THE STRUCTURAL AGING ASSESSMENT PROGRAM: RANKING METHODOLOGY FOR CANDU NUCLEAR GENERATING STATION CONCRETE COMPONENTS

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ABSTRACT

Most of the major structural components in CANDU nuclear generating stations are constructed of reinforced concrete. Although passive in nature, these structures perform many critical safety functions in the operation of each facility. Aging can affect the structural capacity and integrity of structures. The reduction in capacity due to aging is not addressed in design codes. Thus a program is warranted to monitor the aging of safety-related CANDU plant structures and to prioritize those that require maintenance and repairs.

Prioritization of monitoring efforts is best accomplished by focusing on those structures judged to be the most critical to plant performance and safety. The safety significance of each sub-element and its degradation with time can be evaluated using a numerical rating system. This will simplify the utility's efforts, thereby saving maintenance costs while providing a higher degree of assurance that performance is maintained.

This paper describes the development of a rating system (ranking procedure) as part of the Plant Life Management of CANDU generating station concrete structures and illustrates its application to an operating plant.

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INTRODUCTION

Aging of concrete structures is defined as the progressive loss of original mechanical and structural properties caused by physical loads, the effects of plant operation and exposure to the natural environments. Aging may result in noticeable physical changes such as cracking or loss of concrete, or internal changes that require extensive testing to evaluate. Typically for nuclear generating stations, the design safety factors and field quality control during construction result in as-built structures of substantial capacity. Even though some aspects of aging such as increase in compressive strength with time are beneficial, in general, concrete structures undergo degradation from severe operating conditions and exposure to aggressive natural environments.

Integrity of safety-related structures is important to the long-term performance of nuclear generating stations. Figure 1 shows a logic diagram of the 'Plant Life Management' (PLM) Program. Safety and licensing are the two main drivers of this program. For continued operation, CANDU generating station (NGS) safety-related concrete structures must be well maintained.

A numerical ranking procedure is required to focus inspections, maintenance, and rehabilitation of structures most important to public safety. The ranking procedure is a continuous process that involves monitoring of aging and numerical rating of sub-elements with respect to their aging and safety significance. It complements the inspection procedures and prioritizes maintenance of structural elements. By focusing on those structures having the highest importance, available resources for overall plant aging management may be effectively utilized. Because the ranking procedure takes into account the safety significance and aging of the components, the higher ranked sub-elements may require more frequent inspections compared to those that have a lower ranking. Structural components may be re-ranked periodically (i.e., every 3 to 5 years) to confirm or modify their relative ranking.

The report by D. J. Naus [1] provides a detailed account of the structural aging assessment work conducted for US power plants. Methodologies to assess the structural aging of concrete structures by the use of ranking procedures were developed by Hookham [2,3] for US power plants and by R.C. Judges [4] for UK power stations. They provide a logical and sound basis for classifying structural components based on their aging degradation and safety significance. However, these procedures involve the evaluation of a large number of parameters.

It was considered that a simplified methodology based on these procedures can be developed for CANDU structures. The modified ranking methodology described in this paper can be used for prioritizing sub-elements or components of safety related structures. It provides a logical method of selecting components for regular inspection, maintenance and repairs. An application to a typical CANDU 6 station illustrates the methodology.

RANKING METHODOLOGY FOR CANDU STRUCTURES

Figure 2 shows the relation of the proposed ranking procedures to Plant Life Management. As the first step in ranking, all safety-related structures at the particular CANDU facility are identified and sub-elements (components) are defined. An example of a safety related structure is the reactor building, and its sub-elements include components such as the base slab, perimeter wall, and internal walls, columns and floors. To rank sub-elements, a number of factors have to be evaluated for each sub-element that can be presented in a numerical rating system. Initially, these factors are estimated on the basis of the best information available. The source of information can be design drawings, safety documents, inspection reports [5] and a visual examination of the sub-elements. Some of the sub-elements are shown in Figures 3 and 4 of a typical CANDU NGS reactor building. Based on these data, an initial ranking of the components can be done. The top-ranking components from the initial ranking are examined further in more detail which may involve field and laboratory testing. If the degree of damage is found to be significant, a structural evaluation may be required to establish the effect of aging on the structural and functional capacity of the components. If the capacities of the components have degraded below an acceptable level, repairs would be necessary.

PROCEDURE

The proposed procedure is centered on two main parameters: the extent or potential for degradation of the sub-element and the safety significance of the structure.

