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TITLE STATUS OF FISSION YIELD DATA

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Abstract: In this paper we summarize the current status of the recent US evaluation for 34 fissioning nuclides at one or more neutron incident energies and for spontaneous fission. Currently there are 50 yields sets, and for each we have independent and cumulative yields and uncertainties for approximatively 1100 fission products. When finalized the recommended data will become part of Version VI of the US ENDF/B. Other major evaluations in progress that are included in a recently formed IAEA Coordinated Research Program are also summarized. In a second part we review two empirical models in use to estimate independant yields. Comparison of model estimates with measured data is presented, including a comparison with some recent data obtained from Lohengrin (Cf-249 T).

Introduction

Next year will be the 50th anniversary of the discovery of fission. Since the begining physicists and chemists have measured the distribution in masses and charges of the fragments and products following fission. Generally these distributions are called "yields". The definitions of the different types of yields are now reasonably standardized and can be found in the review of Wahl/1,2/.

The most recent review papers on yields by major evaluators in the US, UK, France, and China are in Ref./2/. This is a source of much of the material in our paper.

Most of the mass chain yields for the more important fissioning systems have been measured. For the independent yields the situation is not the same, so models have been developed for estimating the many hundreds of independent yields that have not been measured. Because of space limitations we will not include a discussion of isomeric yields except to note that some evaluations use the simple model in Ref./3/ and others simply assume equal division among isomers.

Libraries of Evaluated Fission Yields

JAMES /2/ has recently reviewed the existing libraries of fission yields. He considers four libraries:

1. The UK unajusted and adjusted libraries, UKFYU1 and UKFYA1, respectively. Adjustment refers to the inclusion of several conservations directly in the evaluation such as total prompt and delayed neutrons,charge, etc. The UK libraries include 15 yield sets for ten fission nuclides. Fractional independent yields were not reevaluated from CROUCH/4/, but did have some readjustment by least squares. The UK evaluations are again in progress and will include a more detailed treatment of uncertainties than previous evaluations. These libraries were started by CROUCH /4/, and include an independent evaluation of chain yields.

2. The US evaluation effort now resides at LOS ALAMOS. This library was first started by RIDER and MEEK of the General Electric Company and RIDER continues to update the data and assist in the evaluation. The 1988 version contains independent and cumulative yields and uncertainties for about 1100 products for each of 34 fissionable nuclides at one or more energies (50 sets). Table 1 lists the completed sets and an additional 10 sets in progress.

TABLE 1
Evaluated Yield Sets for ENDF/B (Ver. G)

Fissionable Nuclide	Fissionable Nuclide
Th-227 (t)	Pu-242 (f)
Th-229 (t)	Am-241 (t,f,h)
Th-232 (f,h)	Am-42m (t)
Pa-231 (f)	Am-243 (f)
U -232 (t)	Cm-242 (f)
U -233 (t,f,h)	Cm-244 (s)
U -234 (f,h)	Cm-245 (t)
U -235 (t,f,h)	Cm-248 (s)
U -236 (f,h)	Cf-249 (t)
U -237 (f)	Cf-250 (s)
U -238 (s,f,h)	Cf-251 (t)
Np-237 (f,h)	Cf-252 (s)
Np-238 (f)	Es-253 (s)
Pu-238 (f)	Es-254 (t)
Pu-239 (t,f,h)	Fm-254 (s)
Pu-240 (f,h)	Fm-255 (t)
Pu-241 (t,f)	Fm-256 (s)
Np-238 (f)	Es-253 (s)
Np-238 (f)	Es-253 (s)
Np-238 (f)	Es-253 (s)
Np-238 (f)	Es-253 (s)

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s=spontaneous, t=thermal, f=pooled fast, h=14 mev

Ten sets are in progress: Cm-243 (t,f), Cm-246 (s,f), Cm-244 (f), Cm-248 (f) Pu-24 (t,h), Np-237 (t), Pu-240 (t).

measured yields are retained and independent yields that are unmeasured are based on the Gaussian Zp model with parameters based on an older U-235 analysis by Wahl except for the six recently studied systems/1/; other exceptions are pairing effects/5/, isomeric yields/3/, and the detailed treatment of decay branching, including direct use of DN precursors. Except for six systems, the Zp(a) values for many systems are based on Ref. /6/. A description is given by RIDER /2/. Model parameters are not well known for many systems because of lack of measured data.

The US evaluation also retains a compilation of all published data, including data unused in the final evaluations, and includes a list of about 1400 publications from 1939 through 1987. A listing of these data (April, 1988) will be supplied to members of the IAEA CRP and to others by request. A complete listing requires about 1200 pages and distribution will be limited until issued as a Los Alamos report. It retains the format of the last widely distributed version /7/. The chain yields of this library are used by other libraries (Wahl, French, Chinese).

