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3.46 Simple estimate of fission rate during JCO criticality accident

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The fission rate during JCO criticality accident is estimated from fission-product (FP) radioactivities in a uranium solution sample taken from the preparation basin 20 days after the accident. The FP radioactivity data are taken from a report by JAERI released in the Accident Investigation Committee. The total fission number is found quite dependent on the FP radioactivities and estimated to be about 4×10^{16} per liter, or 2×10^{18} per 16kgU (assuming uranium concentration 278.9 g/liter). On the contrary, the time dependence of the fission rate is rather insensitive to the FP radioactivities. Hence, it is difficult to determine the fission number in the initial burst from the radioactivity data.

1. Introduction

The power history (or the fission rate) in JCO criticality accident is the key parameter to evaluate the exposure dose and doses from released radioactive materials for workers and general public. In principle, the time dependence of the fission rate can be evaluated from the populations of the Fission Products (FP) after the accident. In this paper, we perform a semi-quantitative analysis of the fission rate using FP radioactivity data in a uranium solution sample taken from the preparation basin 20 days after the accident. The data are taken from a report by JAERI [1] released in the Accident Investigation Committee. The report gives the radioactivities of 7 FP nuclides obtained from two different measurements. In this paper, we only use the results of one measurement (group A data) because the author could obtain only the group A data when this study was reported in the symposium. However, we have confirmed that, even if we include the remaining group B data, the conclusion of this study does not change in the present semi-quantitative analysis.

2. Assumption

It is somewhat unclear whether the uranium sample contains the average concentrations of the FP's in the preparation basis. Furthermore, there is no way to evaluate the FP releases from the preparation basin, either.

Therefore, we postulate that no more than two parameters of the fission rate can be obtained from the FP radioactivity data. For simplicity, we assume that the fission reactions continued for 17 hours at a constant rate after the initial burst as shown in Fig. 1. The two parameters to be estimated are the number of fissions in the initial burst (F_b) and in the following 17 hours (F_c).

3. Method of analysis

The population of an FP nuclide can be calculated in the summation method at any cooling time. The fission yield and decay data required for the calculations are taken from JNDC version 2 [2]. We assume that all the fission reactions are induced by thermal neutrons. In this study, the numerical calculations are performed with a handy computer code [3].

To start with, let us denote N_b (N_c) as the populations of an FP nuclide from a pulse fission (fissions for 17 hours at constant fission rate 1 fission/s). Then, the total population of the FP, N, is given by

$$N = F_b N_b + F_c N_c \,/\, (17 \times 60 \times 60). \quad (1)$$

Here, N_b and N_c are calculated in the summation method while the total population N can be obtained from the FP radioactivity (λN) in Table I.

Equation (1) gives a line in the (F_c, F_b) plane for each FP nuclide. Then, we have 7 lines for the 7 FP nuclides. Ideally, the lines should have a single intersection that gives the values of F_b and F_c.

It is also possible to obtain the values of F_b and F_c from the linear simultaneous equations (Eq. (1)) in the least squares method. However, we do not adopt the least squares but confine ourselves to the graphical method because the uncertainties of the FP radioactivity data are not clear.

4. Results

Figure 2 shows the 7 lines (Eq. (1)) for the 7 FP nuclides. Unfortunately, it is very hard to identify a single plausible intersection in the figure. Hence, from the present radioactivity data alone, it is very difficult to determine the reliable the (F_c, F_b) values.

When the fission number becomes smaller, a lines in Fig. 2 goes to the lower left side because the total fission number F is given by the straight line F=F_b+F_c. From this viewpoint, the lines for ^{95}Zr, ^{131}I and ^{137}Cs seem to imply that portions of these FP's were lost or released from the uranium solution. Actually, a portion of ^{95}Zr was reported to have been be lost in the preparation process before the radioactivity measurement [1]. Furthermore, ^{131}I was detected outside the JCO site although the quantity was quite small.

In spite of these uncertainties, the total fission number may be known well from Fig. 2. We note that the intersections with the axes show the number of fissions in extreme cases with F_c=0 or F_b=0. These values agree so well that the total number of fissions can be estimated to be about 4×10^{16} fission/liter from the FP radioactivity data.

5. Discussions

The assumption of the fission rate model in Fig. 1 is rather crude. However, it should be noted that the total fission number does not vary much in the two extreme cases. This suggests that the FP radioactivity data give good information to estimate the total fission number independently of the detailed time dependence.

Let us turn to the time scale of the initial burst. Even if the initial burst continued for 10 minutes, this time scale is quite small compared with the total duration of the accident; 10 minutes / 17 hours = 1%. Hence, F_b could include the fission numbers in the possible 2nd and 3rd bursts in the order of 10 minutes after the onset of the accident.

