

# 乏燃料水池转运舱氦质谱检漏技术的应用

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**摘要:** 乏燃料水池转运舱是核电站乏燃料水池的组成部分, 用于存放燃料组件倒料设备和水。监测乏燃料水池转运舱的水的泄漏率, 通过气体和水的泄漏率转换, 分析和计算出氦气检漏的泄漏率范围, 并建立检测区域模型, 优化检测范围和流程, 通过范围查找和精确查找的结合, 快速和准确地找到泄漏位置, 以为乏燃料水池的查漏工作提供经验。

**关键词:** 乏燃料水池; 氦质谱; 检漏

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## Application of helium mass spectrometry leak detection technology in spent fuel pit transfer cabin

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**Abstract:** The spent fuel pit transfer module is mainly a part of spent fuel pit of nuclear power plant, which is used to store fuel assembly materials and water. This paper outlines the monitoring of the leak rate of fluid water, predicts the leak rate range of helium gas leak detection through the conversion of gas and water leak rate, establishes the inspection area model, optimizes the inspection scope and process, finds the leak location quickly and accurately through the combination of range search and accurate search, and provides some experience for the leak detection of spent fuel pit.

**Key words:** spent fuel pit; helium mass spectrometry; leak test

核电站乏燃料水池转运舱如果出现超过系统规定限值的放射性物质泄漏, 会引起污染区域扩散, 人员受辐射剂量增加, 从而带来一定的核安全风险。因此, 研究乏燃料水池的泄漏问题, 并制定相应的检测方案, 查找出泄漏位置是很有必要的。

## 1 检测对象的结构

核电厂乏燃料转运舱水池属核安全二级设备。是转运核燃料组件的区域。为防止放射性含硼水泄漏, 混凝土水池内壁会设计有一层钢衬里, 通常称钢覆面。钢覆面以混凝土墙或底板中预埋的支撑骨架为垫板进行组对焊接。整个乏燃料转运舱水池为长方体形状, 池底部有一台倒料机, 其在换料期间转运

燃料组件, 负载运作, 对池底钢敷面施加压力, 转运舱结构示意见图 1。在转运舱底部有一引流管, 用于收集从水池钢覆面泄漏出的水。

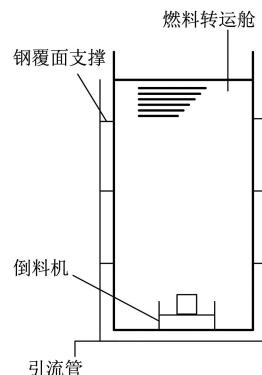


图 1 乏燃料转运舱结构示意图

## 2 泄漏理论分析

水池转运舱的工作介质为水, 检测使用的介质为空气和氦气, 故需将液体的泄漏率转换为气体的

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泄漏率,转换公式如式(1)所示。

$$Q_q = Q_y \frac{\bar{p} \eta_y}{p_F \eta_q} \quad (1)$$

式中: $Q_q$  为气体最大容许体积漏率,  $\text{m}^3 \cdot \text{s}^{-1}$ ;  $Q_y$  为液体最大容许体积漏率,  $\text{m}^3 \cdot \text{s}^{-1}$ ;  $p_F$  为环境大气压,  $\text{Pa}$ ;  $\bar{p}$  为漏孔的平均压力,  $\bar{p} = (p_1 + p_2)/2$ ,  $\text{Pa}$ ;  $p_1$  为漏孔入口端压力,  $\text{Pa}$ ;  $p_2$  为漏孔出口端压力,  $\text{Pa}$ ;  $\eta_y$  为液体动力黏度,  $\text{Pa} \cdot \text{s}$ ;  $\eta_q$  为气体动力黏度,  $\text{Pa} \cdot \text{s}$ 。

对比正常大气压下的气体泄漏率,可换算出不同气体的泄漏率,但其并不能反映真实的泄漏率,目前对流体的泄漏率测量还没有一个较为精确的手段。文章采用估算的公式来计算的泄漏率。

水池转运舱的工作介质为水,监测到在 8 h 内,水的泄漏量为 50 ml。工作压力  $p_1 = 1.2 \times 10^5 \text{ Pa}$ , 环境大气压力  $p_F = p_2 = 10^5 \text{ Pa}$ , 水的动力黏度为  $\eta_y = 1.01 \times 10^{-3} \text{ Pa} \cdot \text{s}$ , 水池深度为 12 m, 池底的平均压力  $\bar{p} = 1.1 \times 10^5 \text{ Pa}$ 。