3) A French library (1987)/2,8/. It is more a working file with the chain yields from the US, but with different parameters for the charge distribution. This file was mainly used for the decay heat calculations.

4) A Chinese library (1987)/2/. Currently the Chinese evaluation contains ten yield sets for six fissioning nuclides. The methodology of evaluation, parameters, and chain yields are based on the US publications, but their data are now being expanded and there is an effort to improve estimated yields.

JAMES /2/ gives a summary of the methods of evaluation and comparisons of data he had available. These older evaluations did not account for the systematics near symmetry /9, 10/, and the charge distribution parameters were developed before the new experimental results from Lohengren were available, but most of his analysis still applies.

Two Models for Charge D[illegible]ibution

Two empirical models, t[illegible]p and the Ap' models have been developed. Both models need to establish the approximate complementarity of mass numbers

$$A'_L + A'_H = A_F \qquad (1)$$

$$A' = A + \nu_A \qquad (2)$$

where L for light and H for heavy, F for fissioning nuclide. The ν_A values are calculated from Y(A) values by a program "NUTP8" It is based on a method first proposed by TERRELL/11/.

The number of neutrons emitted for symetric fission must be assumed. For U235T the observed kinetic energy deficit support value of 4 neutrons and this value is assumed for other fission reactions. The total average number of neutrons ($\bar{\nu}_T$) are divided between heavy and light products by multiplying $\bar{\nu}_T$ by an estimated ratio. This ratio appears to give reasonable agreement with experimental values. The plots of experimental $\bar{\nu}_T$ and the smoothed functions derivated from the "NUTP8" program can be found in the WAHL papers/1,2/ for 4 systems (U235T, U233T, PU239T, CF252I).

Both the Zp AND Ap' models assume that the distribution of yields is Gaussian. Yields are modulated by proton and neutron pairing effects. The effects are applied by either multiplication or division of Gaussian yields by Fz and Fn, the average even-odd proton and neutron factors. The Gaussian width parameters for the two models are equal to the root mean square (RMS) values for Gaussian dispersions corrected for grouping:

$$\sigma = (RMS^2 - 1/12)^{\frac{1}{2}} \qquad (3)$$

It is convenient to compare the maxima in dispersion curves, Zp and A'p with values for unchanged charge division (UCD):

$$Z_{ucd} = A'(Z_F/A_F) \qquad (4)$$

$$A'_{ucd} = Z(A_F/Z_F) \qquad (5)$$

The parameters which are used to represent the two functions

$$\Delta Z = (Z_p - Z_{ucd}) \qquad (6)$$

$$\Delta A' = (A'_p - A'_{pucd}) \qquad (7)$$

are given in the Wahl paper and a summary is given in table 2 for the Zp Model.

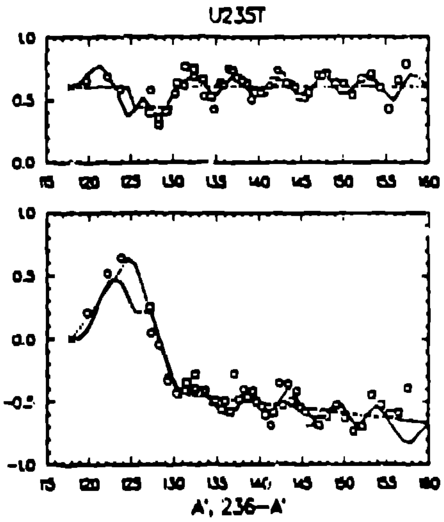

Fig. 1

The figure 1 taken from Ref./1/ shows the variation of RMS and ΔZ for U235T. They have been derived from available data by the method of least squares. A modification of the general least squares program ORGLS is used. The parameters used with the model are given in Table 2.

TABLE 2
PARAMETERS FOR THE Zp MODEL *.

PARA-METER	235U	233U	239PU	252CF	238U	241PU
ΔZ(A'=140)	-0.511	-0.519	-0.544	-0.420	[illegible]	[illegible]
ΔZ/ΔA'	-0.008	-0.0[illegible]5	-0.015	-0.015	[illegible]	[illegible]
σ_Z	-0.531	-0.555	-0.546	-0.589	[illegible]	[illegible]
σ_{50}	0.33	0.[illegible]6	0.35	0.35	[illegible]	[illegible]

Fz	1.27	1.27	1.14	1.05	1.18	1.10
F_N	1.07	1.07	1.05	1.0	1.0	1.0
$\Delta A'_Z$	0.9	0.9	0.9	0.7	0.9	0.9
ΔZ_{max}	0.7	0.7	0.7	0.7	0.7	0.7

The US evaluation uses Fz and F_N from Ref./5/. The above table is based on Ref. /1/.

