行政院及所屬各機關出國報告
（出國類別：考　察　）

反應爐阻板及模型板螺栓檢查技術與經驗考察

服務機關：台灣電力公司
出國人　職　　稱：核能工程監
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出國地區：法國
出國期間：89.12.08 至 89.12.17
報告日期：90.02.15

目　　錄

一、 出國事由

1、反應爐是核能廠最重要的設備，其內部眾多組件在高溫、高壓、及高輻射的嚴苛環境下，極易劣化損壞，輕者造成停機影響營運發電，嚴重者更有可能導致核安事件的顧慮。

2、反應爐內部組件因長期處在高輻射及高溫高壓的運轉狀態，而逐漸衍生一些問題，目前國外電廠已發現有反應爐阻板及模型板螺栓龜裂之情形，國外技術資料亦顯示此項問題已受到各國核能界的重視。法國 PWR 電廠承襲美國西屋公司之技術，其反應爐內部組件亦有類似損壞及劣化情形，且又提早發生。但法國以其工業技術能力，已發展出有別於西屋公司的一套成功且成熟的技術。本廠為防患發生類似事件，需多方學習技術、收集經驗資料，因此有必要派員前往法國考察反應爐阻板及模型板螺栓檢查技術與經驗。

二、 出國行程

89 年 12 月 08 日	往程（台北→巴黎）
12 月 09 日~12 月 15 日	於巴黎考察反應爐阻板及模型板螺栓檢查技術與經驗
12 月 16 日~12 月 17 日	返程（巴黎→台北）

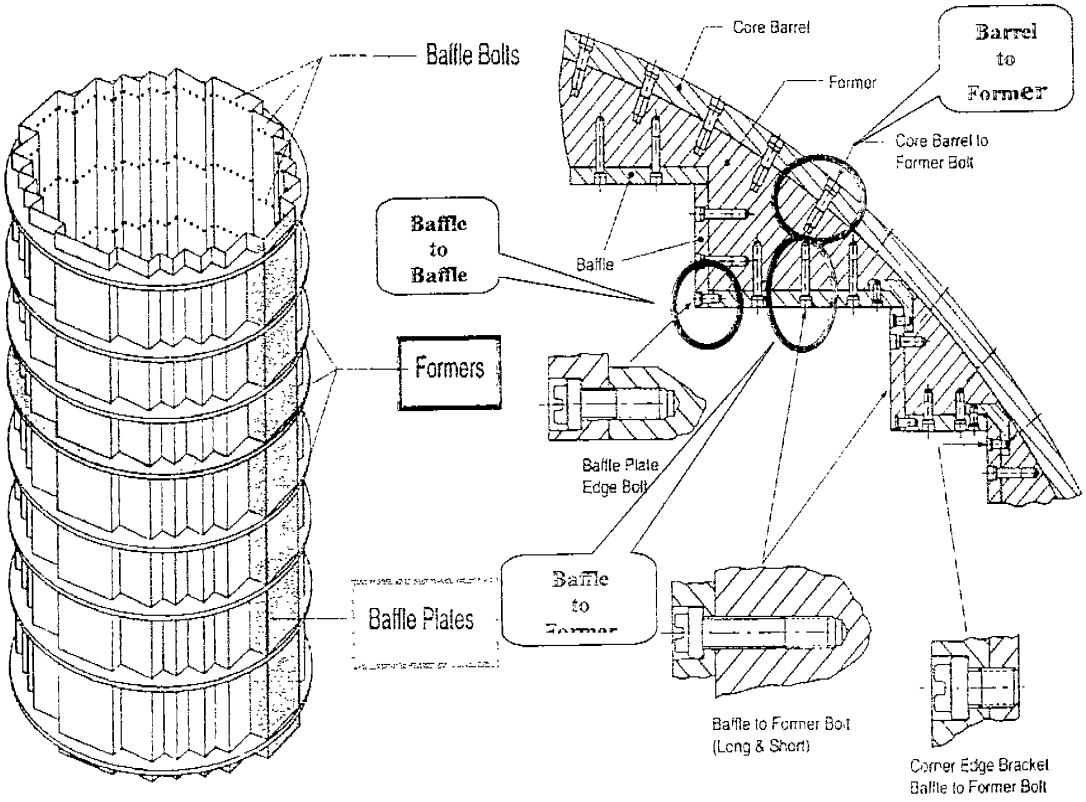
三、考察主要內容

（一）法國反應爐阻板及模型板螺栓檢查技術與經驗

1. 組件介紹：

- 反應爐下內部組件（Lower Internal）主要是支撐核燃料之重量及縱橫向負荷，並引導冷卻水水流。
- 垂直的阻板（Baffle）將圓柱爐心構成燃料組件外圍之方型，並藉由水平的模型板（Former）與圓筒狀的爐心筒（Core Barrel）連結。
- 三者之間以螺栓結合： Baffle to Former、 Baffle to Baffle 、 Barrel to Former 三種螺栓，而以第一種螺栓（以後簡稱 Baffle Bolt）最容易龜裂。
- Baffle Bolt龜裂數量多時，阻板之間會有間隙，冷卻水由此噴入，會損傷核燃料。

阻板、模型板與螺栓之圖示：



2. 阻板螺栓損壞案例：

- 德國於1978年發現阻板有 2mm 間隙，有相當數量的 Baffle Bolt 龜裂，其材質為 X-750。
- EDF Bugey 2，1994年大量發現龜裂，其材質為316。
- Belgium Tihange 1，1995年發現龜裂21支，其材質為316。
- 美國 Point Beach 電廠屬最高危險群，於1999年檢查728支，其中55支有缺陷，螺栓材質為 AISI Type 347。
- 美國 Ginna 電廠1999年檢查639支，其中59支有缺陷，螺栓材質亦為 AISI Type 347。

3. 損壞機制：

- EDF 熱室實驗結果，為輻射促進之應力腐蝕龜裂（IASCC）：Swelling effect

Bolt cracking phenomenology

✓ Stress corrosion cracking assisted by the irridiation (swelling effect)

✓ Occurs in priority at the former plates level of the highest irradiation rate (2 - 3 - 4)

✓ Results based on the expertises performed by EDF (hot laboratory)

- in 1987 from 5 bolts (Bugey)
- in 1992 from 5 bolts (Tihange 1)
- in 1995 from bolts (Tihange 1)
- which confirm the theory

✓ Other expertises driven by EDF on internal elements from Chooz A.

- IAEA（International Atomic Energy Agency）的報告，提及係中子輻射造成的龜裂。
- 確實的機制：究竟是 IGSCC（ Inter Granular Stress Corrosion Crack）或是輻射引起之脆化（Irradiation Embrittlement）尚無定論。

IAEA報告：

IAEA-TECDOC-1119

Assessment and management of ageing of major nuclear power plant components important to safety:

PWR vessel internals

INTERNATIONAL ATOMIC ENERGY AGENCY

October 1999

7.5. CRACKING OF THE BAFFLE BOLTS

In the 1980s inspections indicated baffle bolts cracking. The bolts are made of 316 cold worked stainless steels. They failed by intergranular cracking. Normally, 316 steel is not prone to IGSCC in this water environment and all the bolts cracked were initially located in the second and third rows from the bottom, that is exactly the place corresponding to the highest neutron irradiation. This demonstrates that the neutron irradiation is a significant feature for this cracking, even if the exact mechanism is unknown now. It is difficult to conclude whether the bolts cracked by IASCC or due to irradiation embrittlement, or by other IGSCC phenomena. To date, baffle bolt cracking was observed only in plants with the "down-flow" design.