If no degradation is evident for the sub-elements and if only limited likelihood of degradation exists due to the benign service environment, the ranking procedure is not taken any further. The structure or sub-element may be omitted from the ranking procedure as the degradation rates will be very slow or insignificant. Even if degradation is evident and if the structure has only minor safety significance, it will receive a low ranking.

Each sub-element is assessed using the following ranking formula:

Sub-element ranking (SR) = Degradation Factor (D_f) x Safety Significance (S_s)

1) Degradation Factor (D_f)

The Degradation Factor is based on an estimate of the Extent of Degradation (D_e) and the Impact of degradation (D_i) of the sub-element in terms of its reduction in structural and functional capacity.

Degradation Factor (D_f) = Extent of Degradation (D_e) x Impact of Degradation (D_i).

1a) Extent of Degradation (D_e):

Where degradation of concrete in a sub-element is evident, an estimate is made of the extent of degradation. Also, if the sub-element is located in an unfavorable (severe) service environment that is not accessible for detailed inspection, there would be a high probability of undetected degradation. In this case, the sub-element would be rated for the Likelihood of Degradation based on the severity of the environmental exposure and the type of degradation that can be present under such an environmental exposure condition. The rating is based on a scale of 1 to 10. A lower value is given if there is no evidence of degradation or likelihood of degradation of the sub-element based on the service condition.

A number of mechanisms or modes can cause degradation of concrete elements including the following:

- Reinforcing steel corrosion;
- Attack by chemicals such as chlorides, sulfates, carbon dioxide and nitrates;
- Leaching of calcium from cement by rain water or ground water;
- Freeze/thaw degradation;
- Cracking and spalling of concrete caused by thermal effects;
- Irradiation effects;
- Abrasion, erosion, cavitation; and
- Fatigue.

Degradation of concrete structures can be a direct result of an individual degradation mode or the effect of two or three modes acting in concert. Methods that can be used to detect damage can be grouped as direct techniques and indirect techniques. Direct techniques involve a visual examination of the structure, removal of material from defined distress areas for testing or a combination of the two. Indirect techniques measure the properties of concrete in a non-intrusive manner. Non-destructive techniques include ultrasonic, stress wave, surface hardness and penetrating radar.

1b) Impact of Degradation (D_i)

The impact of degradation on the sub-element may be minor, causing only a local weakening of the sub-element (such as cracking or spalling of a localized nature). On the other hand, the impact of degradation may be high, causing severe weakening of the sub-element and thereby affecting its structural capacity. Another consideration in evaluating the impact is the effect of the sub-element weakening on the stability of the whole structure. If the weakening or loss of the sub-element would affect the structural stability of the whole structure, then the impact would be rated high. Table 1 shows an example of typical Impact of Degradation values (D_i) assigned to various degradation modes. They are based on industry knowledge on the impact of the modes of degradation on reinforced concrete structures.

2) Safety Significance (S_s)

Safety Significance values are assigned on the basis of the safety functions served by the structure and the structural significance of the sub-element. The Safety Significance is calculated as a product of the Safety Function (S_f): and the Component Significance (C_s).

Safety Significance (S_s) = Safety Function (S_f) x Component Significance (C_s).

2a) Safety Function (S_f):

The "safety-related" structures are those that are necessary to ensure the integrity of the reactor coolant pressure boundary, to shut down the reactor, to maintain it in a safe condition, and to mitigate the consequence of a radiation release during a loss-of-coolant accident (LOCA). They are essential to the function of the safety class systems and components, and a failure of these elements would lead to loss of function of safety systems and components housed, supported and protected. In meeting its functional and performance requirements, a safety-related structure may be required to perform one or more of the functions listed below:

1. Containment of radioactive liquids or airborne contamination;
2. Radiation attenuation or shielding;
3. Structural support of nuclear steam supply system and other safety-related equipment, and
4. Protection of communication systems and functions.

If the collapse of a structural element would endanger a safety system, then that structural element should also be considered as a safety-related element.

The Safety Function values are assigned over a range from 1 to 10. A high value would mean that the structure is performing a number of functions that have major safety significance. For example, a factor of 10 is assigned to the reactor building containment structure that provides confinement of radioactive gases and liquids. The rating for the safety-related structure is applied to all its sub-elements. For example, for a containment structure, the same rating will apply to the sub-elements such as the base slab, the perimeter wall, the ring beam and the dome.