The complementary element yields:

$$Y(Z_L) = Y(Z_H)$$

are required to be equal for the A'p model. When too few data exist to derive parameters, the U235T data are assumed be valid for all systems. The parameters for the A'p model can be found in Ref./1/

Estimates of per cent uncertainties in model calculated yields are made with the following equations similar to those proposed by SPINRAD /12/.

$$S_{est} = 100(exp(\delta\mu)^2 - 1)^{\frac{1}{2}} \qquad (8)$$

$$\delta\mu = \alpha + \gamma(\Delta)^4 \qquad (9)$$

with

$$\Delta = (Z - Z_p) or (A' - A'_p) \qquad (10)$$

$$Ln(Y_{cal}/Y_{exp}) = \alpha + \gamma(\Delta) \qquad (11)$$

Generally α = 0.1, γ = 0.05 (Zp) and γ = 0.01 (A'p). Figure 2 shows uncertainty estimates for model calculated yields Dashed lines represent and functions used for es-estimation of uncertainties.

Wahl's Independent yields derived from Zp and Ap' models for the systems U235T,U233T,PU239T,PU241T,U238F,Cf252 are now available on tape from him. The procedure, which produces these complete data sets, gives detailed charge balance, equal yields for complementary elements.Detailed charge balance is not achieved for the other complete independent yield sets,(US, UK,CHINESE).

