95±0.03	5.01 ±0.08	4.75±0.17	4.818±0.067	4.577±0.158
	^{97}Zr	1.047±0.019	5.59 ±0.10	5.85±0.15	5.334±0.107	5.585±0.151
	^{97}Nb	1.047±0.019	5.59 ±0.10	5.85±0.15	5.414±0.076	5.668±0.130
	^{99}Mo	1.031±0.014	6.32 ±0.20	6.52±0.21	6.212±0.087	6.405±0.125
	^{103}Ru	0.97±0.03	6.95 ±0.29	6.65±0.32	6.994±0.140	6.784±0.250
	^{131}I	1.112±0.023	3.74 ±0.09	4.16±0.13	3.856±0.039	4.288±0.099
	^{132}Te	1.015±0.017	5.23 ±0.12	5.31±0.15	5.139±0.103	5.216±0.136
	^{133}I	0.984±0.016	6.92 ±0.19	6.81±0.22	6.973±0.045	6.861±0.120
	^{135}Xe	0.968±0.020	7.69 ±0.26	7.44±0.29	7.608±0.076	7.365±0.169
	^{140}La	1.045±0.024	5.59 ±0.09	5.84±0.16	5.365±0.075	5.606±0.151
	^{143}Ce	0.988±0.017	4.51 ±0.06	4.46±0.10	4.413±0.062	4.363±0.097
	^{147}Nd	0.96±0.04	2.13 ±0.07	2.05±0.10	2.003±0.056	1.923±0.096
Concerns	Other than the lack of details on some of the systematic checks and error analysis, the major concern is the thermal yields used by the authors to generate Y^{fis}. As the table above shows, most of the thermal yields used by the author are 2-5% higher than the thermal yields listed in England and Rider. The last column in the table above is the ^{239}Pu fission spectra chain yields using the ratio measured by Yurova and the England and Rider ^{239}Pu thermal chain yields values.					