日本福岛核电站事故后的海洋放射化学

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摘要:由于对环境影响的关注,日本福岛核电站事故后,人们进行了大气、陆地和海洋环境人工放射性核素变化监测与研究,研究的主要核素是^{131}I、^{137}Cs、^{134}Cs 和^{129}I。除了关注浓度水平的变化外,还进行了通过大气和海流对事故释放的放射性核素运行路径的模拟研究。研究表明,受气候条件的控制,事故释放进入大气的放射性核素先经过太平洋到达北美,然后越过大西洋到达欧洲,最后绕北半球一周后到达中国。除事故核电站周边外,全球大气中^{131}I 活度浓度在 mBq/m^3 量级,^{137}Cs 活度浓度在 0.1~1 mBq/m^3 量级。事故释放进入海洋的放射性核素将随海流向东输运,然后在北太平洋随环流输运。研究也发现在离开源地不远的海区,由于混合进入 200 m 水深以下的次表层水,在远离事故核电站海区水体的^{137}Cs 活度浓度可达 100 Bq/m^3,但大部分水体^{137}Cs活度浓度在 Bq/m^3 量级,仅稍高于本底水平。

关键词:日本福岛;核电站事故;海洋环境;放射化学

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Marine Radiochemistry Progress After Fukushima Daiichi Nuclear Power Plant Accident

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Abstract: Because being paid close attention to environment impact from the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident, artificial radionuclides in the atmosphere, land and ocean were studied and monitored. The main nuclides detected are ^{131}I, ^{137}Cs, ^{134}Cs and ^{129}I. When the concentration levels are measured, the transport path of radionuclides in the atmosphere and ocean were simulated. The results showed that controlling by climate condition, the airborne radionuclides released by FDNPP accident reached America via the Pacific, and then arrived to Europe over Atlantic, and finally transported to China. Over the globe the activity concentration of ^{131}I from FDNPP accident is in the order of magnitude of mBq/m^3, and 0.1-1 mBq/m^3 for ^{137}Cs. The nuclides released to the sea headed eastward with the ocean current and then would circulate in the North Pacific. With mixing, the radionuclides went down to 200 m depth, where not very far from FDNPP. In the open ocean far from FDNPP, the ^{137}Cs activity concentration may be in the order of magnitude of 100 Bq/m^3, but most of waters is in the Bq/m^3 level, only slightly higher than background.

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Key words: Fukushima; nuclear power plant accident; marine environment; radiochemistry

2011 年 3 月 11 日,日本东部近海发生 9.0 级大地震。地震及其引发的海啸导致东京电力公司福岛第一核电站(FDNPP,38.3°N,142.4°E)发生事故,向大气和海洋排放大量放射性物质。这些进入大气和海洋的放射性物质将向何处去,对海洋生态环境的影响如何,成为人们极为关注的问题。

福岛核电站事故后,全球从事放射性监测,核安全,应用放射性核素进行地球化学、海洋学、大气科学、环境科学、生态学研究的机构和科学家总动员,进行了大量监测与研究工作,发表的研究文章与评述文章数以万计,四年来经久不衰。

人们对事故的放射性核素释放量进行了估算[1-16],对大气放射性水平的变化进行了监测[17-54],并对大气放射性物质的输运途径进行了模拟[55-64]。事故后很长一段时间内,人们对事故排放的放射性物质造成的陆地[65-81]和海洋放射性水平的变化[82-120]与放射性核素在海洋中的输运途径[119-128]进行了研究。

日本福岛核电站事故已经过去四年,在人们心中的阴影也逐渐消淡。核事故释放的进入大气的放射性物质或沉积在陆地或沉积在海洋中,除了对核电站周边陆地环境造成严重影响外,即除日本外,对其它国家的环境影响在无关紧要的水平。事故排放入海的放射性物质,基本都在太平洋,量很大;在事故核电站周边海域,短时间的放射性水平也相当高,但显然对具有庞大水体的海洋来说,总体讲也不会产生宏观的影响,而且事故释放的放射性物质也远低于核实验的大气沉降,甚至低于前苏联切尔诺贝利核电站事故和一些后处理厂的排放量[129]。人们对进入海洋的放射性物质的研究除关注海洋中放射性水平的提高外,主要集中在放射性物质在海洋中的输运途径上。也有研究认为该事故对海洋学研究有正效应,例如,事故释放入海的放射性物质可用于示踪北太平洋的环流等[130]。