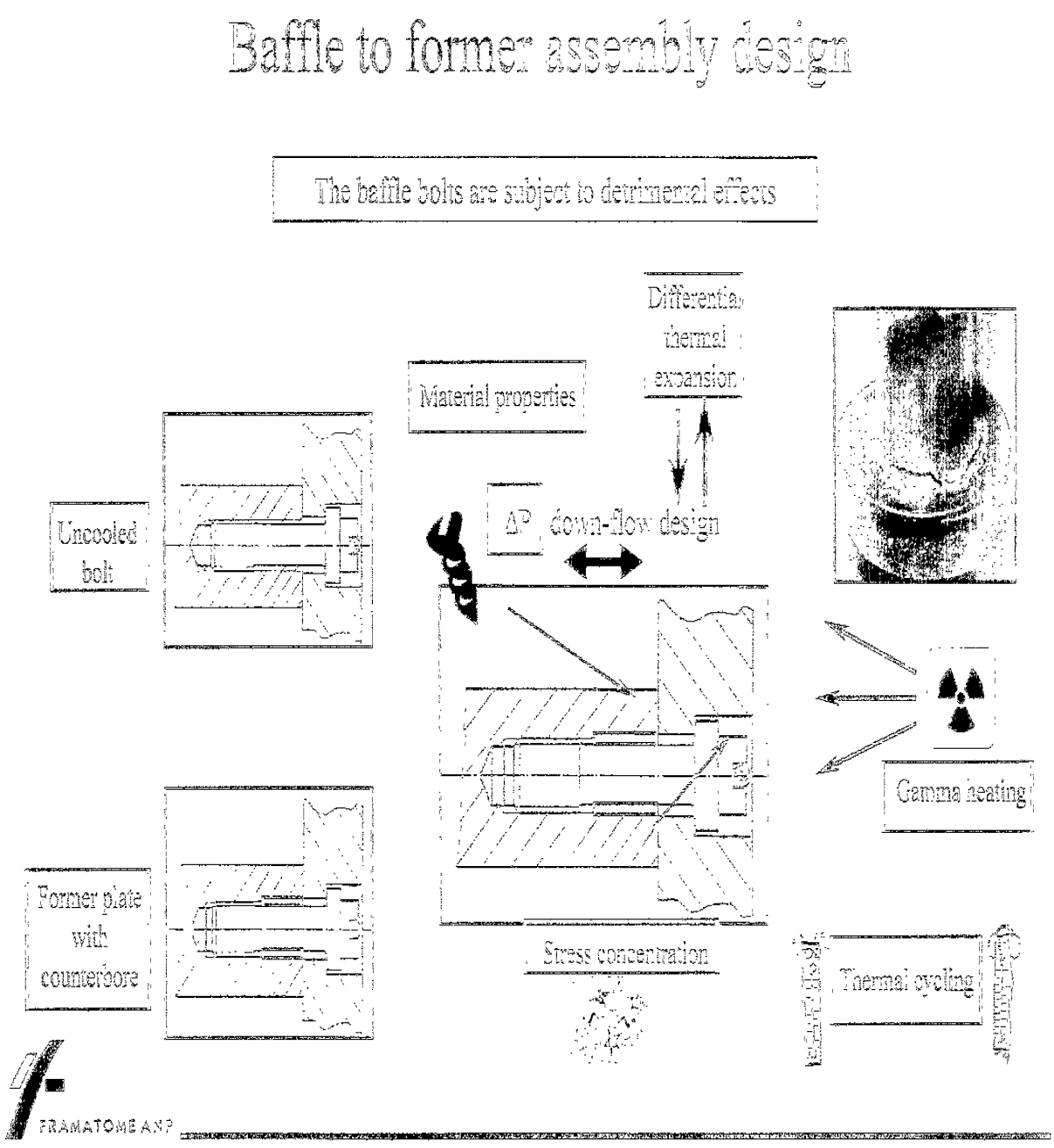
This cracking is a concern and made necessary the development of ultrasonic methods for the non-destructive examination of the bolts. In France, in 1994, the maximum number of bolts with a suspicion of cracking was 57 on one plant (Bugey 2). The indications are significantly different from plant to plant. Measures are taken to be able to make an efficient non destructive examination of the bolts and to replace them if necessary.

In Belgium, the situation is similar at Tihange 1. Twenty-one bolts were detected as cracked in 1991 and 90 bolts replaced in 1995 (as reported at the 1995 meeting of the International Working Group on Life Management of Nuclear Power Plants).

The possibility of changing all the lower internals is also studied in Europe and in Japan [19, 20].

In Germany, damage to the baffle former structure was first discovered in 1978 at a PWR plant. During the inspection, an enlarged gap of approximately 2 mm was found between two baffles. An ultrasonic examination revealed that a number of the Inconel X-750 baffle former bolts were defective (some bolts gave no back echo, others gave back echoes which did not correspond to the bolt length. When the bolts were removed, some of them

■ 阻板螺栓承受之不利因素：

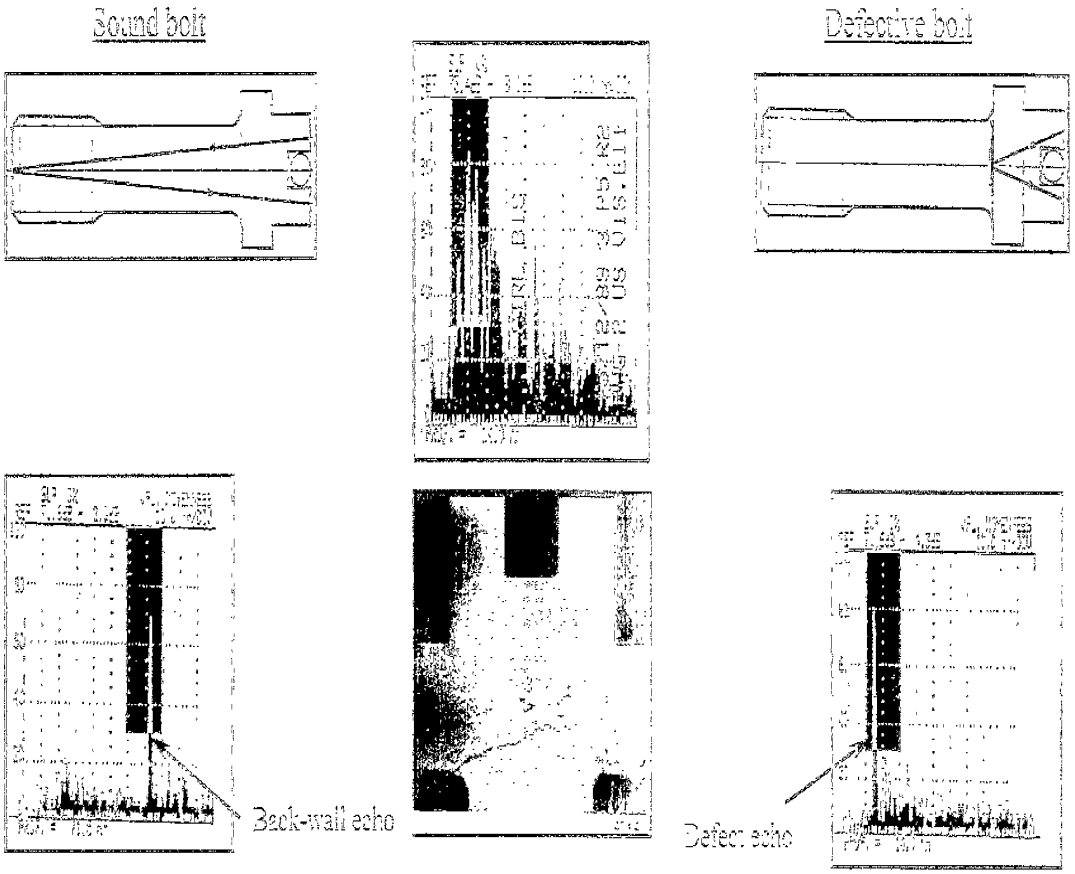


4.法馬通公司(Framatome) 的檢查方法及經驗：

■ 程序書驗証

Inspection

Qualified procedure



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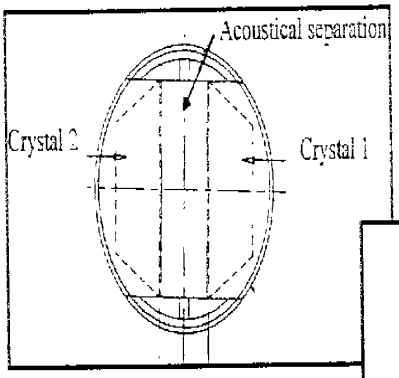
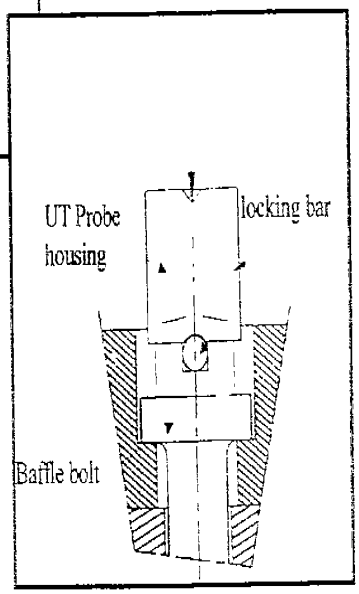
■ UT 探頭

Inspection

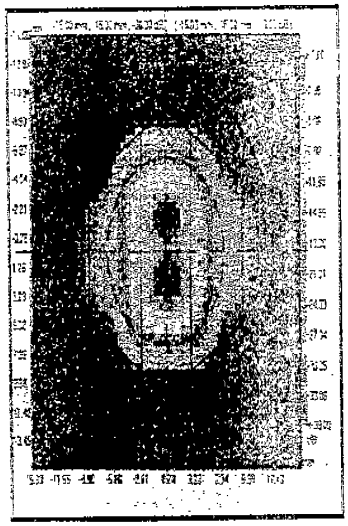
Qualified procedure : UT probe



Twin crystal
probe (4 MHz)



UT probe
fitted to the bolt head



Ultrasonic beam pattern
simulation in a plate
at 15 mm depth

E/1 - R/2

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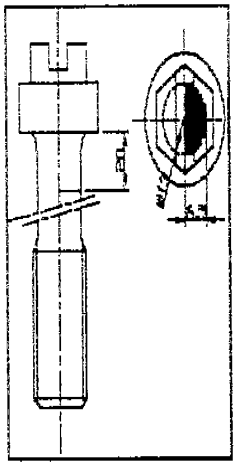
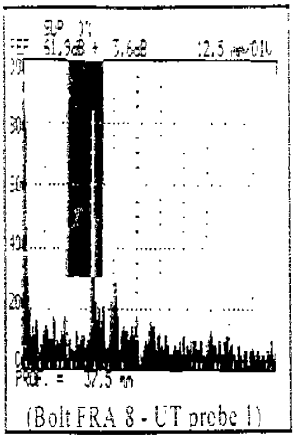
■ 測試結果

Inspection

Qualified procedure : Test results

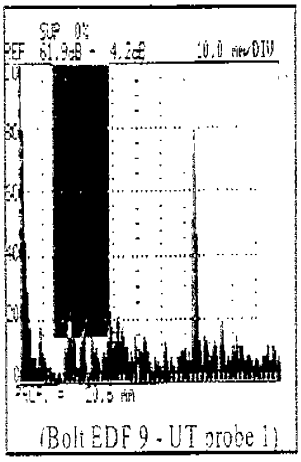


In the shank
fatigue crack type defect,
50% of shank cross-section,
oriented at 0°



(Bolt FRA 8 - UT probe 1)

Sound Bolt



(Bolt EDF 9 - UT probe 1)

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■ 性能驗證

Inspection

Qualified procedure : performance demonstration

✓ **Detection of :**

- *Under head* Fatique crack type defect
  - 25% of the shrank cross-section
  - S/N greater than 10 dB whatever the orientation.
- *In the shank* Fatigue crack type defect
  - 50% of shank cross-section
  - S/N greater than 12 dB whatever the orientation.