根据式(1),氦气的动力黏度  $\eta_q = 1.89 \times 10^{-5} \text{ Pa} \cdot \text{s}$ , 可得  $Q_q = Q_y \frac{\bar{p} \eta_y}{p_F \eta_q} = 1.005 \times 10^{-2} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ , 即该系统用氦气检漏时,泄漏率为  $1.005 \times 10^{-2} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ 。

空气的动力黏度为  $\eta_q = 1.84 \times 10^{-5} \text{ Pa} \cdot \text{s}$ , 可得  $Q_q = 1.035 \times 10^{-7} \times 10^{-2} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ , 即该系统用空气检漏时,泄漏率为  $1.035 \times 10^{-2} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ 。

### 3 检漏难点和方法选择

乏燃料水池的检漏受以下几个因素影响。

(1) 残留水干扰。乏燃料水池转运舱泄漏后,水池钢敷面与混凝土墙会残留大量流出水,在现有条件下,无法去除这些残留水,从而对检测产生较大影响。

(2) 池壁冷凝水干扰。核电站位于沿海地带,空气湿度大,盐分含量高,空气中的水份易在池壁内壁凝结成水,长时间后形成水滴,存在堵塞泄漏口的可能性。

(3) 检测灵敏度问题。通过液体泄漏率换算出的气体泄漏率为  $1.005 \times 10^{-2} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ , 则所选择的检漏方法灵敏度要高于  $10^{-3} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$  (要高于所测泄漏率一个数量级)。

(4) 池壁尺寸因素。水池尺寸为深 12 m, 长 15 m, 宽 3 m, 池壁的面积大会延长检测人员的工

作时间,而增加其受辐射风险。

(5) 沾污风险。该乏燃料水池转运舱已服役,池壁表面有放射性物质,存在放射性污染,增加了检漏工作的实施难度和风险。

(6) 本底干扰。水池为半开口式结构,采用氦气为示踪气体时,会干扰仪器的显示值。

(7) 钢敷面承压。钢敷面设计时,承受正向压力,并不能承受背面(指钢覆面与水接触面的反面)的正向压力。

通过分析,对以上的难点可采取以下的应对措施:对于(1)中的问题,可以排空水池中的水并空置 2 个月,以使残留水尽可能减少;对于(2)中的问题,可将检测时机选择在秋冬季,如来年 2 月前,此时空气中水蒸气少,湿度对于泄漏率的影响会降低;对于(3)中的问题,可采用真空罩气泡法和质谱仪吸枪氦罩法来解决,这两种方法采用空气和氦气等作为特征气体,对钢覆面无腐蚀,且空气和氦气不易残留,较易排空,后期处理简单;对于(4)和(5)中存在的问题,应用核电站积累的相关工程经验可以消除。

综上所述,可采用的方法为真空罩气泡法和质谱仪吸枪氦罩法,真空罩气泡法的最小检测灵敏度为  $10^{-5} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ , 质谱仪吸枪氦罩法最小检测灵敏度为  $10^{-9} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ 。第一步采用真空罩气泡法对钢覆面的焊缝进行检测,如未发现缺陷,扩大检测范围;第二步将水池底面与侧面的母材和焊缝,分成数个检测区域,每个区域相互隔离,避免气体逸散,采用氦罩法对池壁进行检测,快速查寻到泄漏的大致范围后,再采用真空罩气泡法进行精确定位。

#### 3.1 氦质谱仪吸枪氦罩法检测原理

氦质谱仪吸枪氦罩法检测设备主要由氦质谱仪、吸枪和辅助泵、塑料膜、氦气等组成(见图 2)。其基本原理是用塑料膜将被检件的外部覆盖住,以保证其密封性,被检件的内部充入一定的氦气,吸枪插入塑料膜内进行检测,如果有泄漏,氦质谱仪读数超过本底值,表明被塑料膜覆盖的区域有泄漏。吸枪氦罩法的检测灵敏度为  $10^{-2} \sim 10^{-9} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ 。吸枪检漏时,检漏仪的反应值与检漏仪的入口压力和收集包的体积无关<sup>[1]</sup>,故可以采用面积较大的塑料膜覆盖钢覆面,使用数量较少的塑料收集包,在较快的时间内完成塑料收集包的制作。实际泄漏率可由式(2)得到。