日本核电站事故后,中国很多单位进行了陆地和大气放射性水平监测[131-153],对放射性物质通过大气和海洋的输运进行了模型预测[126-128],但关于海洋环境放射性研究的报道甚少[95,110,140]。本文对福岛核电站释放的放射性物质、事故后全球各地大气与海水中放射性水平的变化、大气和海洋对放射性核素的输运过程研究进行综述。

1 已探测的事故释放的放射性核素

核反应堆长期运行会产生很多种放射性核素,当发生事故时会释放出来。但是这些核素大部分半衰期很短,所以进入环境并被探测到的核素种数较少。表 1 列出一些研究者报道的日本核电站事故释放的放射性核素,为叙述方便,列出衰变数据[154]。这其中一些核素研究的文章多,而大部分核素的研究文章很少,可以从以下几方面讨论。(1) 大部分被测定的裂变产物衰变发出高能量和高丰度的 γ 射线,例如 ^{131}I、^{134}Cs、^{137}Cs,测定这些核素利用了 γ 谱方法测量核素制样简单、识别直观的优点,所以研究的文章很多。(2) 表 1 中的大部分核素半衰期在天到几十天时间尺度,只能在事故发生的短时间内探测到,从时间上限制了研究的可能性和可操作性。由于这种原因,大多数的海洋放射性水平变化研究的核素是较长寿命的 ^{137}Cs、^{134}Cs 和 ^{90}Sr。(3) 随着质谱技术(包括加速器质谱)的发展,对长寿命的放射性核素,包括 ^{14}C、^{129}I 和超铀元素 Pu、Am 和 Cm 的同位素探测灵敏度极大提高,所以日本福岛核电站事故后出现了这些核素的研究。但除 ^{129}I[3,68,78,81,84-85,141] 和 Pu 同位素[7,30,98,102,117] 外,其它核素的研究较少[98,102]。有两方面的原因,一是质谱技术在环境放射性监测中应用不普及;二是这些长寿命核素的环境水平研究的不够,测量结果是否明显高出本底水平的判断存在或然性。

2 事故放射性释放量与入海通量

2.1 事故放射性物质释放量

日本福岛核电站多个机组在 2011 年 3 月 12 日至 23 日之间发生多次事故,在空间上是点源,在时间上以脉冲形式往环境中多次释放放射性物质,包括气体释放和废水排放,使得释放量(以放射性活度计,A)的估算很困难,但还是有研究者进行了释放量的估算。表 2 列出事故 ^{131}I、^{133}Xe、^{137}Cs、$^{239+240}$Pu 和 ^{241}Pu 的释放量,但没有列出网上数据。由表 2 可知,不同研究者给出的释放量不同,有些核素的差异还较大,从数值上看也有可能是重复引用,但还是能看出福岛核事故以下核素的释放量:$^{239+240}$Pu 在 GBq 量级,^{241}Pu 在 100 GBq 量

级,^{137}Cs 在 10 PBq 量级,^{131}I 在 100 PBq 量级,^{133}Xe 最高,在 10 EBq 量级。

Hou 等[3]通过测定福岛核电站周边近海海水中的^{129}I 分布,估算得到核电站事故直接释放入海的^{129}I 为 2.35 GBq,大气沉降入海的为 1.09 GBq,核事故总的^{129}I 释放量为 8.06 GBq (1.2 kg)。Steinhauser 等[9]将福岛核电站事故的放射性释放量与切尔诺贝利核电站事故进行了比较发现:易挥发核素,包括惰性气体、碘、铯和碲,切尔诺贝利事故的释放量比福岛事故高一个量级;而锕系核素,福岛核事故比切尔诺贝利事故低 4 个量级;除惰性气体外,切尔诺贝利事故总放射性释放量为 5 300 PBq,福岛事故为 340～800 PBq。