✓ **Limit of performance :**

Under head ***IGSCC*** *type defect, 25% of shank cross-section,*

is ***not detected.***

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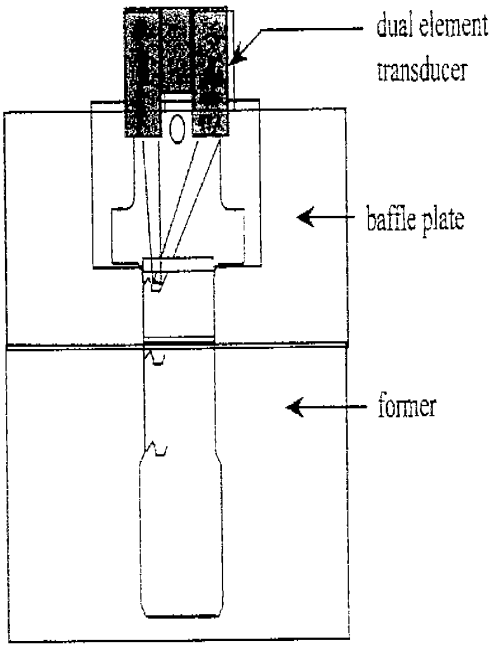
■ 探頭設計

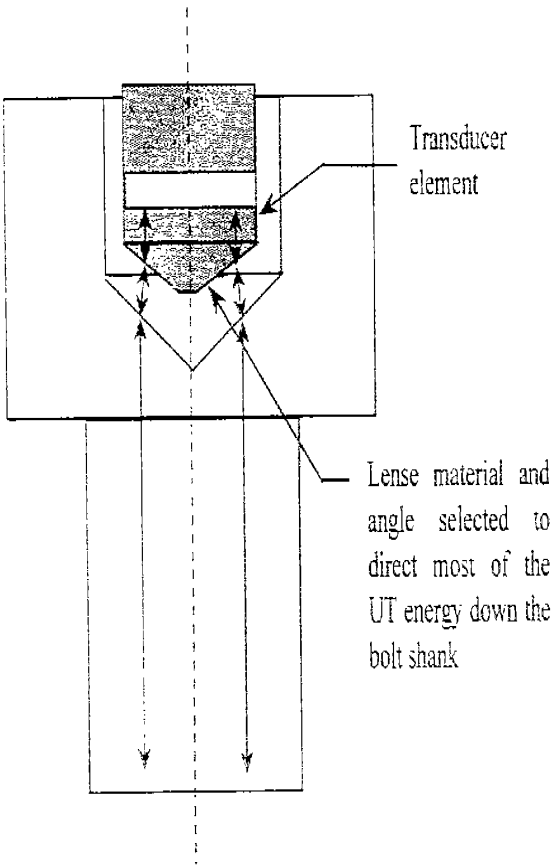
Inspection

Qualified procedure : probe design

External hex bolt inspection method



Hex drive UT transducer



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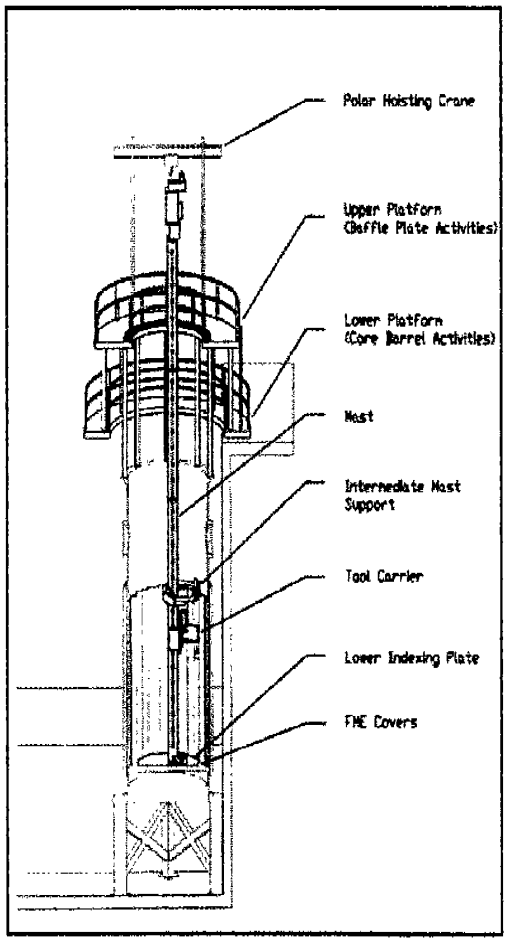
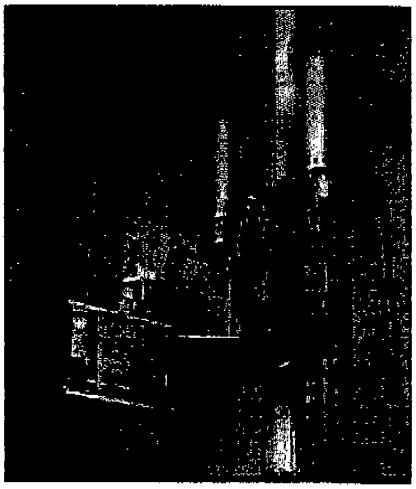
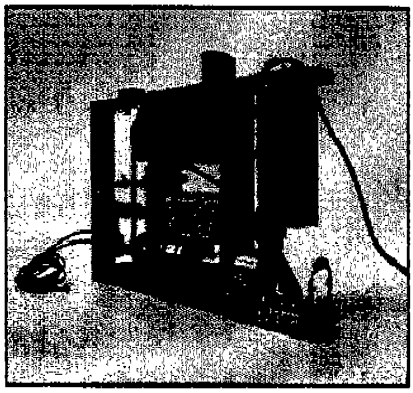
■ 螺栓檢查過程

Inspection

Bolt inspection process







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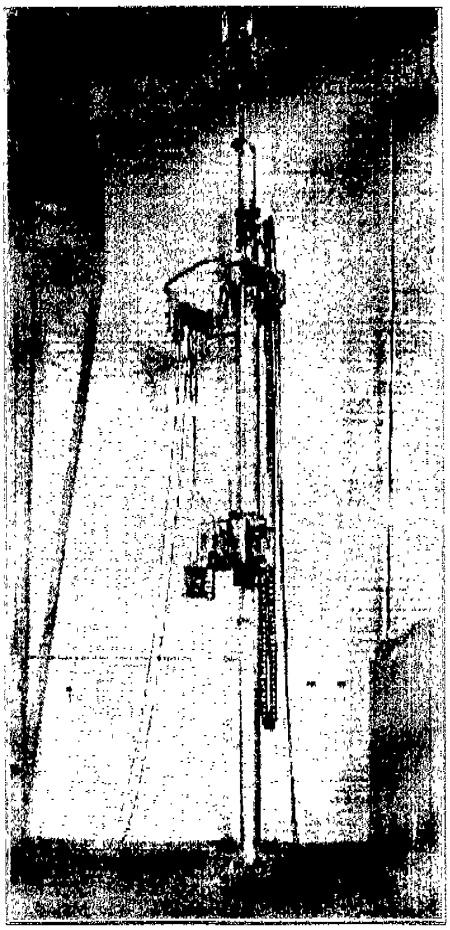
■ 主桿設備

Inspection

Inspection mast



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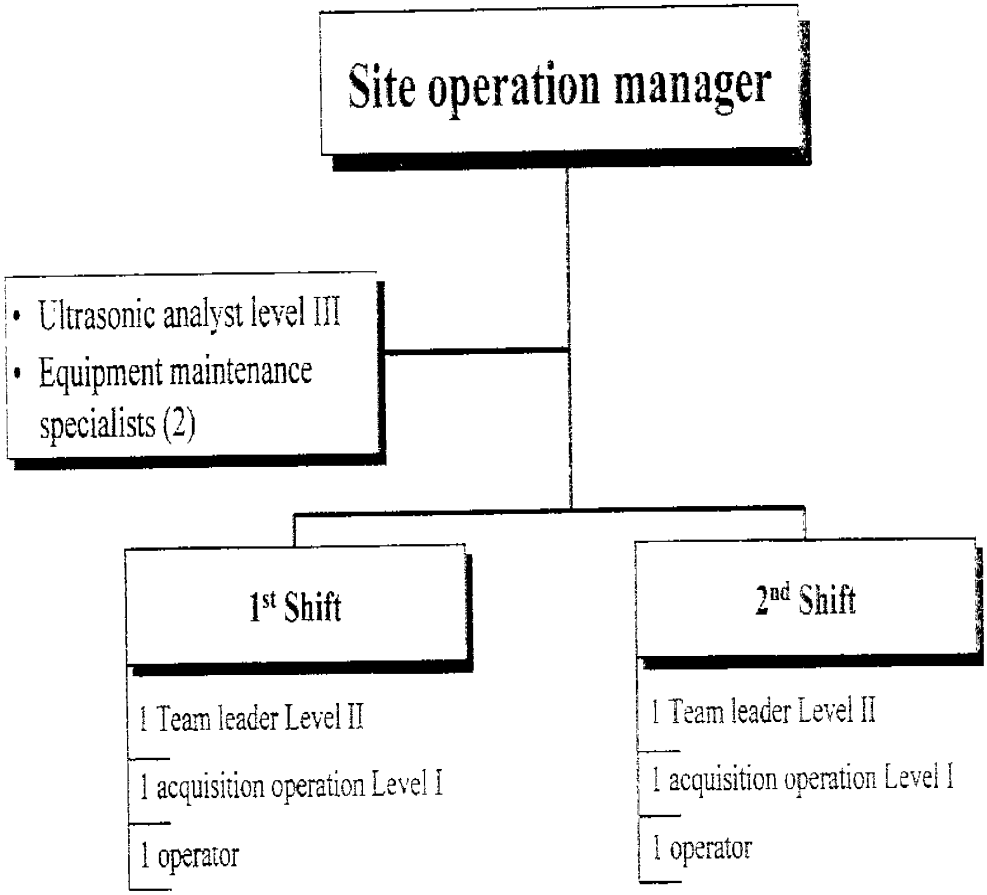
■ 現場人員組織