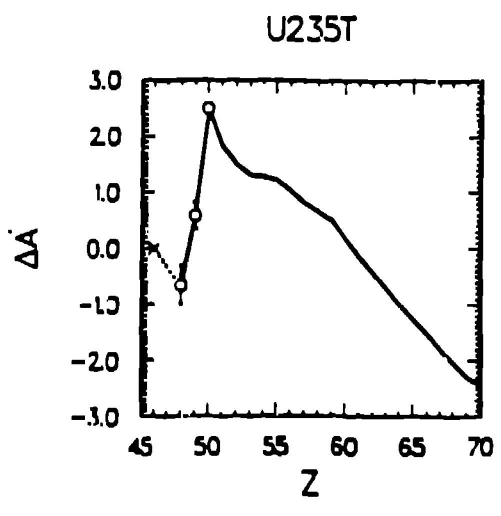

Fig. 2a

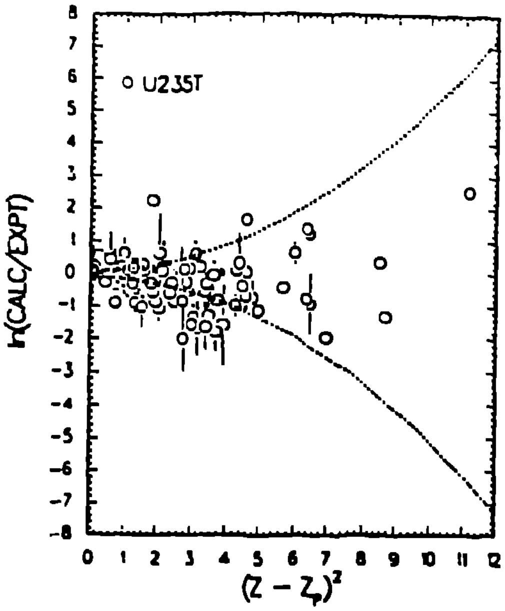

Fig. 2b

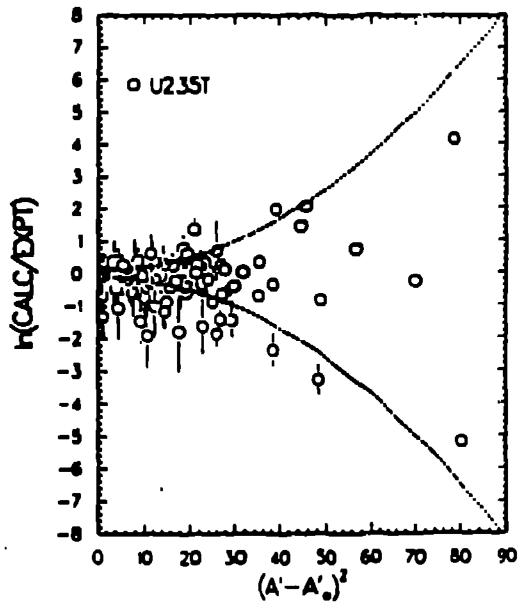

Fig. 2c

It is important to keep in mind that empirical model predictions tend to be increasingly uncertain as measured data become sparse as, e.g., with very small yields. Paramneters are averaged over large mass ranges and different evaluators use different parameters. The models are not consistently used by all evaluators. For example, DICKENS/13/ notes that the Gaussian sigma depends on the even-odd character of charge apart from the modulation by pairing; for cumulative yields, some use Sheppard's correction, etc. Wahl's analysis, being the most recent for fractional yields and the most detailed, is presented above. His Zp and sigma values are used in six of the 50 sets in the US evaluation, and the French use all the parameters and model in their calculations. The reader should be aware that all of the major evaluations differ in their emphasis, in the treatment of uncertainties, in the inclusion of measured data, in the treatment of decay branching, in pairing parameters and in the way these are applied, in isomeric yields, and in the data included per set and number of sets.

Emission of neutrons following beta decay changes the initial mass distributions of both independent and mass number yields. 271 precursors have now been measured or calculated by ENGLAND, et al, /14/. Using the sets of yields and the delayed neutron emission probabilities the total delayed neutron yields can be derived.

New experimental Techniques

Various methods to measure fission yields have been used since the discovery of the fission. These include radiochemical and mass spectrometric measurements, gamma spectrometry with or without radiochemical separations, on line isotopic separations (OSIRIS, SOLIS,etc...) recoil separators, *HIAWATHA* and *LOHENGRIN*. DENSCHLAG /14 / has done a survey of all these methods.

The LOHENGRIN Spectrometer

The fission product spectrometer "Lohengrin" at the high flux reactor of the ILL (GRENOBLE, FRANCE) has been described many times /16/. The masses are identified through a combination of electric and magnetic fields. Fission fragments are focussed onto parabola inside a reaction chamber. Each parabola is characterized by a fixed ratio A/q of mass number A to ionic charge q. Different points on a parabola correspond to different kinetic energies E of the fragments. Mass resolving powers A/DA of about 1000.0 are routimely available. To determine nuclear charges Z, the method is based on the specific ionization, along the particle trajectory. We have to decompose the total fragment energy E into E = DE + Eres with DE being the energy loss in absorber of fixed thickness and Eres being the residual energy. The spectrometer gives DE from the field settings, while Eres is measured with a ionization chamber.

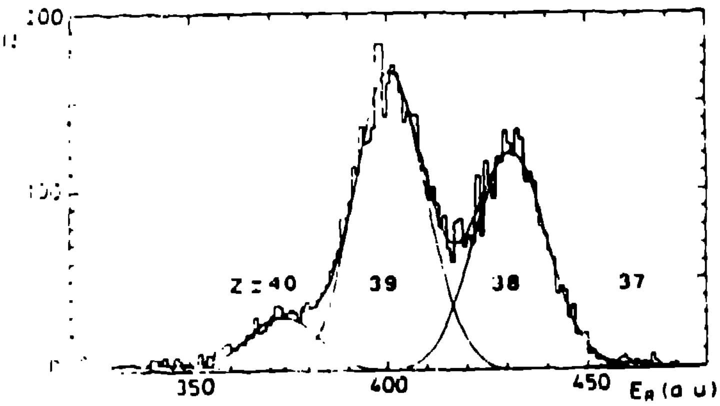

Fig. 3

The figure 3 shows residual energy spectra decomposed into charge components. It is clear from this figure that the uncertainty on low FI is high. See charge 37.

Since each measurement applies to an individual ionic charge state (q) and to an individual kinetic energy of the fragments a complete distribution has to be carried out over the whole range of kinetic energies and over most of the ionic charges produced.

Physical Results

Up to now U235T, U233T, Pu239T have been measured at Lohengrin and used in evaluations. The large range of measurements allow a determination of the proton and neutron Odd-Even effect for other systems. Figure 4 represents the variation of the proton effect with the fission system. Other data indicate that pairing is very energy dependent. Figure 5 from the US evaluation shows this.