表 1　已探测的源于福岛核电站事故的放射性核素衰变数据

Table 1　Decay data of radionuclides detected from FDNPP accident

核素 (Nuclides)	半衰期 (Half-life)	衰变类型 (Decay mode)	主要射线能量(Energy of main ray)/ keV(分支比(Yield))	部分文献 (Some references)
^{3}H	12.3 a	β^-	β^-:18.6(100%)	[54]
^{14}C	5 730 a	β^-	β^-:156(100%)	[80]
^{35}S	87.38 d	β^-	β^-:166.8(100%)	[88]
^{89}Sr	50.5 d	β^-	β^-:1 495(99.99%)	[83]
^{90}Sr	28.8 a	β^-	β^-:546(100%)	[83]
^{95}Nb	35 d	β^-	β^-:159.8(100%);γ:765.8(99.8%)	[46]
^{110}Ag^{m}	249.8 d	β^-	β^-:83.5(66.8%),530.3(30.45%); γ:657.8(94.4%),884.7(74%)	[74]
^{129}Te^{m}	33.6 d	β^- 内转换(Internal conversion, IT)	β^-:1 603(31.8%);β^-:695.9(3.1%); X:27.5(15%)	[46]
^{132}Te	3.204 d	β^-	β^-:215(100%);γ:49.7(15%),228.2(88%); X:28.6(38.5%),32.3(13.5%)	[133]
^{129}I	1.57×10^{7} a	β^-	β^-:154(100%);γ:39.5(7.51%); X:29.5+29.8(56.9%)	[81]
^{131}I	8.02 d	β^-	β^-:606.3(89.9%); γ:284.3(6.14%),364.5(81.7%),637.0(7.17%)	[26]
^{133}Xe	5.29 d	β^-	β^-:346(99%);γ:81.0(38%);X:31(26.2%)	[133]
^{134}Cs	2.06 a	β^-	β^-:88.6(27.3%),657.9(70.23%); γ:604.7(97.6%),795.9(85.5%)	[26]
^{136}Cs	13.2 d	β^-	β^-:341.1(70.3%),408.0(10.5%),681.6(13%); γ:818.5(99.7%),1 048(80%),1 235.4(20%)	[46]
^{137}Cs	30.2 a	β^-	β^-:514(94.4%),1 176(5.6%); γ:661.7(85%)	[26]
^{238}Pu	87.7 a	α	α:5 456.3(28.98%),5 499.0(70.91%)	[103]
^{239}Pu	24 110 a	α	α:5 105.8(11.5%),5 144.3(15.1%), 5 156.6(73.3%)	[97]
^{240}Pu	6 564 a	α	α:5 123.7(26.4%),5 168.2(73.5%)	[97]
^{241}Pu	14.29 a	β^-	β^-:20.8(100%)	[97]
^{241}Am	432.2 a	α	α:5 442.9(13.3%),5 485.6(85.1%); γ: 59.5(35.8%)	[103]
^{242}Cm	162.8 d	α	α:6 069.4(25.9%),6 112.7(74.1%)	[103]
^{243}Cm	29.1 a	α	α:5 742.1(11.5%),5 785.2(73.2%)	[103]
^{244}Cm	18.1 a	α	α:5 762.7(23.6%),5 804.8(76.4%)	[103]

表 2 估算的福岛核事故放射性释放量

Table 2 Estimated discharges from FDNPP accident

气态/液态 (Gas/Liquid)	$A(^{131}I)$/PBq	$A(^{133}Xe)$/EBq	$A(^{137}Cs)$/PBq	$A(^{239+240}Pu)$/GBq	$A(^{241}Pu)$/GBq	文献 (References)
气态(Gas)			24.4			[8]
液体入海(Liquid into sea)			12～41			[1]
气态(Gas)	150		12			[2]
气态(Gas)				1.0～2.4	110～260	[7]
液态(Liquid)			5.1～5.5			[4]
气态(Gas)		15.3	36.6			[5]
		12.2～18.3	20.1～53.1			
气态(Gas)	65.2～380		6.1～62.5			[9]
	190～380		12			[10]
	120～380		6～53			[12]
			5.5～9.7			[14]