Inspection

Site organization and schedule



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■ 與韓電之合約

Inspection

Kori 1 contract

- ✓ Proposed UT & VT inspection of:
  - 728 Baffle-Former Bolts
  - 176 Edge Bolts
  - Locking Pin Welds
- ✓ Proposed inspection schedule
  - 5 Days (Shift work 2X12hrs)

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■ 經驗

Inspection

Framatome experience except USA

Plant	No.
❒ Fessenheim 1, 2	5280
❒ Bugey 2, 3, 4, 5	11,973
❒ Gravelines 1	960
❒ Tricastin 2	960
❒ Tihange 1	2880
❒ Kori 1	1024
Total	**23,077**

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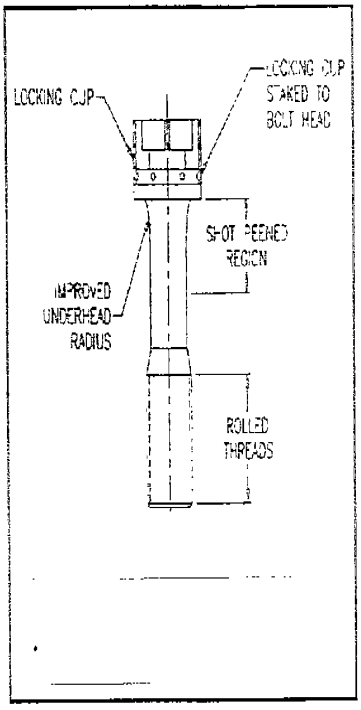
5. 阻板螺栓設計改善：

■ 設計方面
螺紋由車製改為滾壓，減少殘留應力。
螺栓頭與 Shank 之轉變區採用複合曲線，減少應力集中
應力集中區施以珠擊，預施壓應力。

Replacement bolting design

- **DESIGN:**
  - Functionally Interchangeable with Original Bolts
    - Same Length
    - Same Rolled Threads
    - Same Bearing Area
    - Fits Existing Counterbore
    - Locking Feature Incorporated
  - Improvements Over Existing Design Consisting of:
    - Compound radius underhead to shank transition radius
    - Radius transition and shank shot peened
    - Flat Head Surface for Improved UT
  - Locking Device does not Require Enlargement of Counterbore
  - Locking Device Consists of Mechanically Attached "Crimp Cup"
    - Annealed 304 L SS
    - Provides Anti-Rotation and Bolt Capture Function
    - Integrates with Grooves to be Cut Inside Counterbore
    - Crimped at Four Places into Grooves in Counterbore



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■ 材料方面
由 Type 347 改用 Type 316 10% CW 之不鏽鋼

Replacement bolting design

- **Materials:**
  - Baffle Bolts & Edge Bolts

    SA-193 Grade B&C Class 1 (Type 347 nuclear grade SS)

    OR

    SA-193 Grade B&M Class 2 (Type 316 nuclear grade SS with 10% CW)
  - Newer Nuclear Grade materials have restricted chemical composition, controlled residual elements, & controlled heat treatments to provide specified grain size - increases resistance to stress corrosion cracking.
- **Qualification:**
  - Justified Mechanically as "Replacement-in-Kind" with Enhancements
  - Mechanical Testing Program to Justify "Crimp Cup" Capture Feature
  - Torque Versus Load Qualification