It is also noted that the FP radioactivities were measured after a quite long cooling time compared with the duration of the criticality accident; 17 hours / 20 days = 3.5 %. This is the major reason for the difficulty in evaluating the time dependence of the fission rate from the FP radioactivity data.

6. Conclusions

The fission rate during JCO criticality accident is estimated assuming simple time dependence using the FP radioactivity data taken from preparation basin 20 days after the accident. The total number of fissions is found quite dependent on the FP radioactivities and estimated to be about 4×10^{16} per liter, or 2×10^{18} per 16kgU (assuming uranium concentration 278.9 g/liter). On the contrary, the time dependence of the fission rate is rather insensitive to the FP radioactivities. Hence, it is difficult to determine the fission number in the initial burst from the radioactivity data.

References

[1] "Analysis of a uranium solution sample" by JAERI (October 27, 1999) released during the forth Accident Investigation Committee (October 29, 1999) in Japanese.
[2] K. Tasaka, et al., JNDC Nuclear Data Library of Fission Products - 2nd Version, JAERI-1320 (1988).
[3] K. Oyamatsu, Easy-to-use Application Programs to Calculate Aggregate Fission-Product Properties on Personal Computers, Proc. 1998 Sympo. on Nucl. Data, JAERI-Conf 99-002, pp. 234-239, 1999.

Table I. The FP radioactivity data analyzed from a uranium solution sample taken from the preparation basin 20 days after the accident [1].

nuclide	half life (s)	radioactivity (Bq/ml)
^{95}Zr	5.53×10^{6}	2.15×10^{5}
^{99}Mo	2.38×10^{5}	4.34×10^{4}
^{103}Ru	3.41×10^{6}	1.77×10^{5}
^{144}Ce	2.46×10^{7}	6.91×10^{4}
^{131}I	6.95×10^{5}	1.89×10^{5}
^{137}Cs	9.52×10^{8}	1.48×10^{3}
^{140}Ba	1.10×10^{6}	5.31×10^{5}

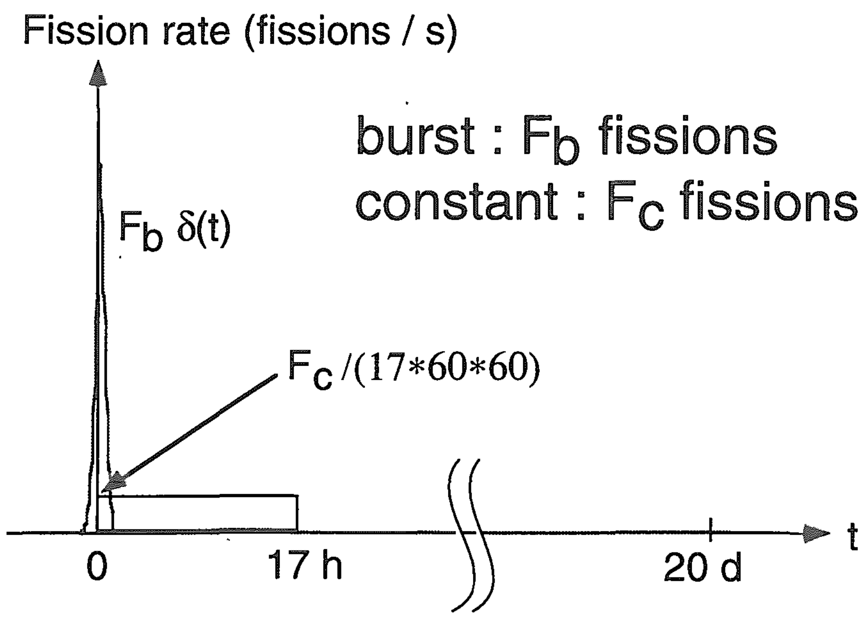

Fig. 1. Fission rate model. The time t=0 corresponds to the beginning of the accident.