2b) Component Significance (C_s):

Each structure is composed of several sub-elements, and they are all treated as distinct components of the structure. The Component Significance value takes into consideration the relative importance of each component (sub-element) to the others, and its contribution to the overall integrity of the structure. The rating system uses a scale from 1 to 10; 10 for components having the highest structural importance. The primary load-carrying sub-element for each structure is typically the foundation, which must distribute the loading to the underlying soil or rock. Because the foundation is an essential component of any structure and the loss of foundation is fatal to the integrity of the structure, it is given a rating of 10. Similarly, columns and walls are supporting elements for floor slabs and hence they are given a higher rating compared to the slabs.

APPLICATION TO A TYPICAL CANDU 6 STATION

This methodology can be illustrated numerically by applying it to a typical CANDU NGS reactor building structure. From design drawings and documents, the structural components (sub-elements) of the reactor building were identified. Figures 3 and 4 show an elevation and a plan of the reactor building with some of the sub-elements identified for illustration purposes.

Degradation Factor (D_f):

Table 2 shows the evaluation of the Degradation Factors (D_f) for a typical CANDU 6 station reactor building. Sub-elements of the reactor building are identified in column 2 and relevant degradation modes are shown in column 3 under 'Degradation', for each concrete sub-element. For example, for the base slab, the major degradation modes identified are reinforcement corrosion, chemical attack and leaching of calcium from the concrete. All these modes can cause degradation of concrete; however, some of the degradation modes can cause more severe damage compared to others. Considering the evidence or likelihood of degradation of the sub-element, the extent of degradation is estimated and is shown in column 4 under 'Degradation Extent (D_e). The impact factor selected for each mode of degradation is given in Column 5 under 'Impact Factor' The Degradation Factors are obtained as a product of Extent of Degradation and Impact of Degradation in columns 4 and 5. The highest of the Degradation Factors is selected as the Degradation Factor (D_f) for the ranking evaluations.

Safety Significance of Sub-Elements

Table 3 shows the calculations leading to the Safety Significance (S_s) and ranking of the sub-elements. Column 3 indicates the Degradation Factor as obtained from Table 2, column 7. Column 4 in Table 3 indicates the factors assigned to the Safety Functions performed by the sub-elements and the 'Component Significance' is given in column 5. Safety Significance Factors (S_s) are obtained by multiplying column 4 and 5 and dividing by 10.

Ranking

The sub-element ranking is obtained by multiplying the Degradation Factors (D_f) in column 3 in Table 3 by the Safety Significance Factors in column 6. The item numbers in Table 2 are re-arranged in Table 3 to present the numerical rating of sub-elements starting from a maximum value to the minimum. The sub-element ranking for the reactor building, is shown in column 7. The ranking values range from 90 to 448 out of a maximum possible theoretical value of 1000. A ranking value of 1000 would indicate significant degradation of a concrete sub-element. The dome, outside face, has the highest ranking value of 448. Figure 5 shows a graphical representation of these ranking values. Thirteen elements have a ranking higher than 160. The internal walls and slabs rank lower. This is because of the favorable operating environment they are subjected to and because of their lower Safety Significance.

The ranking of sub-elements obtained in this analysis suggests priorities for field inspections and damage identifications. Sub-elements with a higher rank would require subsequent detailed examination and potential repairs compared to those with a lower ranking.

The Degradation Factors (D_f) will be revised based on the results of inspection and maintenance. The (D_f) rating of similar sub-elements of a structure may differ due to localized defects or exposure conditions causing the ranking the order of sub-elements to change.

CONCLUSIONS

This paper describes a technique for ranking sub-elements of a concrete structure on the basis of their overall importance and safety significance. The ranking procedure can be used to identify the sub-elements that need further inspection and maintenance.

It is recommended that the ranking assessment should be repeated every few years for safety-related structures to address the results of inspections and repairs. Repairs made to a sub-element would lower the relative ranking of that sub-element; thus bringing other sub-elements to the top of the ranking list. This procedure can also be applied to other structures of CANDU generating stations even though they may have different configurations, and their sub-elements may have different safety significance.