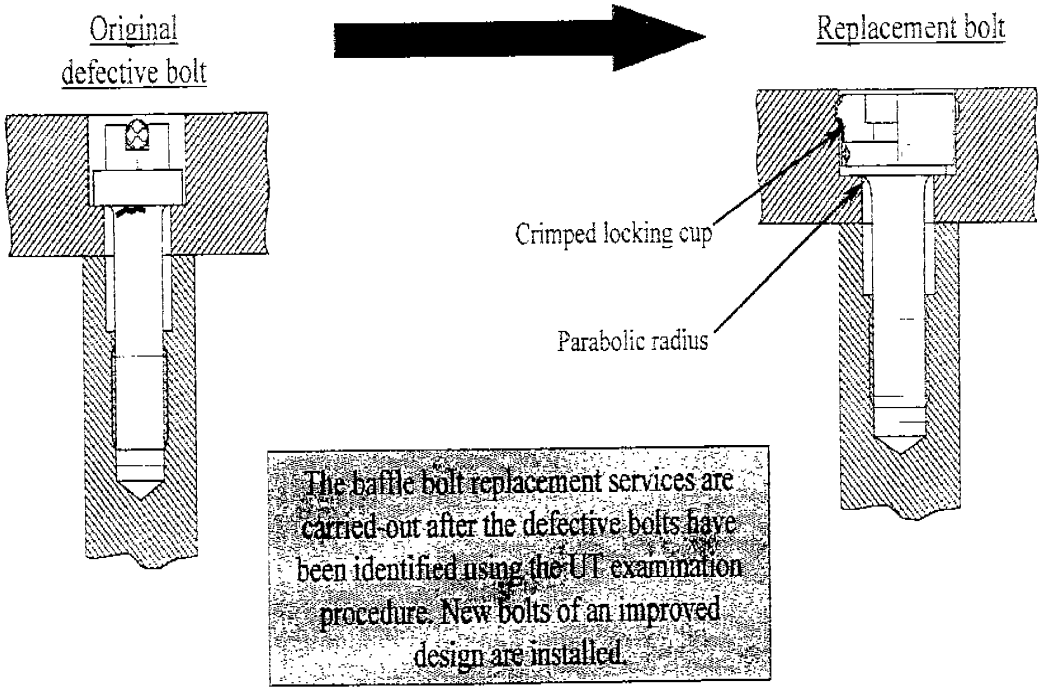
6. 阻板螺栓更換對策：

■ 先檢查，再更換有缺陷之 Bolt。
■ 不檢查，直接更換模式分析選定之 Bolt。
原設計太保守，裝了太多 Bolt， 經模式分析後，選出必需的 Bolt。

7. 法馬通公司的更換方式及經驗：

■ 更換螺栓之設計

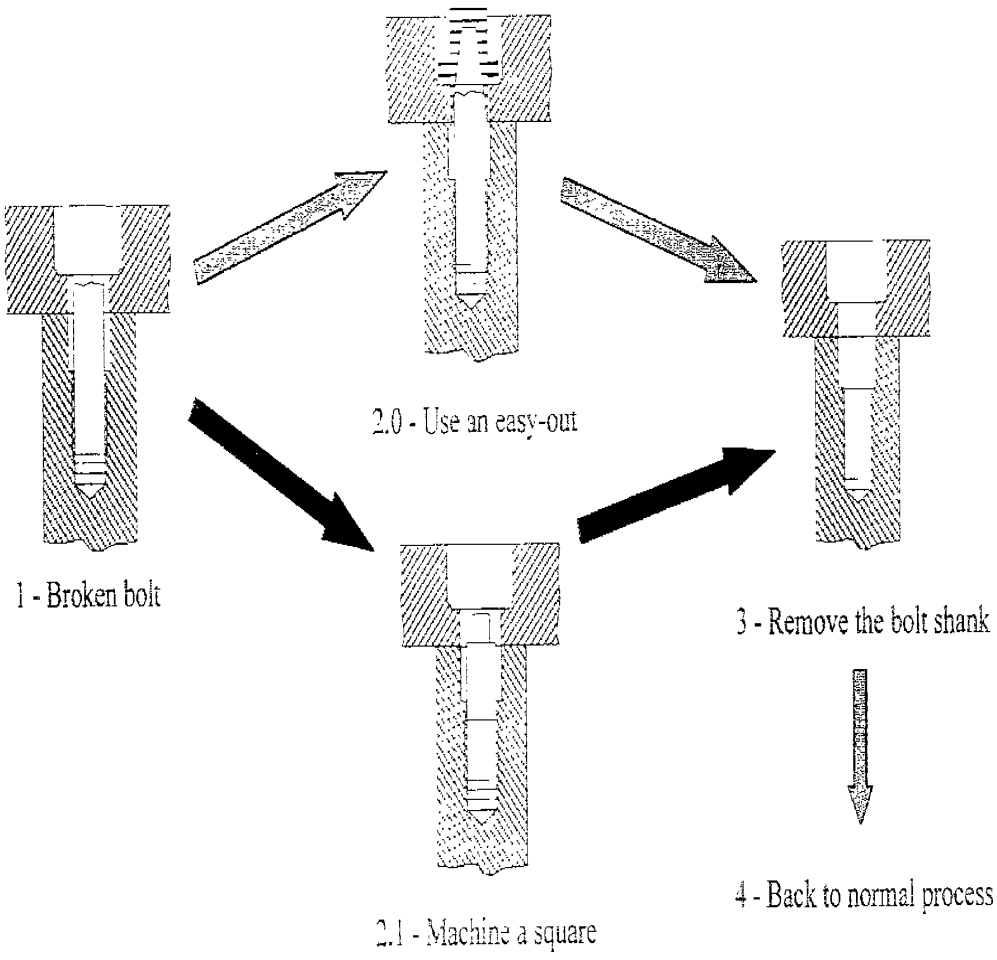
Replacement bolting design



■ 螺栓斷裂之應變措施

Repair method and technique

Contingency situation : Broken bolt



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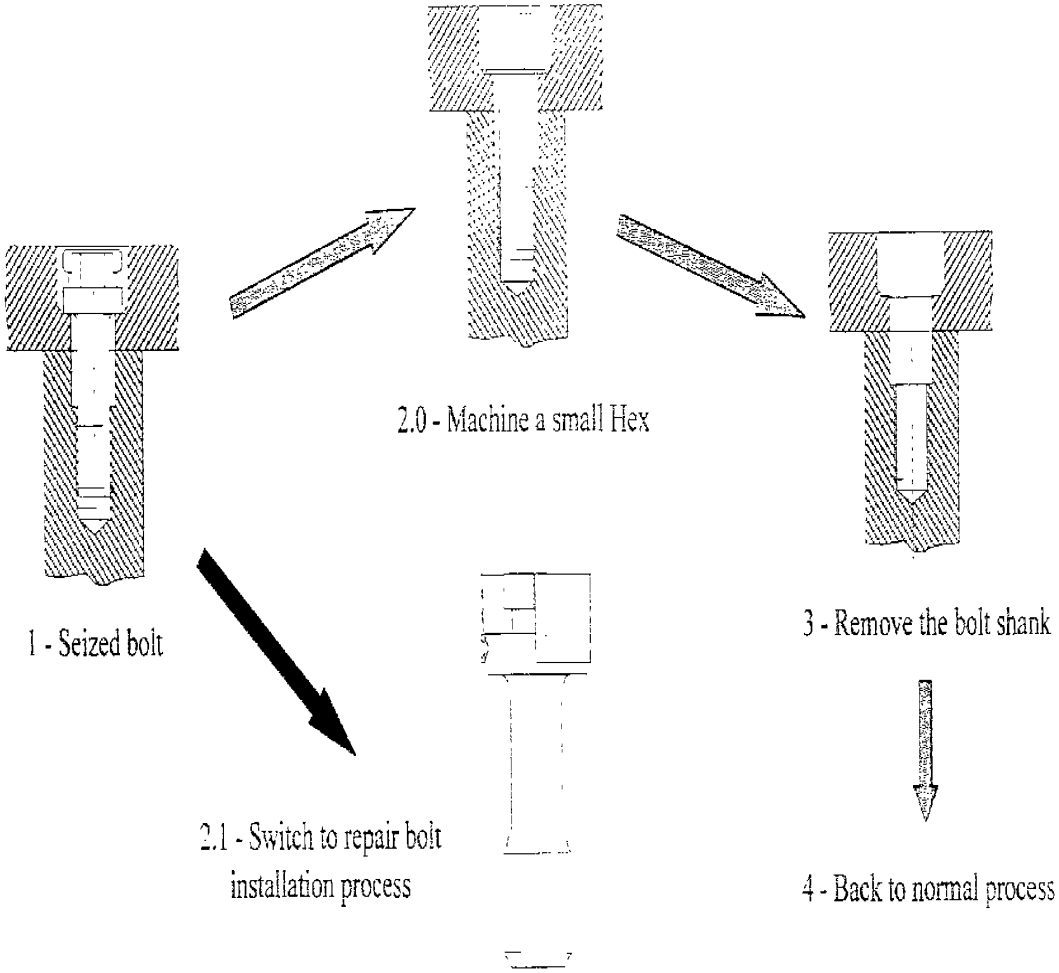
■ 螺栓卡死之應變措施

Repair method and technique

Contingency situation : Seized bolt



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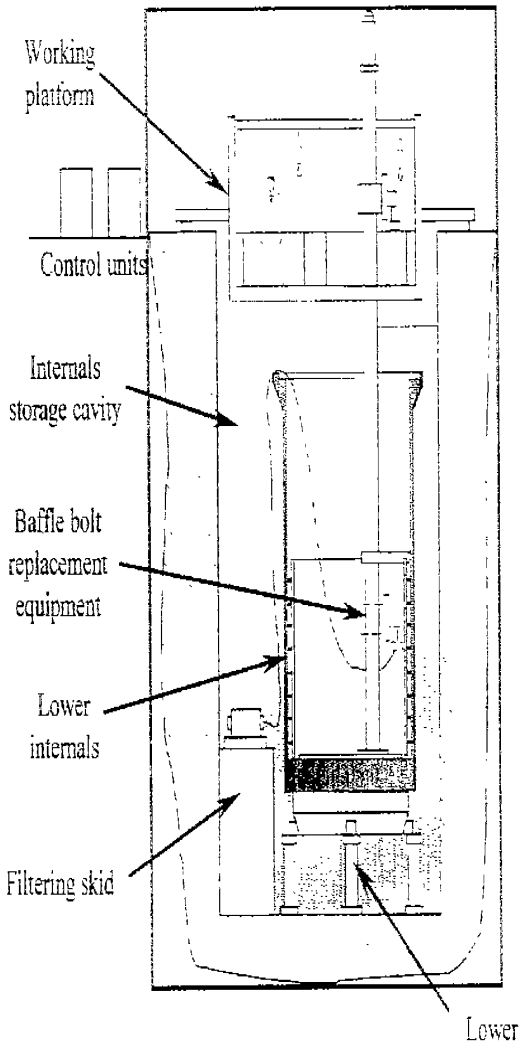
■ 設備佈置

Equipment description : General lay out



The baffle bolt activities are performed in plant cold shutdown conditions with the core unloaded, the lower internals stored on their stand, the refuelling pool full of water and the pit filtration system running

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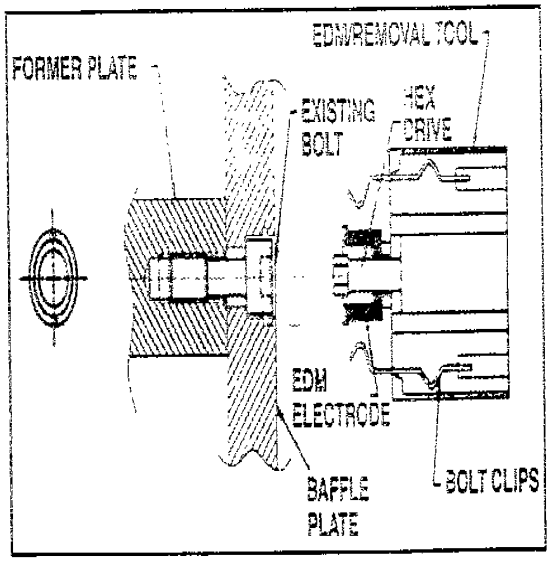
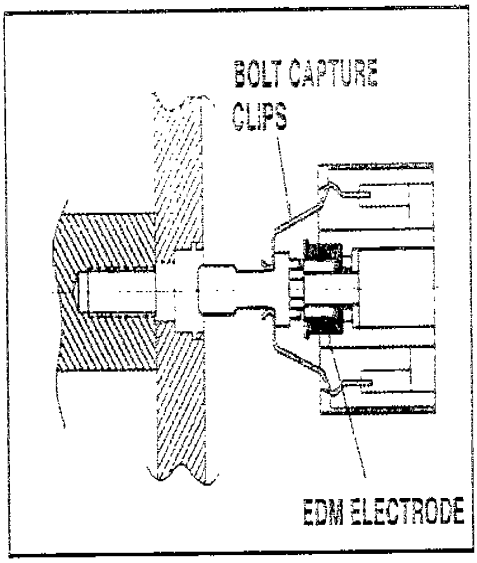
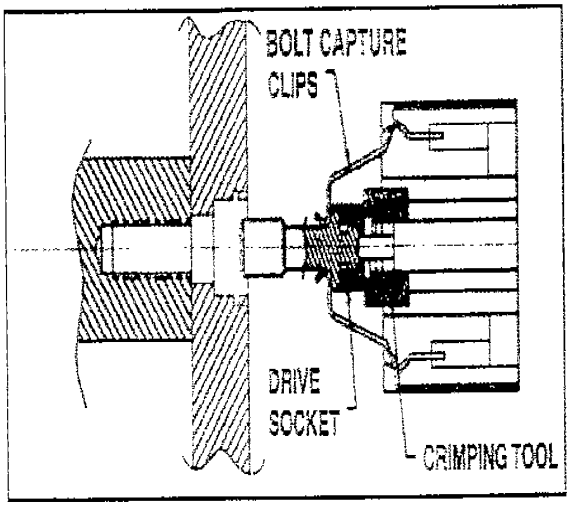
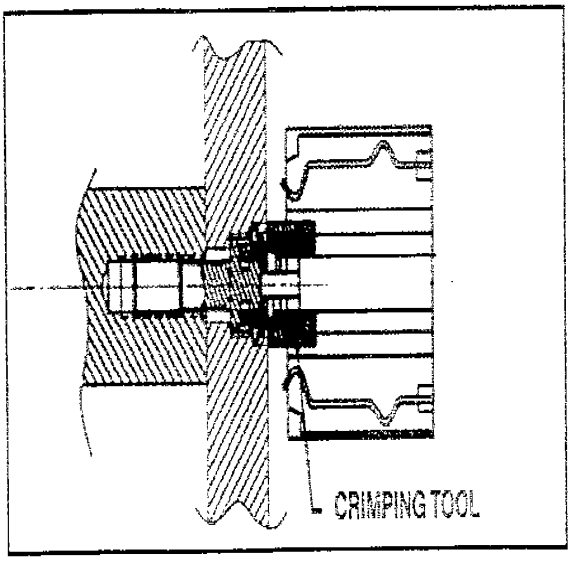
■ 更換之步驟