$$Q_L = K \cdot Q_s / \beta \quad (2)$$

式中: $Q_L$  为实际泄漏率;  $K$  为机器因子;  $Q_s$  为仪器读数;  $\beta$  为氦气浓度。

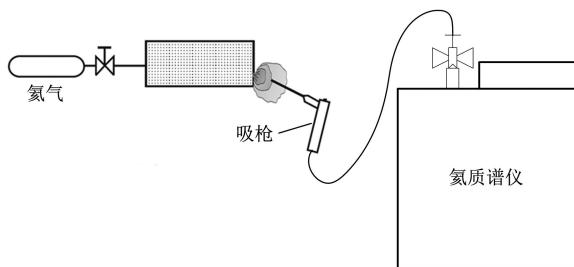


图 2 氦质谱仪吸枪氦罩法检测设备框图

### 3.2 真空罩法检测原理

真空罩检漏技术属于气泡泄漏检漏法的一种,检漏设备主要由真空罩、真空泵、真空表、放气阀等组成<sup>[2]</sup>。该方法主要用于检测不能直接加压的承压部件的泄漏。其原理和基本方法为:在被检部件局部区域涂刷起泡剂,并在其上放置真空罩,对真空罩抽真空以使局部区域的内外两侧形成压力差,如果被检部件中存在穿透性缺陷,则缺陷位置处的起泡剂会因气体通过而形成气泡,气泡冒出的位置可判定为漏孔位置,根据泄漏点气泡的大小和出现频次可判断泄漏程度。真空罩气泡法的灵敏度为  $10^{-4} \sim 10^{-5} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ ,其检测原理示意如图 3 所示。

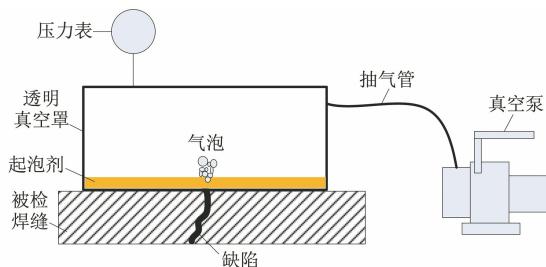


图 3 真空罩气泡法检测原理示意

气泡位于液面上方时,气泡内的压力  $P_b$  可用式(3)表示。

$$p_b = p_a + 4\sigma/D_b \quad (3)$$

式中: $D_b$  为测得气泡的直径;  $\sigma$  为表面张力系数;  $p_a$  为大气压力。

对于检测温度  $T$  和气泡内的压力  $P_b$ ,泄漏率如式(4)所示。

$$L = n \cdot \frac{\pi}{6} D^3 \quad (4)$$

式中: $n$  为气泡形成的频率;  $D$  为气泡直径。

折算到标准状态下气体的泄漏率为(对于液面上方的气泡)<sup>[3]</sup>

$$L_s = \frac{T_s}{T} \frac{P_b}{P_s} = \frac{\pi n}{6} \frac{T_s}{T} \frac{P_a + 4\sigma/D_b}{p_s} D_b^3 \quad (5)$$

式中: $T_s, P_s$  分别为标准状态下的温度,气压。

由式(3)~(5)可以推导出气泡泄漏法检测时的泄漏率,但并不是很精确,其可以作为一个参考值来研判泄漏率的数量级。

### 4 检测分区的建立

先采用真空罩气泡法对钢覆面焊缝进行检测,若未发现缺陷,扩大检测范围,再次用氦质谱仪吸枪氦罩法进行检测。

#### 4.1 真空罩气泡法检测分区的建立

真空罩气泡法操作方便,对检测顺序的要求不高,对钢覆面焊缝采用自上而下的方式进行检测。

#### 4.2 氦质谱仪吸枪氦罩法检测分区的建立

参考文献[1]中提到①吸枪法可以对单点泄漏率进行定量检测;②吸枪检漏时,检漏仪的反应值与检漏仪的入口压力和收集包的体积无关;③收集包的体积与检漏仪的入口压力会影响测试的时间,为缩短吸枪检漏的周期,可以采用较小的收集体积和较大的入口压力。

由于转运舱钢覆面的检测区域较大,故收集包采取以下的分布方案:①对于压应力小的区域采用体积大的塑料收集包;②对于压应力大的区域采用体积小的塑料收集包。

根据钢敷面的结构以及流体的流向,将其分为三个大区域,分别为 W、B、F,其中 W 区为侧面墙壁,分为 12 个小区;B 区为底面,分为 12 个小区;F 区为前部和尾部,分为 4 个小区,具体分布如图 4 所示。可见,W 区靠近引流管,F 区距离引流管较远,B 区与引流管距离最近,B 区采用体积大的收集包,W 区和 F 区采用体积小的收集包。