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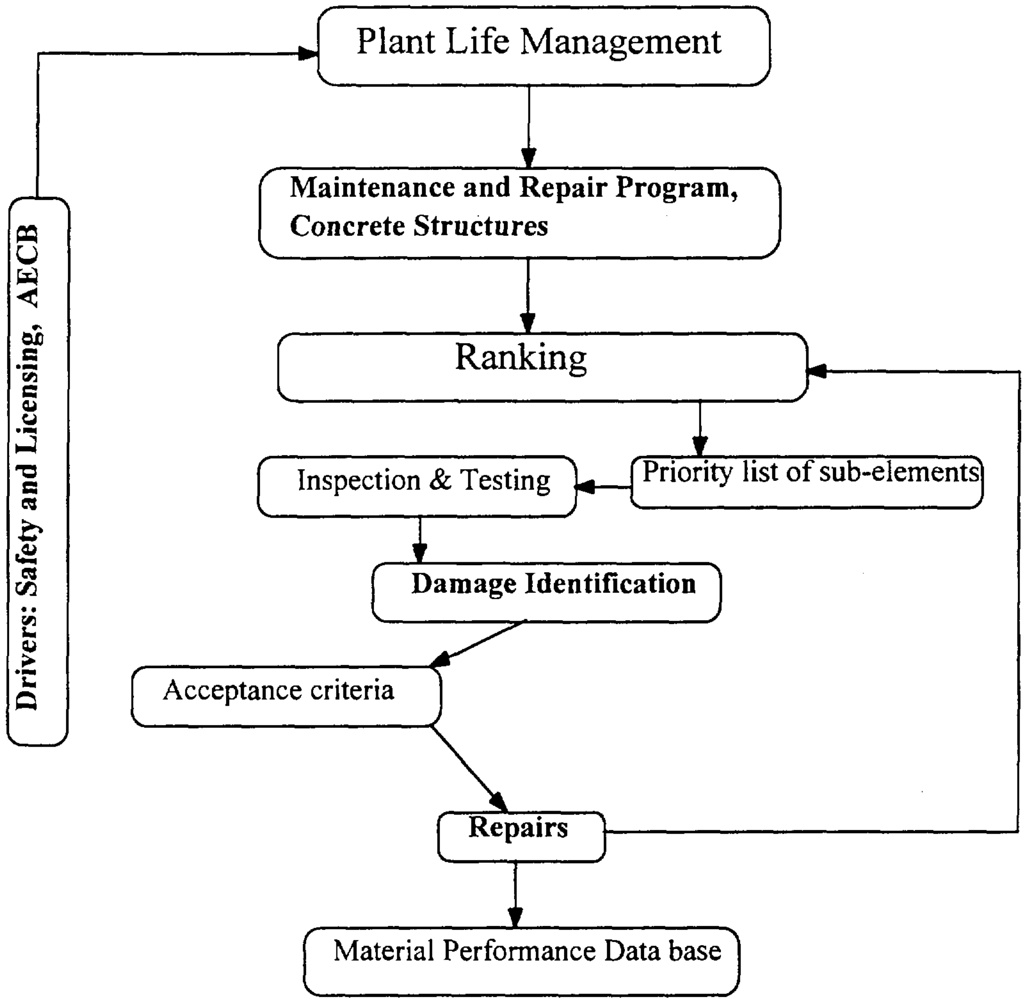