Equipment description : Bolt replacement process









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■ 1995 於 Tihange 1 之經驗

Equipment Experience : Tihange 1 - 1995

✓ *960 RV Internals Bolts Inspected*

- Production Rate of 223 Bolts Per Day Achieved
- Original Bolt Design Is External Hex With Locking Bar

✓ *Replacement Bolts Supplied*

✓ *91 RV Internals Bolts Replaced*

- Production Rate of 9 Bolts Per Day Achieved
- Operations Analyzed to Increase Future Productivity

✓ *Contingency Bolt Removal Processes Utilized*

✓ *Site Schedule Met*

- 23 Days Scheduled
- 22 Days Actual

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■ 1998 於 Point Beach 之經驗

Equipment Experience : Point Beach - 1998

On-site performance :

✓ *Inspection* :

- All 728 bolts were inspected using specific probe developped for inner hex design
- Duration of complete inspection: 3 days
- 55 bolts with indications (7,5 %). Most are located on plates 1, 3, 8

✓ *Replacement* :

- 176 bolts removed and 175 installed. One bolt could not be installed due to former plate alignment (replaced by 2 adjacent ones)
- 46 bolts among the 55 with indications were replaced
  - 28 were load tested and found OK
  - 9 had the bolt head come off during removal or at very low load during testing
  - 6 remain in storage and 3 transported to a hot cell for further testing

■ 1999 於 Ginna 之經驗

Equipment Experience : Ginna - 1999

On-site performance :

✓ *Inspection* :

- All 728 bolts were inspected
- Duration longer than Point Beach 2 due to excessive welds on the locking washers
- 59 bolts found defective by procedure

✓ *Replacement* :

- A bolt replacement pattern of 56 bolts was chosen by RG & E
- Approximately 6 days duration:
  - 38 locations required contingency operations
  - 14 of these locations required multiple contingency operations (bolt head removal and burn square ; increase diameter of the baffle plate hole)

EDM debris system using 1 micron filter and 0,1 micron finishing filter

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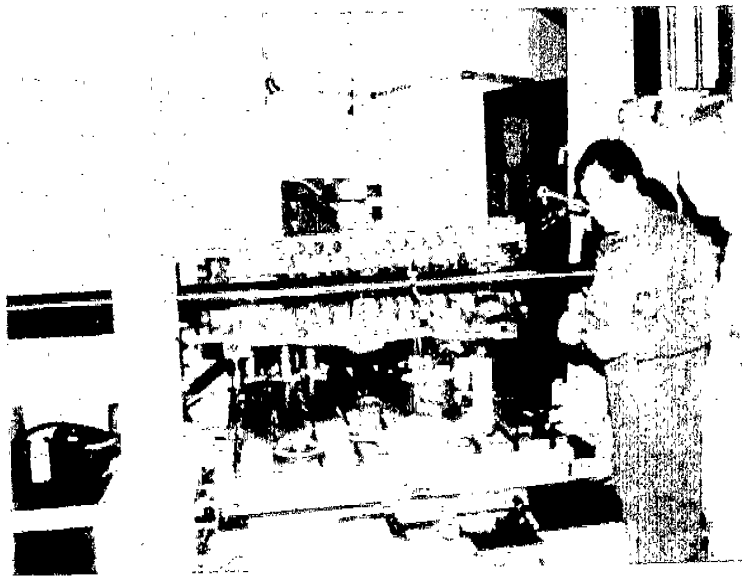
（二）法馬通公司幾項值得學習的技術

1. 法馬通概況：

- 併購B&W後，目前正併購 Siemens 的核能部門；將來全世界 PWR 廠商只剩：西屋（BNFL/ABB）、三菱及 Framatome 三家。
- 各層主管正準備接受英語測驗，邁向國際化。
- 無新機組訂單，龐大的人力設備轉向少量多樣化的工作，例如：
  - 利用潛水艇技術，生產 Wind Turbine。
  - 積極進入歐、美、韓、中、台市場。
  - 整修 Flowserve（美國公司）之 離心式充水泵(CCP)。

REPAIR WORK



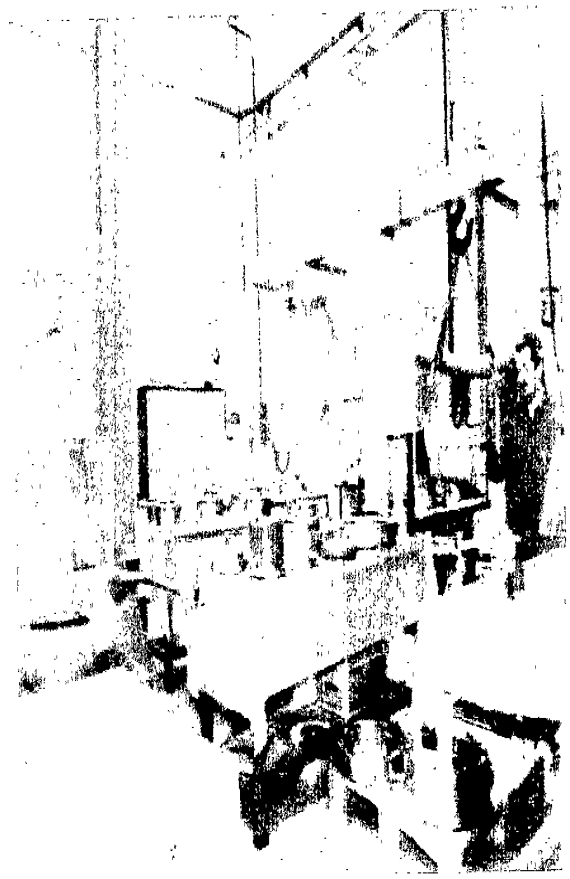
Refurbishing charging pumps from TIHANGE 1 for Flowserve

SOMANU FRAMATOME

MARKETING DEPARTMENT

□ 整修並驗證各廠 RCP 軸封。

MODIFICATION AND REQUALIFICATION WORK



Requalification of shaft seals, n° 2 bearings and seal housings of primary pumps from EDF, Tihange 1 and 2, Ringhals, Asco, Almaraz, Koeberg, Doel (over 100)

SOMANU
FRAMATOME

MARKETING DEPARTMENT

□ 提供 Your Self Service Shop。

Somanu Somanu

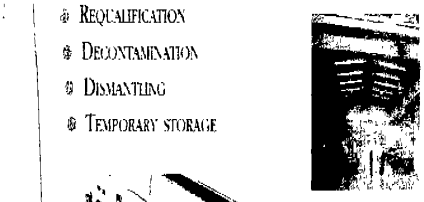
YOUR SELF SERVICE SHOP

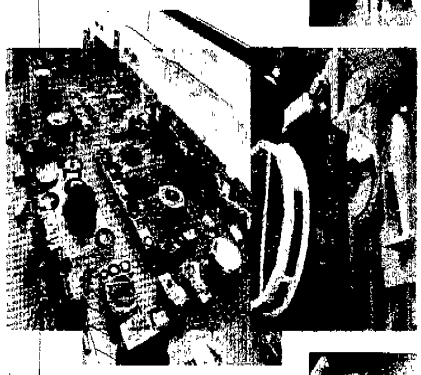
- Nuclear plant operators
- Nuclear industries
- Manufacturers of components for the nuclear industry

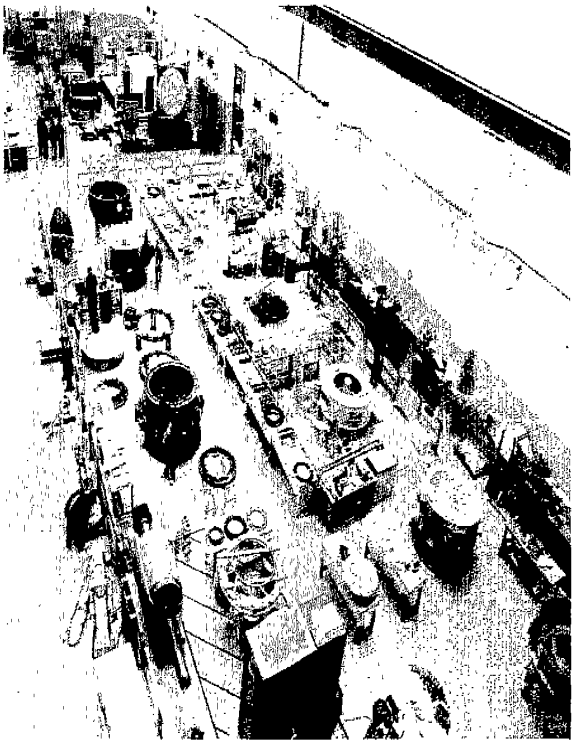
SOMANU places its plant and equipment at the disposal of the customer and offers him three options.