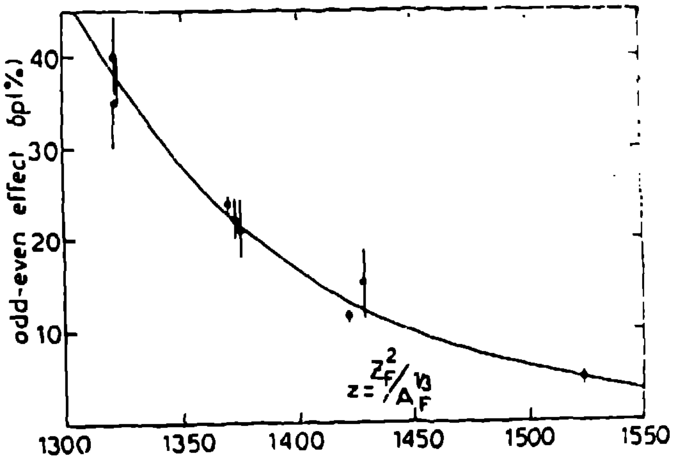

Fig. 4

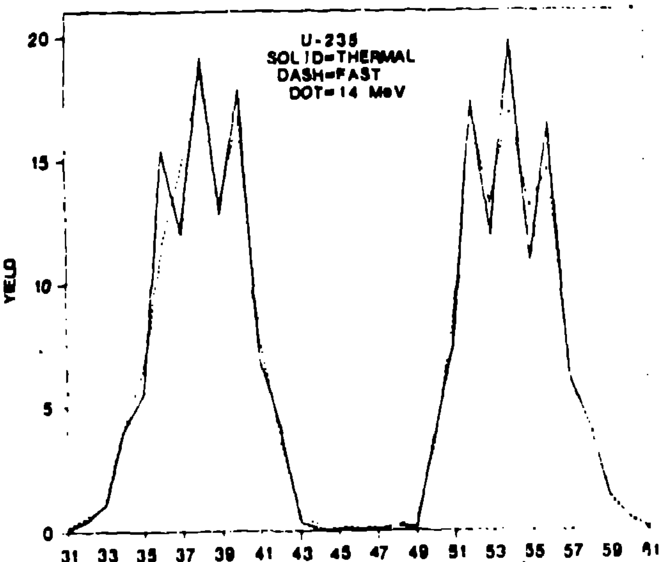

Fig. 5 SUM OF DIRECT YIELDS BY CHARGE (VER. G)

Application of Models to New Lohengrin Data

CF249T has been recently measured at Lohengrin /17/. Fractionnal independent yields are given from masses 85 to 120. Following the method described in /1/, we have first calculated the ν_A. A complete data set of chain yields is in the 1981 US library/7/. The agreement between these values and those measured at Lohengrin is good. Only chain yields for masses 94,95 have higher values at Lohengrin.To establish the NUa calculation, a NUt value of 4 1 /18/ and the same ratio as in CF262 are taken. Figure 6 compares