Figure 1: Plant Life Management Program

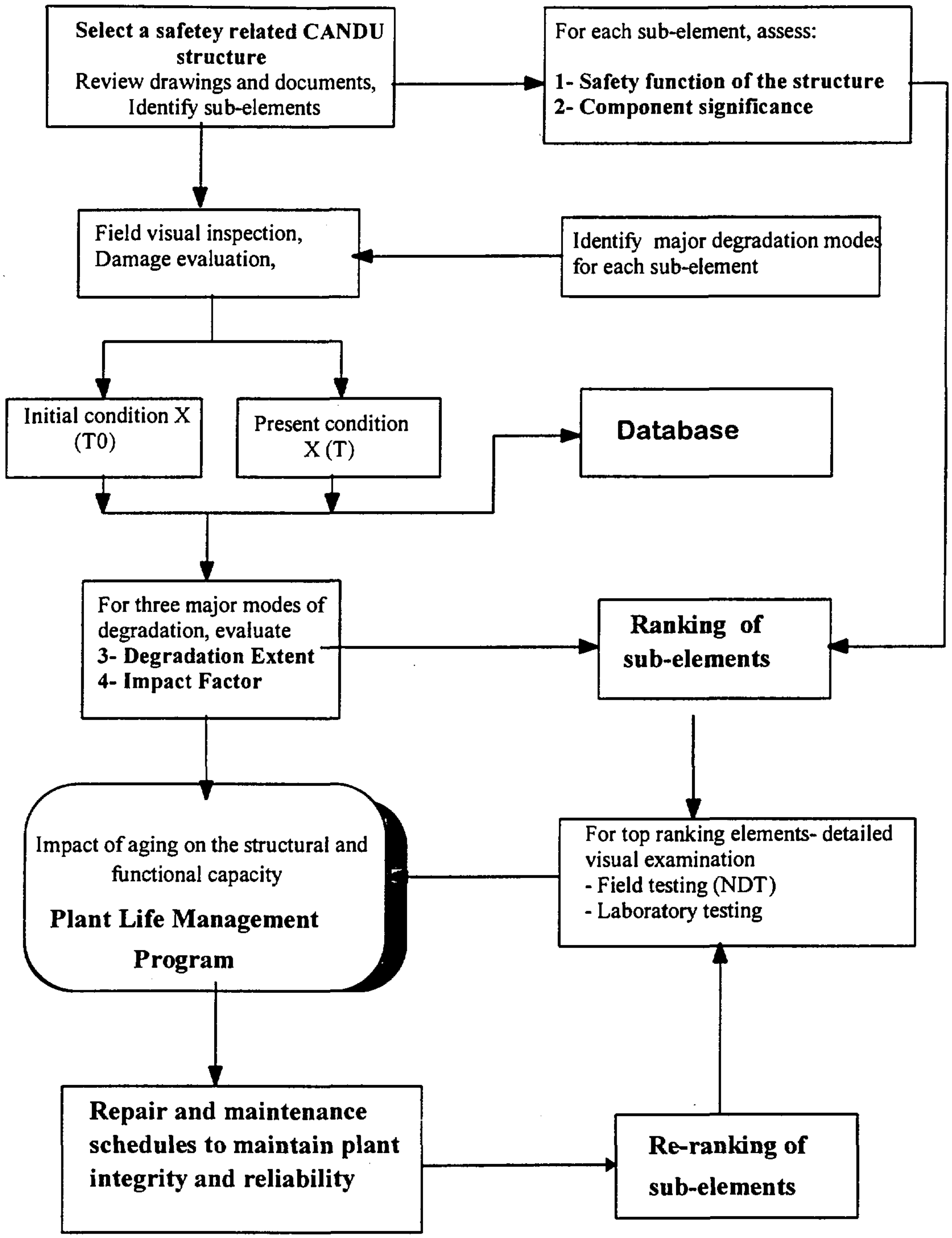

Figure 2: Ranking Program: Tie-in With Repair And Maintenance

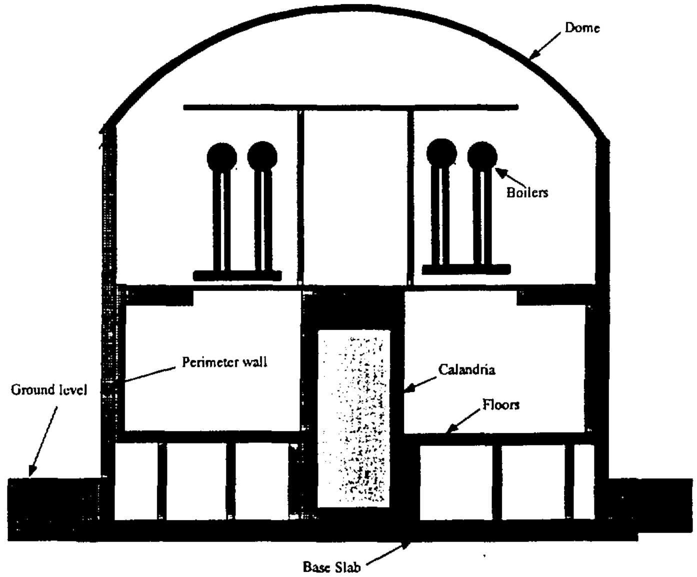

Figure 3:--A typical CANDU 6 Generating Station, Reactor Building, General Elevation