2.2 不同核事件释放的放射性核素入海量比较

至今,核试验落下灰仍然是全球环境中最主要的人工放射性贡献者,其次依次是切尔诺贝利核事故、放射性废物处置、后处理厂排放和福岛核事故。在进入海洋的源项中,也是以核试验落下灰为主,其次是海洋放射性废物处置、后处理厂排放和核事故排放,福岛核事故和切尔诺贝利核事故释放入海的放射性物质在同一水平。不同核事件^{137}Cs释放量($A_0(^{137}Cs)$)与入海量估算值($A(^{137}Cs)$)列入表 3。切尔诺贝利事故向环境排放的放射性物质远高于福岛核事故,但由于切尔诺贝利远离海洋,可以预见,事故释放的放射性物质大都沉积在陆地上,事实是事故后东、北欧,特别是波罗地海周边地区陆地沉积了大量放射性物质。福岛核电站位于东海边,加上事故发生时盛行西风,所以,事故释放的气载放射性物质约 70%～80%沉降在西太平洋[116]。而液体的排放也都进入海洋。

表 3 不同核事件^{137}Cs释放量与入海量估算值

Table 3 Discharges and the amount into sea for ^{137}Cs from nuclear events

事件(Events)	$A_0(^{137}Cs)$/PBq	$A(^{137}Cs)$/PBq	文献(References)
核试验(Nuclear test)	948	603	[129]
Sellafield 后处理厂排放(Discharge from Sellafield)	38.8	38.8	[129]
Cap de La Hague 后处理厂排放(Discharge from Cap de La Hague)	0.96	0.96	[129]
切尔诺贝利核电站事故(Chernobyl accident)	85	15～20	[155-156]
海洋放射性废物处置(Sea dumpling)		78～82	[1]
福岛核电站事故(FDNPP accident)		12～41	[1]

3 事故后不同海域放射性核素浓度水平变化与输运

3.1 福岛核电站邻水体放射性浓度变化

事故后先是气载放射性物质的沉降,接着是放射性废液排放入海,使核电站周边海域水体放射性水平明显提高。3 月 24 日前在距核电站 10 km远的两个采样点,海水中的^{137}Cs浓度分别为 9～13 Bq/L 和 20～100 Bq/L。在 3 月 26 日至 4 月 8 日,由于放射性废液的排放,使核电站邻近海域水体平均^{137}Cs活度浓度水平达 1.57×10^4 Bq/L,最高水平达 6.8×10^4 Bq/L,海水中

的^{137}Cs 浓度升高三个量级。由于海洋巨大的稀释能力,在一个月之后,核电站邻近 2 km 以内,水体中的^{137}Cs 活度浓度降低至 10^2 Bq/L 水平,2 个月后降至 10 Bq/L 量级水平[1]。

3.2　远离福岛核电站海域水体中放射性核素浓度变化

3.2.1　^{134}Cs 和^{137}Cs　开阔海域,包括日本沿岸,水体中的^{137}Cs 活度浓度本底水平为 1～4 Bq/m^3[157]。由于半衰期仅 2.06 a,除核设施周边海域外,全球大部分海域探测不到^{134}Cs,太平洋探测到的^{134}Cs 来自福岛核事故。事故发生至今,人们对北太平洋海水的^{134}Cs 和^{137}Cs 进行了广泛研究[86,92-94,104-108,113-116]。在一些研究中给出了比本底高得多的^{137}Cs水平。Povinec 等[89]给出在距事故核电站 30～600 km 海域水体中的^{137}Cs 活度浓度为 1.8～3 500 Bq/m^3,^{134}Cs/^{137}Cs 活度比接近 1。Men 等[110]给出西北太平洋、包括台湾海峡和巴士海峡水体中的^{134}Cs和^{137}C活度浓度分别为 ND(未探测到)～9.68 Bq/m^3 和 0.41～18.1 Bq/m^3。Kaeriyama 等[93]给出的北太平洋^{134}Cs和^{137}Cs活度浓度为 10～153 Bq/m^3。从空间和时间分布上看,每个研究者或不同研究者给出的结果离散较大,这是由于放射性液体随时间呈脉冲式排放,并随水团在海洋中运移,受污染的水体放射性浓度较高,未受污染水体放射性浓度则较低。Povinec 等[89]和 Men 等[110]的研究均发现在约 200 m 水深,存在^{137}Cs 浓度极大值。