ON SITE OPERATIONS ON CONTAMINATED EQUIPMENT

- Maintenance
- Repair
- Evaluation
- Requalification
- Decontamination
- Dismantling
- Temporary storage







General view

- *reducing unit outage times*
- *reducing maintenance costs*
- *reducing congestion in plant buildings*
- *limiting radiation exposure.*

FRAMATOME

2.學習心得：

■ RCP No.1軸封新購價每組台幣 500萬，Framatome 可將舊軸封 Refurbish 並驗證，只需 1/3 價格。
本廠累積用過軸封有10組，可經由此一方式變成堪用備品，以節省維護經費。

■ 本廠未有拆除與更換軸封 Face Plate 及封環之經驗，可經由 Self Service 方式派員前往學習。

■ Framatome 驗證軸封之設備，學自西屋；而韓電已向 Framatome 購買乙套，本廠應可自行研發。

■ 倘能進行前述工作，本廠 RCP 軸封維修能力就可完全建立；不必每次大修（三年）丟棄乙套軸封，可減少廢料與節省成本。

（三）<u>法國電力公司幾項值得學習的技術</u>

1.法國核能發電概況：

900MW @34部機
1200MW @ 1部機（快中子）
1300MW @20部機
1450MW @ 4部機（自行研發）

■ 機組標準化，備品少並大量累積運轉及維修經驗。

■ 面對綠黨強力抗爭：

□ 已達成零排放目標。

□ 中止 Life Extension、 Uprating 計畫。

□ 面對電價競爭：
→由單一供應商(法馬通)，再引進西屋公司競標(Baffle Former Bolt 更換）。
→積極建立核心技術，與台、韓、中及各國建立技術交換管道，並參加各大供應商舉辦之 Work Shop 及事故處理小組，例如參加美國 V.C.Summer 電廠之反應爐管嘴龜裂處理小組。