		F1	F2
W1	B1	B2	W12
W2	B3	B4	W11
W3	B5	B6	W10
W4	B7	B8	W9
W5	B9	B10	W8
W6	B11	B12	W7
		F3	F4

图 4 检测分区示意

### 5 检测结果

#### 5.1 真空罩气泡法的检测结果

采用表 1 所示的检测参数,实施检测(检测时间为 2018 年 4 月)。

表1 真空罩气泡法的检测参数

名称	参数
真空罩体积/L	6
抽气泵抽速/(L·s <sup>-1</sup> )	60
真空表量程/精度/MPa	0~ -0.01/0.005
压力/MPa	-0.055
保压时间/s	30
环境剂量/( $\mu$ SV·h <sup>-1</sup> )	50

对高度 2 m 以下的钢覆面焊缝检测未发现气泡。

## 5.2 氦质谱仪吸枪氦罩法的检测结果

检测参数见表 2, 检测时间为 2019 年 1 月份。

充入氦气 40 L, 体积浓度为 15%, 充入完成后, 5 min 内收集包的数据如表 3 所示。

表2 氦质谱仪吸枪氦罩法的检测参数

名称	参数
氦质谱检漏仪最小可检漏率/(Pa·m <sup>3</sup> ·s <sup>-1</sup> )	$1.7 \times 10^{-10}$
数字压力计量程/MPa	量程 0~1, 精度 0.05
标准漏孔	出口 10 Pa, 漏率: $2.9 \times 10^{-8}$ Pa·m <sup>3</sup> ·s <sup>-1</sup>
机器因子	1 000
环境剂量/( $\mu$ S·V·h <sup>-1</sup> )	50

充入氦气 40 L, 体积浓度为 15%, 充入完成后, 20 min 内收集包的数据如表 4 所示。

表3 5 min 内收集包的泄漏显示值

Pa·m <sup>3</sup> ·s <sup>-1</sup>			
区域名称	显示值	区域名称	显示值
W1	$5.8 \times 10^{-8}$	B1	$5.8 \times 10^{-8}$
W2	$6.0 \times 10^{-8}$	B2	$6.0 \times 10^{-8}$
W3	$6.0 \times 10^{-8}$	B3	$5.8 \times 10^{-8}$
W4	$6.3 \times 10^{-8}$	B4	$5.9 \times 10^{-8}$
W5	$8.6 \times 10^{-8}$	B5	$5.8 \times 10^{-8}$
W6	$5.9 \times 10^{-8}$	B6	$5.8 \times 10^{-8}$
W7	$5.8 \times 10^{-8}$	B7	$8.7 \times 10^{-8}$
W8	$5.8 \times 10^{-8}$	B8	$6.1 \times 10^{-8}$
W9	$6.0 \times 10^{-8}$	B9	$4.8 \times 10^{-6}$
W10	$5.8 \times 10^{-8}$	B10	$9.1 \times 10^{-8}$
W11	$6.2 \times 10^{-8}$	B11	$8.3 \times 10^{-8}$
W12	$5.8 \times 10^{-8}$	B12	$6.9 \times 10^{-8}$
F1	$8.9 \times 10^{-9}$	F3	$7.2 \times 10^{-8}$
F2	$9.3 \times 10^{-9}$	F4	$6.8 \times 10^{-8}$

根据采集所得的数据, 得出如图 5 所示的泄漏区域分布示意图, 从图 5 可知, 以 B9 区域为中心, B7、B10、B11 以及 W5 共 5 个区域存在泄漏的可能性, 根据文

献可知, 0.1 mm 的泄漏孔对应着  $10^{-1}$  Pa·m<sup>3</sup>·s<sup>-1</sup> 泄漏率, 0.01 mm 的泄漏孔对应着  $10^{-3}$  Pa·m<sup>3</sup>·s<sup>-1</sup> 泄漏率, 0.1 mm 和 0.01 mm 的泄漏孔可以通过肉眼观察到, 分析有以下的可能性: ① B9、B7、B10、B11、W5 这 5 个区域都有泄漏, 但是泄漏点的泄漏率不超过  $10^{-4}$  Pa·m<sup>3</sup>·s<sup>-1</sup>, 为多个小泄漏点的累积泄漏; ② B9 区域存在大的泄漏点, 因收集包和固定胶布固有的密封性问题, 收集包的密封性能不足以密封住氦气, 存在氦气弥散至附近区域的现象, B7、B10、B11、W5 区域的显示值高于本底是受到了 B9 区域泄漏点的影响。