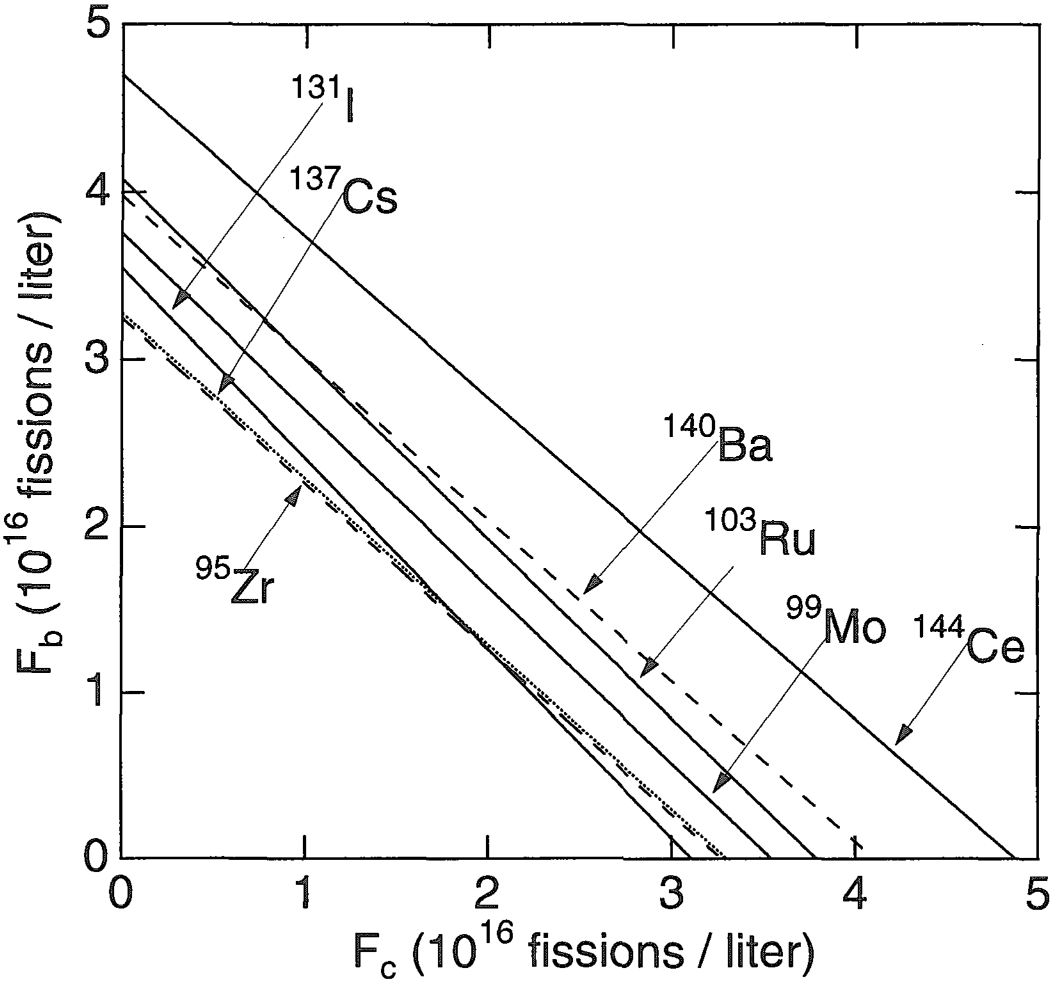

Fig. 2. Fission number in the (F_c, F_b) plane. The values of F_c and F_b are shown as the concentrations in the uranium solution sample.

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国際単位系 (SI) と換算表

表 1　SI 基本単位および補助単位

量	名　称	記　号
長　　さ	メートル	m
質　　量	キログラム	kg
時　　間	秒	s
電　　流	アンペア	A
熱力学温度	ケルビン	K
物　質　量	モル	mol
光　　度	カンデラ	cd
平　面　角	ラジアン	rad
立　体　角	ステラジアン	sr

表 3　固有の名称をもつ SI 組立単位

量	名　称	記号	他の SI 単位による表現
周　波　数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁　　束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光　　束	ルーメン	lm	cd·sr
照　　度	ルクス	lx	lm/m^2
放　射　能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 2　SI と併用される単位

名　称	記　号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ eV = 1.60218 \times 10^{-19}\ J$
$1\ u = 1.66054 \times 10^{-27}\ kg$

表 4　SI と共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ Å = 0.1\ nm = 10^{-10}\ m$
$1\ b = 100\ fm^2 = 10^{-28}\ m^2$
$1\ bar = 0.1\ MPa = 10^5\ Pa$
$1\ Gal = 1\ cm/s^2 = 10^{-2}\ m/s^2$
$1\ Ci = 3.7 \times 10^{10}\ Bq$
$1\ R = 2.58 \times 10^{-4}\ C/kg$
$1\ rad = 1\ cGy = 10^{-2}\ Gy$
$1\ rem = 1\ cSv = 10^{-2}\ Sv$

表 5　SI 接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

(注)

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eV および 1 u の値は CODATA の1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は，JIS では流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC 閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表2のカテゴリーに入れている。

換　算　表

力	N($=10^5$dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s($N \cdot s/m^2$)＝10 P(ポアズ)(g/(cm·s))

動粘度　$1\ m^2/s = 10^4$ St(ストークス)(cm^2/s)

圧力	MPa(＝10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J($=10^7$ erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal ＝ 4.18605 J (計量法)
　＝ 4.184 J　(熱化学)
　＝ 4.1855 J　(15 °C)
　＝ 4.1868 J (国際蒸気表)

仕事率　1 PS (仏馬力)
　＝ 75 kgf·m/s
　＝ 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86 年 12 月 26 日現在)