3.2.2　^{129}I　日本福岛核电站事故后,人们对海洋中的^{129}I 进行了研究,这是以往核事故中很少见的。Tumey 等[85]于事故后的 2013 年 5 月在北太平洋采样,测定了海水中的^{129}I,给出 2013 年 5—6 月海水中的^{129}I/^{127}I 原子比为(2.16～5.16)×10^{-11}。天然丰度^{129}I/^{127}I 原子比为 10^{-12},由于核工业的发展,使海洋上层水^{129}I/^{127}I 原子比水平提高,所以,从数值分布并不能看出核电站事故对太平洋^{129}I 水平的影响,可能是大气沉降量有限,而液体排放的放射性物质还未运移到研究海区。Hou 等[3] 2011 年 6 月 3—17 日从福岛核电站向东 40～530 km 远的太平洋采样,给出海水中无机^{129}I/^{127}I 原子比为(0.26～21.95)×10^{-10},稍高于中太平洋约一个量级。Suzuki 等[84]对核电站事故发生前后邻近海域^{129}I 水平进行了调查,给出事故前表层水^{129}I/^{127}I原子比为(3.13～6.38)×10^{-11};事故后为(4.47～362)×10^{-11}。平均看事故后的^{129}I 浓度比事故前升高近 8 倍。

3.3　放射性物质在海洋中的输运

福岛核事故发生后一段时间,释放进入海洋的放射性物质存在于距离核电站很近的海域。有一些研究者依据大洋环流格局,用数值模拟的方法估算了福岛核事故释放入海的放射性物质在海洋中可能的运移路径和预期到达某海域的时间[126-127]。在福岛核电站邻近的北太平洋,黑潮与亲潮流交汇后形成向东的北太平洋暖流,所以可以大致估算得核事故释放的进入海洋的放射性物质将随北太平洋暖流输运。

Aoyama 等[119]在太平洋 38°N—42°N、121°E—120°W 海域,于 2011 年 3 月至 2012 年 3 月,采样研究水体中的^{134}Cs 和^{137}Cs,发现放射性水团主体沿 40°N 纬度线输运。在 2012 年 3 月到达国际日期变更线,并推算出北太平洋暖流流速达 8 cm/s,低于黑潮流流速 20 cm/s。

3.4　事故液体排放使北太平洋放射性水平的提高

设北太平洋的面积占整个太平洋面积的1/3,福岛核事故输入的放射性在北太平洋混合层(设为 100 m)均匀分布,可以计算得福岛核事故将使北太平洋^{137}Cs 活度浓度提高 4.5 Bq/m^3。当然 Pevinec 等[89]的综述认为福岛核事故输入到太平洋的放射性可能比 27 PBq 要低一个量级,这样算下来,福岛核事故使北太平洋^{137}Cs 活度浓度提高 0.45 Bq/m^3。但是,可以预期的是核事故排放的放射性实际使开阔海域放射性水平的提高非常有限,原因是铯是亲岩元素,极易吸附在粘土矿物上沉积进入沉积物,这个过程在近岸海域特别重要。实际上大气层核试验造成的海洋放射性水平的提高也远低于估算的输入总量在全球海洋的平均值。

4　事故后大气放射性核素浓度与入海通量

大部分研究者报道大气气溶胶样品中探测到^{131}I、^{134}Cs 和^{137}Cs;一些研究者报道还探测到^{132}Te。一些实验室报道探测了^{133}Xe(表 1)。除气体核素将在大气中衰变掉外,其余核素最终归宿或是在大气中衰变掉,或是沉降到陆地和海洋。