表4 20 min 内收集包的泄漏显示值

		Pa·m <sup>3</sup> ·s <sup>-1</sup>	
区域名称	显示值	区域名称	显示值
W1	$5.8 \times 10^{-8}$	B1	$5.8 \times 10^{-8}$
W2	$6.0 \times 10^{-8}$	B2	$5.8 \times 10^{-8}$
W3	$6.0 \times 10^{-8}$	B3	$5.8 \times 10^{-8}$
W4	$6.3 \times 10^{-8}$	B4	$5.8 \times 10^{-8}$
W5	$3.4 \times 10^{-7}$	B5	$5.8 \times 10^{-8}$
W6	$5.9 \times 10^{-8}$	B6	$5.8 \times 10^{-8}$
W7	$5.8 \times 10^{-8}$	B7	$2.4 \times 10^{-7}$
W8	$5.8 \times 10^{-8}$	B8	$5.8 \times 10^{-8}$
W9	$6.0 \times 10^{-8}$	B9	$5.4 \times 10^{-6}$
W10	$5.8 \times 10^{-8}$	B10	$3.6 \times 10^{-7}$
W11	$6.2 \times 10^{-8}$	B11	$4.1 \times 10^{-7}$
W12	$5.8 \times 10^{-8}$	B12	$6.9 \times 10^{-8}$
F1	$8.9 \times 10^{-9}$	F3	$7.2 \times 10^{-8}$
F2	$9.3 \times 10^{-9}$	F4	$6.8 \times 10^{-8}$

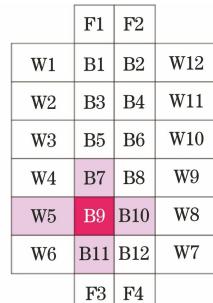


图5 泄漏区域分布示意图

通过重新测量, 找到位于池底母材上的区域 B9, 仪器读数为  $6 \times 10^{-6}$  Pa·m<sup>3</sup>·s<sup>-1</sup>, 超过本底 3 个数量级, 机器因子为 1 000。机器因子是在内部校准后要考虑的检漏仪与测量模式以及使用的测量模式 (GROSS/FINE) 下抽真空系统中泵的有效氦抽速之比。最终的检测结果是测量漏率与机器因子的乘

积。B9 区域泄漏点的测量值如表 5 所示。

表 5 B9 区域泄漏点的 4 次测量值

次数	机器因子	仪器显示值/(Pa·m <sup>3</sup> ·s <sup>-1</sup> )
第一次	1 000	$6 \times 10^{-6}$
第二次	1 000	$4.7 \times 10^{-6}$
第三次	1 000	$3.9 \times 10^{-6}$
第四次	1 000	$7.2 \times 10^{-6}$
均值		$5.45 \times 10^{-6}$

经过核算,得出真实的泄漏值为

$$Q_L = \frac{K \cdot Q_s}{\beta} = \frac{1000 \times 5.45 \times 10^{-6}}{0.15} = 3.6 \times 10^{-2} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$$

后续采用真空罩气泡法进一步确认,检测参数如表 1 所示。真空罩气泡法验证后  $\sigma = 7.2 \times 10^{-2} \text{ N} \cdot \text{m}^{-1}$ ,气泡直径为 5 mm,  $n$  为 4,真空度为  $-0.05 \text{ MPa}$ 。得出  $L_s$  为  $1.3 \times 10^{-2} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ ,  $Q_L$  为  $3.6 \times 10^{-2} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ ,两者换算的值在同一数量级内,表明泄漏值的数量级是准确的。

## 6 结论

(1) 氦质谱仪吸枪氦罩法和真空罩气泡法是有效的检漏方法,两者结合起来,可明显地检测出  $10^{-4} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$  以下泄漏率的泄漏点,并大幅提高检测效率。

(2) 沿海地带湿度大,易形成冷凝水附着于钢覆面上从而堵塞缺陷口,应在排空水池干燥 2 月后,来年后的 2 个月份前进行检测为佳。

(3) 服役期间的燃料水池,低放射性环境对泄漏检测无影响。

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