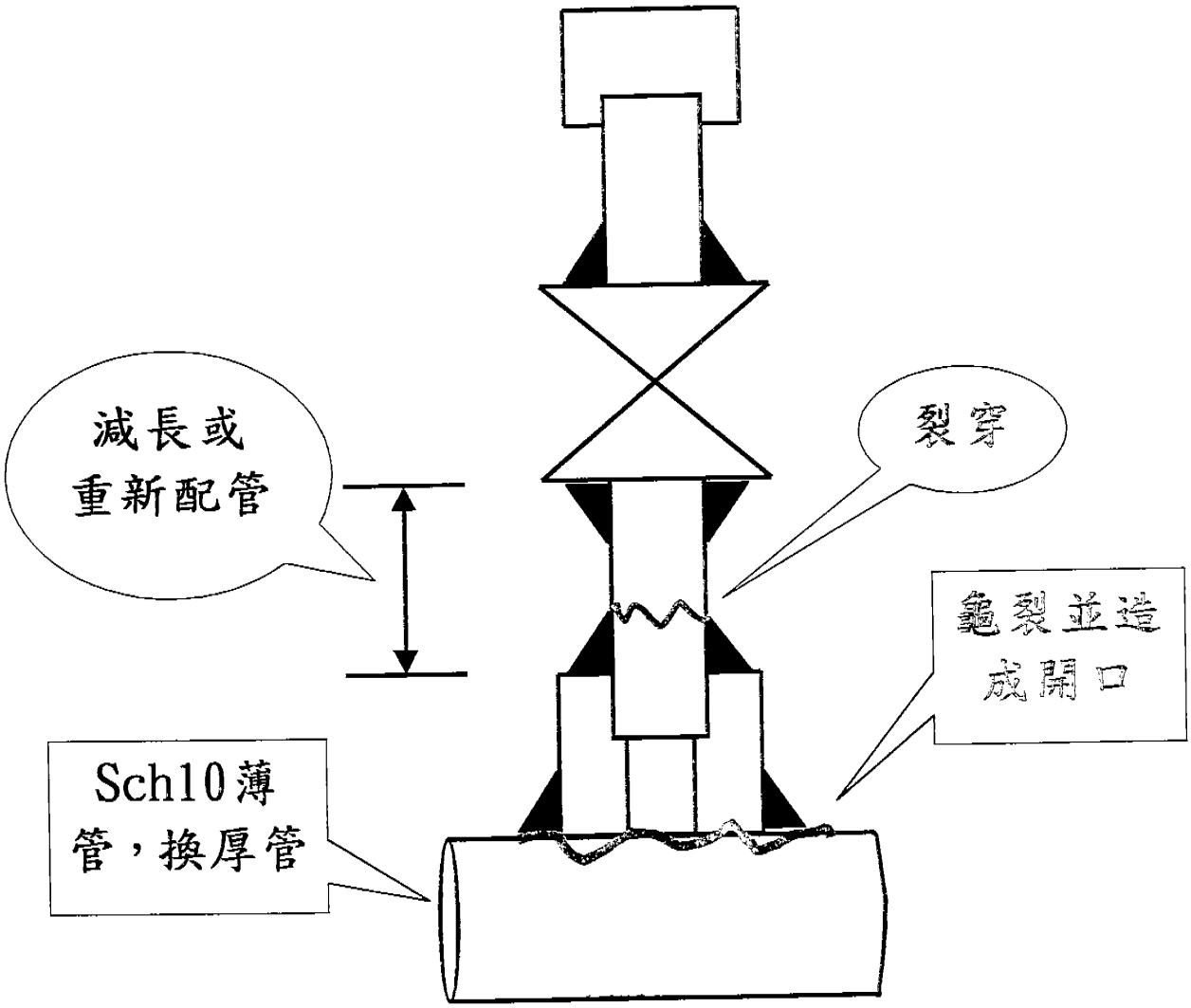
2.學習心得：

■ 洩水及逸氣管路（Drain & Vent）因振動引發之高週波疲勞破壞：

□ EDF 之經驗及改善方法：

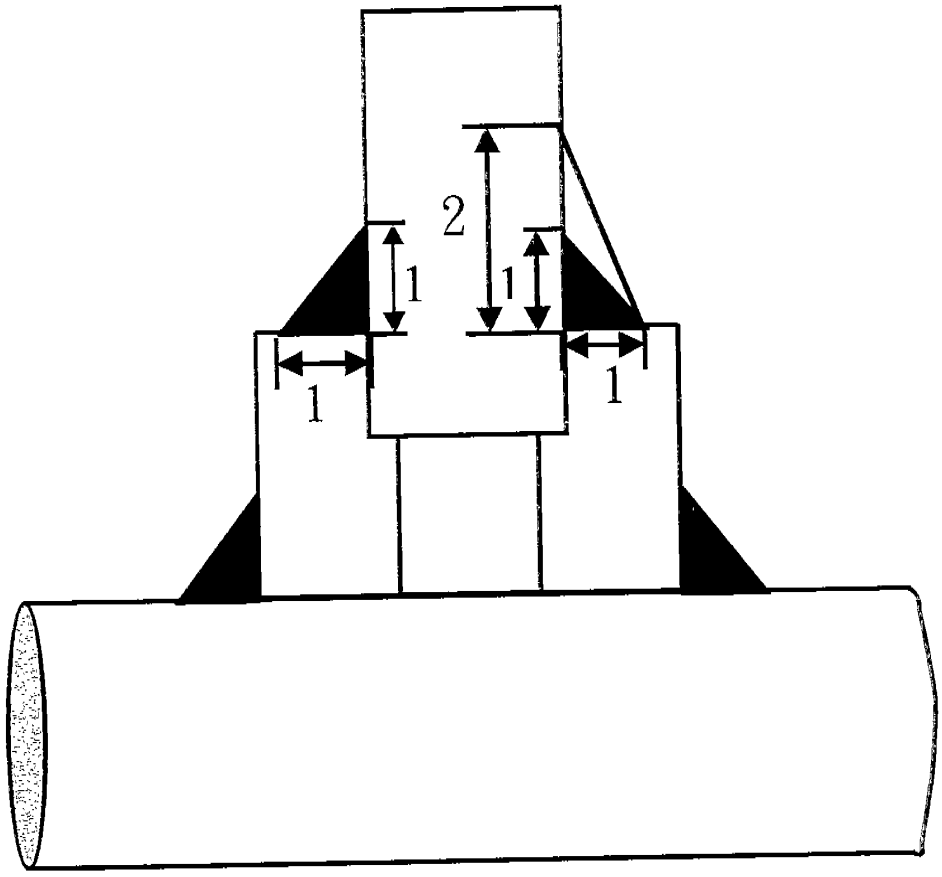
→減長或重新配管，消除振動。

→Sch10 薄管才會發生，換厚管。



□ 核三目前作法：
→拆除 CCP 後備最小流量管路。
→採用 EPRI 之改善方法。

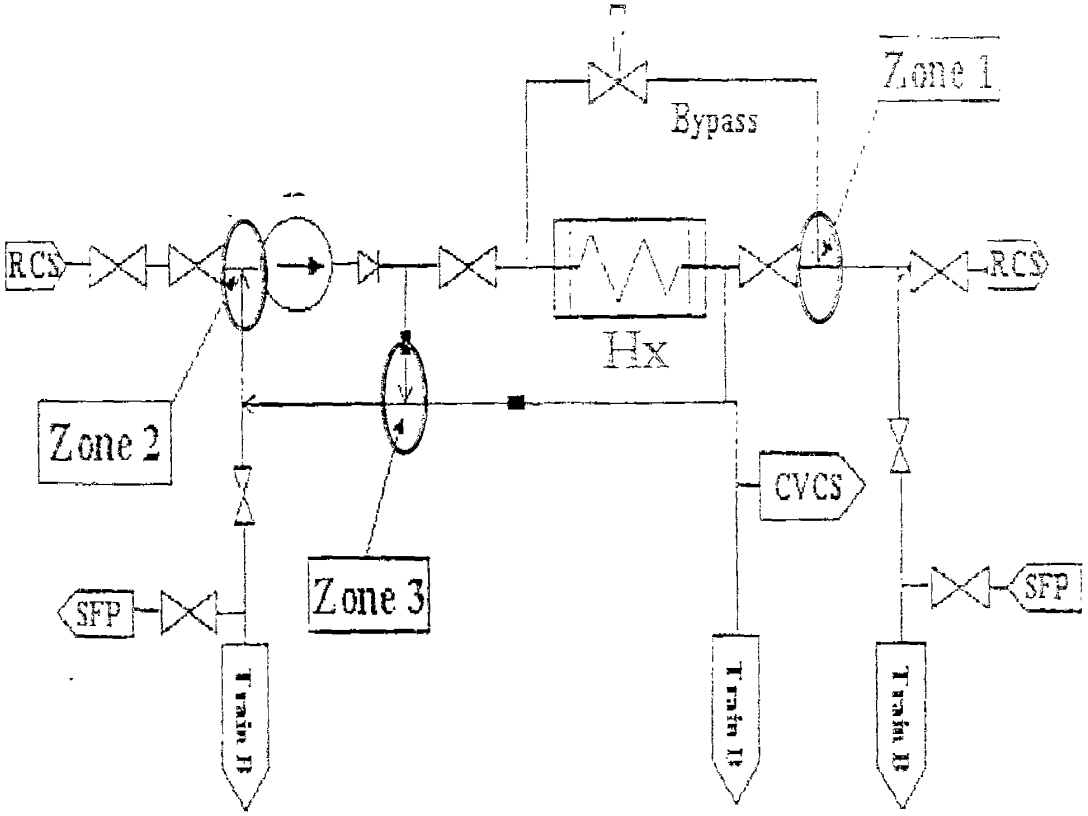
•Weld Overlay Repair
•1*1 weld →2*1 weld



□ 本廠可學習之處：
實際量測管路振動值，改善管支架或重新配管，從根源處解決問題。

■ 冷熱管交接處之熱疲勞龜裂

□ EDF之經驗：



→檢查８個機組（5個900MW、 3個1300MW ），全部發現有龜裂。
→所有機組全部換管。
→換下之舊管作為 UT 之 Mock-up。
→ UT探頭為 2.25MHz，有45° 、60° 、75° 。

▫ EDF之改善方法：

→新管內表面採精密加工，較能抗疲勞。

→新管內表面精密加工時，特地殘留壓應力。

→採取運轉限制。

RHR 在 77℃ 才運轉，出口 55℃，降低 △T。

△T 最高限制 90℃。

每一 燃料循環（ Cycle）限定只能運轉 100小時。

每運轉 400小時執行 MUT 一次。

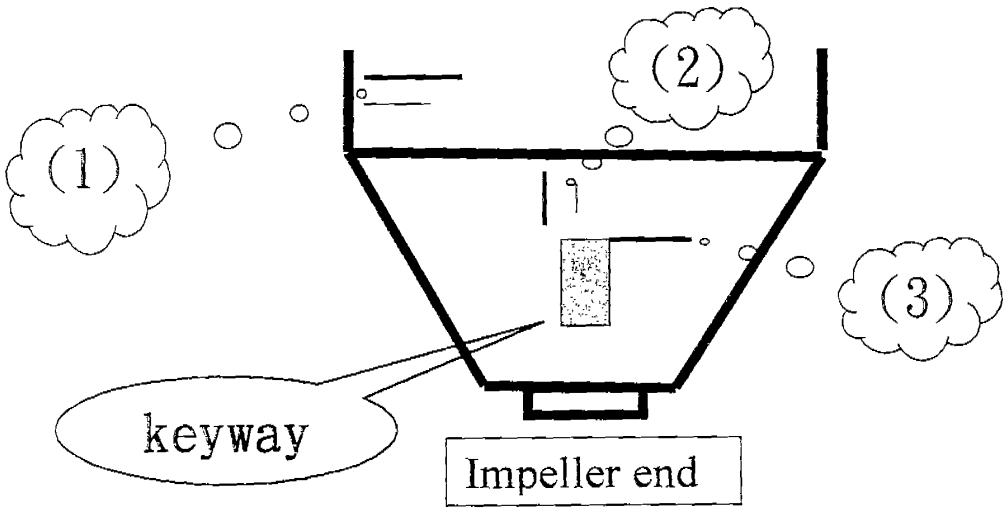
■ RCP(反應爐冷卻水泵）軸 UT 檢查

▫ EDF 發展之技術 ：

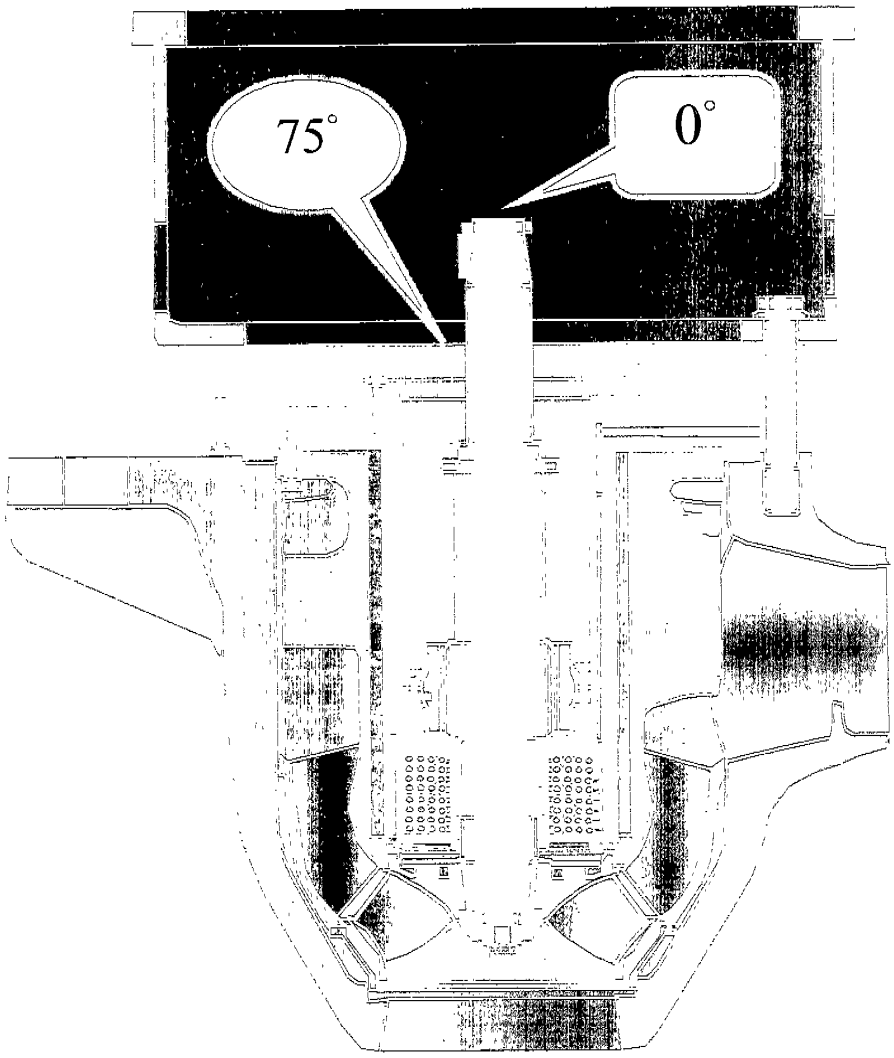
→軸不必全部分解就可執行。

→有0° 、75° 探頭。

→目前只能偵測(1) 、(2) 、(3)之龜裂，尚無法 Sizing。



RCP 軸 UT 檢查示意圖



四、心得與建議：

■ 阻板及模型板螺栓檢查與更換

□ UT 檢查技術經改進後，已成熟，其檢查之精確度及進度都已能接受。

□ 更換技術則因經驗不多，並且每次更換都有突發問題，仍在繼續改進中。 Framatome 有 3 部機組經驗；在法國 1 部、美國 2 部。（據 Framatome 人員口頭報告，西屋在 EDF 標得一部機組的更換合約，但執行得不太成功。）

□ 本廠阻板及模型板螺栓材質屬較新的 316CW，冷卻水往上流，且有冷卻孔，屬低危險群。

□ 而且阻板不是壓力邊界，螺栓斷裂後也不會造成鬆脫件(Loose Part)，因此尚無立即檢查更換之急迫性。

□ 因此建議待更換技術更成熟後，再視情況執行。

■ 法國電力公司參訪觀感

核三廠與 EDF 的經營策略非常相近，均認為發展自己的核心技術，才能安全地、經濟地、永續地營運。EDF 有眾多機組與為數龐大且積極的研發人員，累積相當豐富的運轉與維修經驗，若能建立良好的交流管道，對本廠營運將有莫大助益。