4.1　事故后大气中放射性核素的浓度

事故发生后,全球大气中测量的^{131}I、^{134}Cs、^{137}Cs和^{133}Xe 水平列入表 4 。由表 4 可知:日本本土大气中的放射性浓度最高,^{131}I、^{134}Cs 和^{137}Cs 活度浓度在 Bq/m^3 量级,比其它地区高 2～3 个量

级;美国的^{131}I 最大活度浓度为 103.6 mBq/m^3,加拿大的最大活度浓度为 9.76 mBq/m^3;欧洲探测到的^{131}I 最大活度浓度为 6.0 mBq/m^3;中国大气中^{131}I 活度浓度小于 7.9 mBq/m^3;美国探测到大气中^{134}Cs 和^{137}Cs的最大活度浓度分别为 3.44、3.40 mBq/m^3;加拿大和欧洲探测到这两个核素的最大活度浓度均低于 1 mBq/m^3;大气氡活度浓度约在 10 Bq/m^3 量级,所以福岛核电站事故对远离日本的公众增加的辐射剂量极为有限。

未受污染大气中人工放射性核素浓度很低,所以大部分研究并未考虑非事故情况下大气本底的影响。研究表明:这种影响是存在的,樊元庆等[135]研究了 2006 年 11 月—2010 年 6 月北京地区大气气溶胶^{137}Cs 的活度浓度为 0.77～25.42 μBq/m^3,而同时期^{131}I 活度浓度为 1.17～1 704 μBq/m^3。两个核素的浓度与研究者报道的核事故影响条件下大气气溶胶中两个核素的浓度(表 4)在可比较的水平。

4.2 放射性物质通过大气的输运

东亚,从日本到东海,再到南海,属季风气候,冬季盛行东北风,风由日本吹向中国的东海,经台湾海峡吹向南海北部;夏季盛行东南风,风由南海

表 4 福岛核电站事故后世界各地大气中放射性核素的活度浓度

Table 4 Activity concentration of radionuclides in the atmosphere over the world following FDNPP accident

地区 (Area)	采样日期 (Date)	气态或气溶胶 (Gas or aerosol)	$C(^{131}I)$/ (mBq·m^{-3})	$C(^{134}Cs)$/ (mBq·m^{-3})	$C(^{137}Cs)$/ (mBq·m^{-3})	$C(^{133}Xe)$/ (mBq·m^{-3})	文献 (References)
日本(Japan)	3.15—3.19		3 000～5 800	100～1 400	140～3 000		[26]
美国(US)	3.14—4.27		0.004～103.6	ND～3.44	ND～3.40		[26]
加拿大(Canada)	3.17—3.31		0.01～9.76		ND～0.04	ND～2 000	[26]
欧洲(Europe)	3.8—4.11		ND～6.0	ND～0.13	ND～1.0		[26]
中国北京 (Beijing, China)			ND～5.98			ND～945	[134]
中国贵阳 (Guiyang, China)	3.17—4.28		2.4～7.9		0.02～0.07		[136]
中国西安 (Xi'an, China)			ND～3.92	−0.26	ND～0.31	5 500	[133]
中国西部某地 (Somewhere, China)		气溶胶(Aerosol)	ND～0.95	ND～0.25	ND～0.24	ND～100	[137]
中国山西 (Shanxi, China)		气溶胶(Aerosol)	0.052～5.02	<0.026～0.48	<0.022～0.52		[138]
		气态(Gas)	0.34～2.89				
中国广州 (Guangzhou, China)			0.028～1.5	0.014～0.076	0.014～0.076		[131]
中国深圳 (Shenzhen, China)		气溶胶(Aerosol)	0.05～0.52	0.036～0.090	0.030～0.11		[131]
中国浙江 (Zhejiang, China)		气溶胶(Aerosol)	<0.012～1.2	<0.002～0.5	<0.002～1.1		[132]
		气态(Gas)				4 600	
中国台湾 (Taiwan, China)			0.014～0.588	0.001 9～1.12	0.002 4～1.44		[43]
中国(China)			<0.012～7.9	<0.002～0.48	<0.002～1.44	945～5 500	