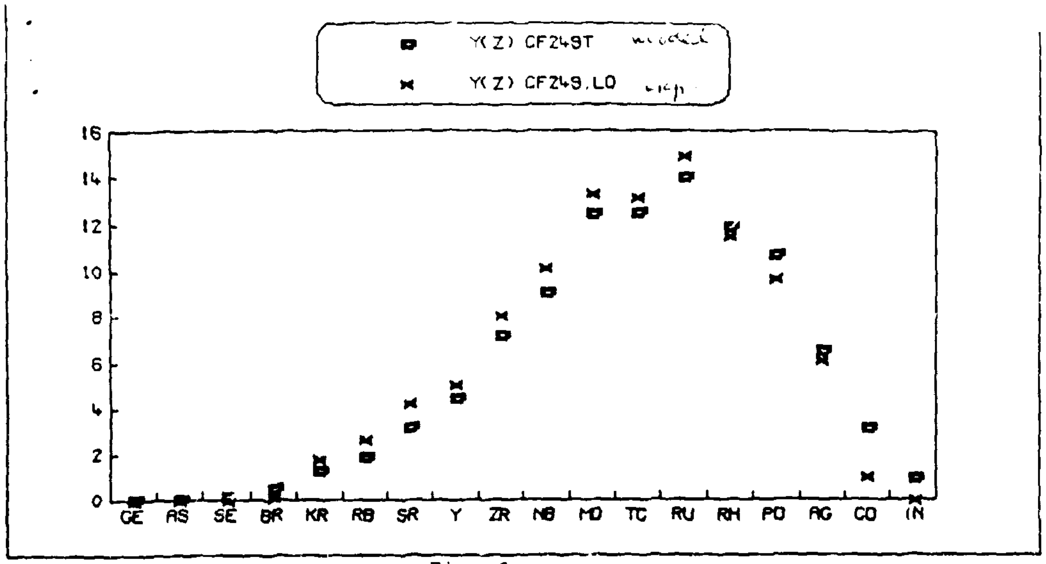

Fig. 6

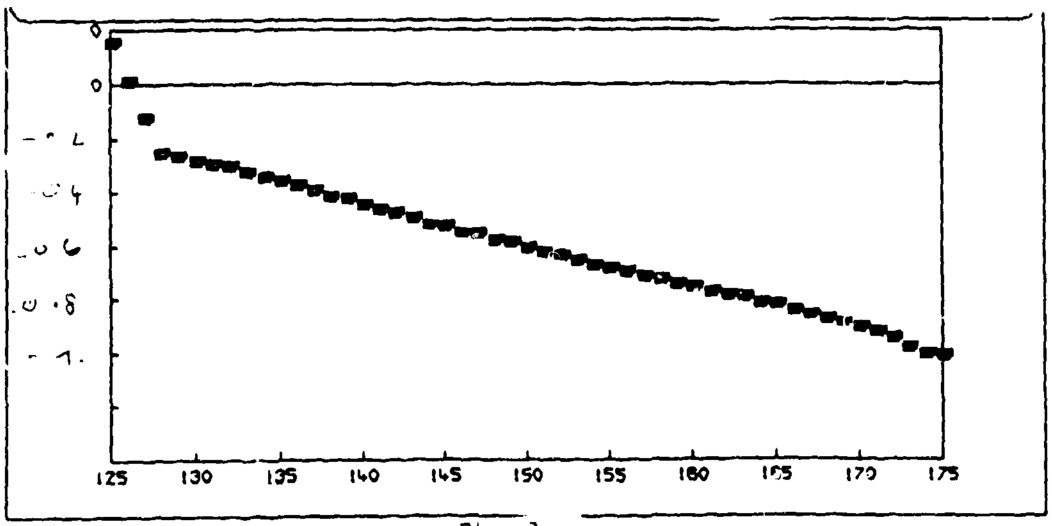

Fig. 7

The parameters to calculate DZ/DA' are the average values for 252CF and 241Pu in Table 2. Fz and Fn are taken from /18/.

The figure 7 represents the DZ/DA' function for Cf249T.

Now it is possible to estimate all independent yields in CF249T using the program "EFPYA" of Ref./1/. We have not compared these with the 1988 US evaluation.

Table 3 is a part of the comparison of calculated and experimental charge distribution data. YI>0.01 are in good agreement. We have already seen the very large experimental uncertainty for the low yields. So it is worthless to try to compare these low data.

Figures through show mass chain yield plots from the 1988 US evaluation.

Conclusions

Evaluated yields through 1987 are now availavle for 50 fission- ing systems. Six systems have had a recent, detailed analysis for distribution parameters. A similar effort is needed for other systems. Evaluation and modeling continues in the US, UK, China, and France. The new IAEA CRP may assist in resolving differences, and in defining needed experimental and evaluation support. Space has not permitted a discussion of problems and detailed differences in evaluations such as energy depen- dence, treatment of decay processes, and use of data measured before and after delayed neutron emission. We have chosen to summarize the most recent evaluations and modeling and to provide some recent Lohengrin data and its modeling.

Experimental Charge-Distribution Data.

NUCLIDE	EXPERIMENTAL VALUE	CALCULATED VALUE	LIM. SYM.	RATIO (RATIO
37 Rb 96	1.300E-02	3.128E-02		2.406
38 Sr 96	3.010E-01	6.492E-01		2.157
39 Y 96	5.510E-01	2.877E-01		0.522
40 Zr 96	1.360E-01	3.133E-02		0.230
38 Sr 97	1.000E-01	2.910E-01		2.910
39 Y 97	5.380E-01	5.556E-01		1.033
40 Zr 97	3.180E-01	1.466E-01		0.461
41 Nb 97	4.400E-02	1.645E-03		0.037
38 Sr 98	3.900E-02	8.902E-02		2.283
39 Y 98	3.230E-01	4.262E-01		1.320
40 Zr 98	5.150E-01	4.717E-01		0.916
41 Nb 98	1.230E-01	1.237E-02		0.101
38 Sr 99	1.100E-02	1.004E-02		0.912
39 Y 99	2.260E-01	2.370E-01		1.049
40 Zr 99	5.170E-01	6.782E-01		1.312
41 Nb 99	2.270E-01	7.148E-02		0.315
42 Mo 99	1.800E-02	3.222E-03		0.179
39 Y 100	5.500E-02	6.213E-02		1.130
40 Zr 100	5.950E-01	7.268E-01		1.222
41 Nb 100	2.860E-01	1.891E-01		0.661
42 Mo 100	6.400E-02	2.098E-02		0.328
39 Y 101	1.300E-02	1.070E-02		0.823
40 Zr 101	3.000E-01	4.218E-01		1.406
41 Nb 101	6.390E-01	4.621E-01		0.723
42 Mo 101	4.800E-02	1.052E-01		2.193

RATIOS — ALL EXP. VALUES

NO. WITH RANGE BRACKETING 1.00:	19	(15.0 %)
NO. BETWEEN 1.00 AND 2.00:	32	(25.2 %)
NO. BETWEEN 0.50 AND 1.00:	26	(20.5 %)
NO. > 2.00:	12	(9.4 %)
NO. < 0.50:	38	(29.9 %)