注(Note):ND 为未探测到(ND means no detected)

经台湾海峡吹向东海,再吹向日本。日本福岛核电站事故发生在早春,本来的东北风提前转向为西南风。整体看,在事故发生后一段时间内,受当时气象条件的控制,福岛核事故释放的气载放射性核素会穿过太平洋,到达北美洲大陆后,再穿过大西洋到达欧洲,然后经西亚到达东亚。漂移过程中一路沉降,输运距离越远,放射性浓度越低。

福岛核电站事故多次释放放射性物质到环境中。第一次发生在 2011 年 3 月 12 日,3 月 14 日污染气团到达俄罗斯东部。向东的放射性气团漂过太平洋 17 日到达美国西海岸,之后穿过北美洲和北大西洋,3 月 19 日和 20 日冰岛一个站点探测到放射性物质,并且污染气团到达斯堪的纳维亚北部,23 日欧洲很多国家探测到福岛核电站事故释放的放射性;中国 27 日报道探测到来自福岛核电站事故的放射性[136]。从事故发生的 15 天,福岛核事故释放的放射性物质弥散遍及整个北半球,而且以赤道为界,事故发生的四周内放射性物质局限于北半球。到 4 月 13 日,在南半球的亚洲太平洋地区,澳大利亚、裴济、马来西亚和巴布亚新几内亚探测到福岛核电站事故的放射性,但短寿命的核素^{131}I和^{133}Xe水平已很低[26]。

4.3　释放进入大气的放射性核素的入海量

研究认为福岛核电站事故的气载放射性物质 19%沉积在日本,仅 2%沉积在亚洲和北美洲,其余主要部分沉积在太平洋[25]。根据表 4 的数据,假设大气中的^{137}Cs活度浓度为 10 mBq/m^3,按受污染大气厚度为 1 000 m 计算,如果这些放射性全部沉积在地表或海洋表面,在混合层混合均匀,可以计算得海洋中^{137}Cs活度浓度水平提高为 0.05 Bq/m^3,比目前海洋中的^{137}Cs本底水平低 2 个量级。

5　结语与展望

(1) 核事故会使大范围环境放射性水平提高,但远离事故核电站或核设施地区的放射性水平变化极为有限。福岛核电站事故后全球的环境监测结果也说明这一点,除日本本土外,其它国家报道的大气中^{131}I的活度浓度大都低于 10 mBq/m^{3}量级,而^{134}Cs和^{137}Cs活度浓度大都低于 mBq/m^3 量级。以后的研究工作可能要集中在日本周边海域,包括放射性水平、生物效应和核素化学形态变化等。

(2) 日本核电站事故是一次研究北太平洋环流的很好机会,也是研究北半球大气环流的难得机会。海洋放射化学未来最重要的研究方向是人工放射性核素的海洋生物地球化学。这是人们迫切想知道福岛核电站事故对环境影响应当选择的研究方向。

(3) 核反应堆事故排放最多的放射性核素是^{3}H和^{14}C,但却很少有测量^{3}H和^{14}C的报道。原因是采用计数方法测量这两个核素的采样量大,样品预处理方法困难,将加速器质谱方法应用于环境样品测量可解决该问题。另外,由于对^{131}I剂量影响的关注,人们迫切想了解事故造成的某地^{131}I的沉降量,但由于^{131}I半衰期仅 8 d,事故后很快衰变殆尽,为此人们提出用长寿命的^{129}I作为替代物[88,158],而环境中的^{129}I测量也需要加速器质谱方法。

(4) 放射性监测的重要性在于通过监测避免事故的发生,也就是说常规监测比应急监测更重要,即低水平——环境水平的放射性测量更重要。目前的问题是要解决环境监测中存在的困难。对于事故后环境放射性水平和对环境影响的研究,应开展长寿命核素,如^{14}C、^{129}I等的研究。由于加速器质谱方法日臻成熟,开展这方面的工作已具备了条件。

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