NO. OF VALUES INCLUDED: 127

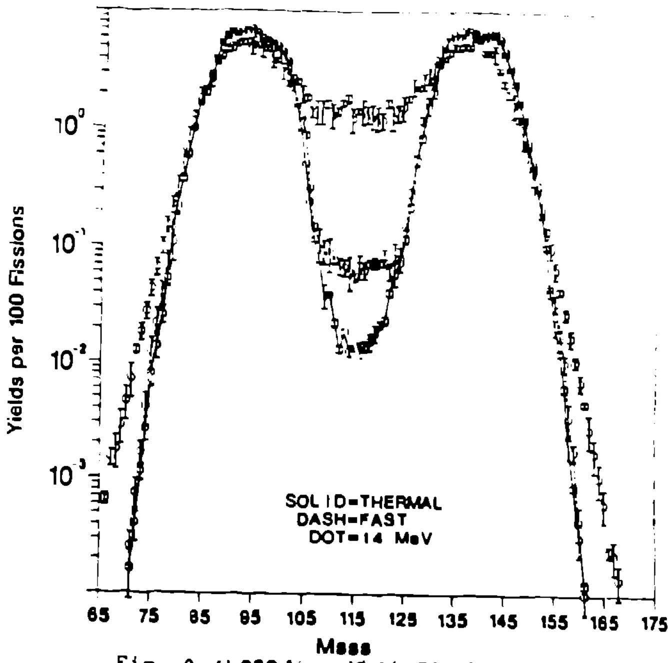

Fig. 9 U-233 Mass Yields (Version G)

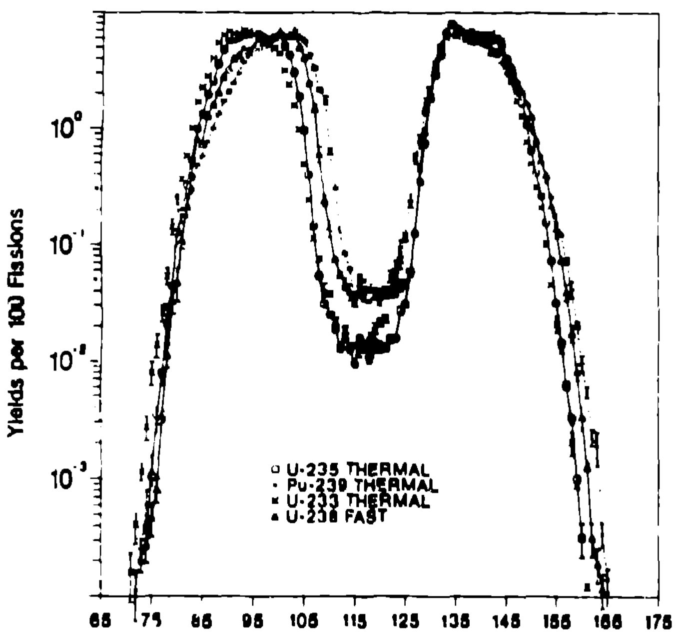

Fig. 8 Comparison of Mass Yields (Version G)

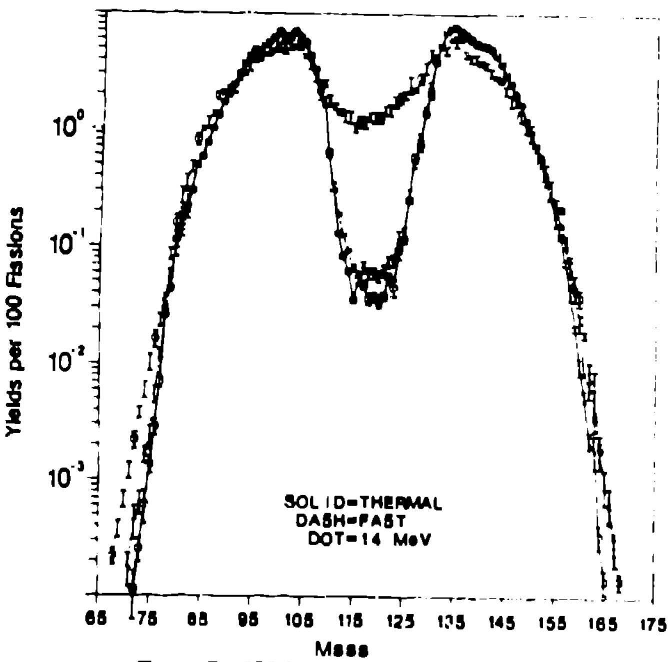

Fig.10 Pu-239 Mass Yields (Version G)

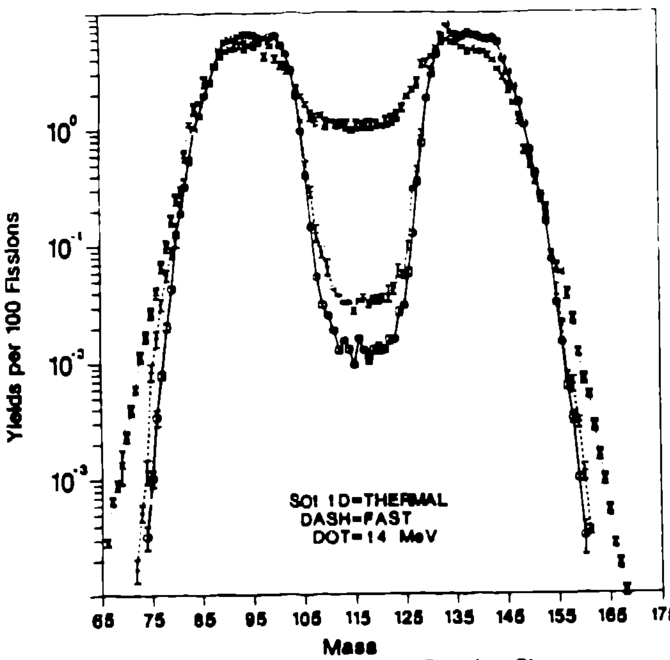

Fig. 11 U-235 Mass Yields (Version G)

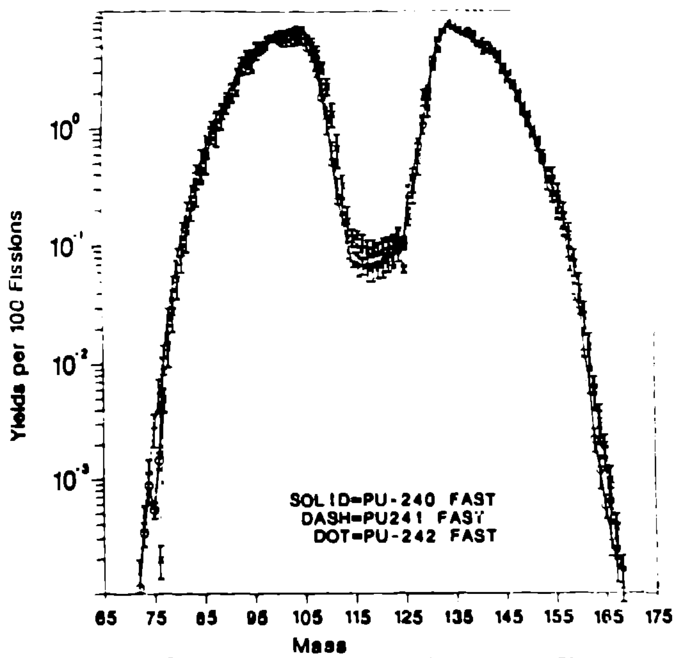

Fig. 13 PLUTONIUMS Mass Yields (Version G)

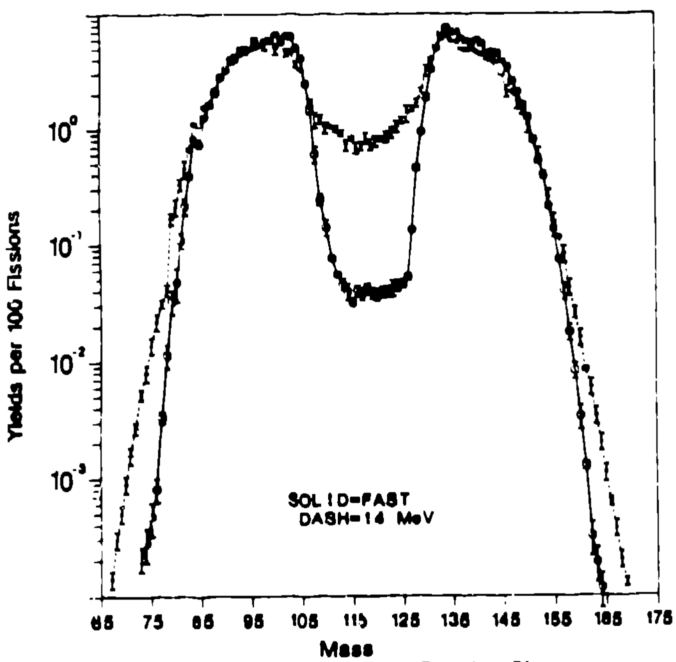

Fig. 12 U-238 Mass Yields (Version G)

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