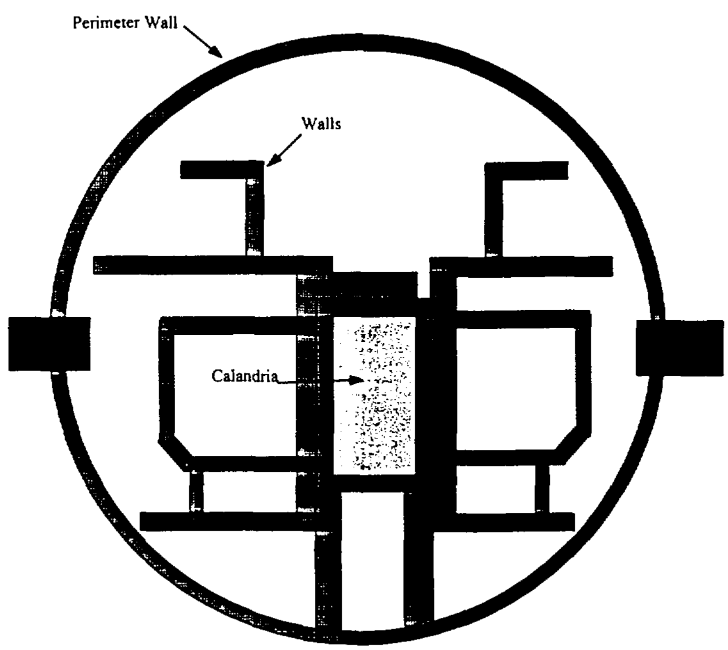

Figure 4: A typical CANDU 6 Generating Station, Reactor Building, General Plan

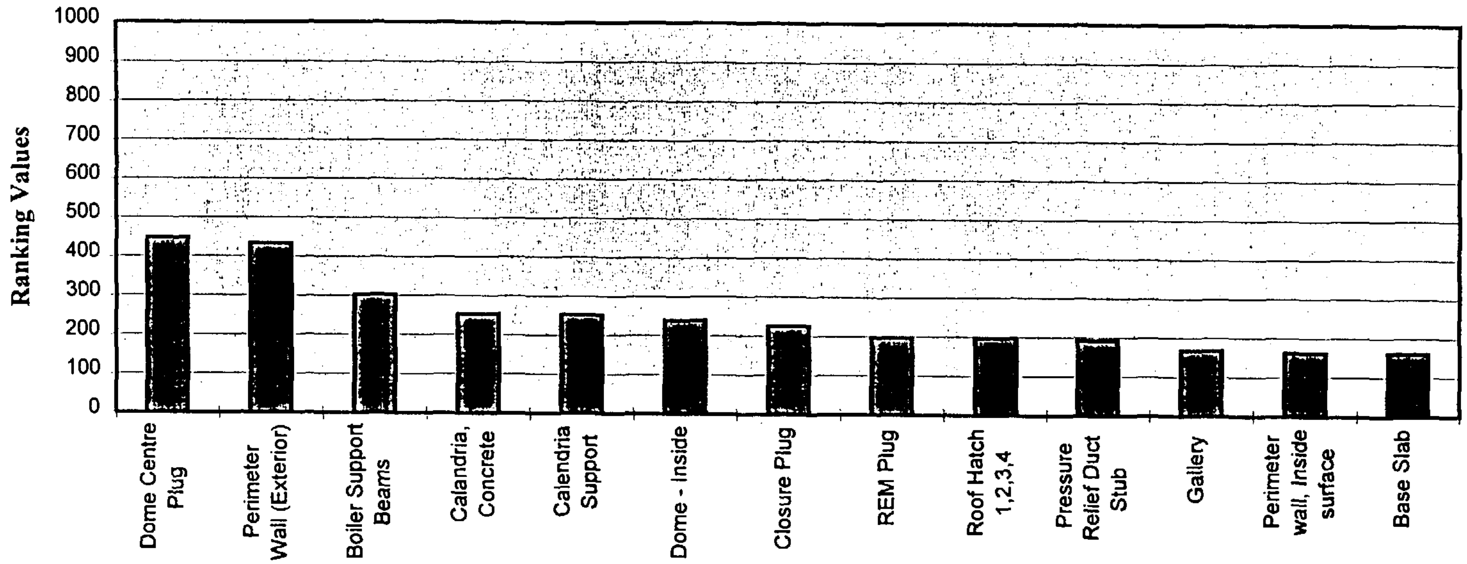

Figure 5: Graphical presentation of ranking values of sub-elements obtained in column 7, Table 3

Table 1: Typical Impact Factors assigned to Degradation Modes

Degradation Mode	Impact Factor
Reinforcement corrosion	8
Chemical attack	7
Elevated temperature	6
Thermal exposure/cracks	6
Leaching	4
Abrasion, erosion, cavitation	3
Irradiation	3

Table 2: Calculated Degradation Factors based on the Impact Factors given in Table 1

	2	3	4	5	6	7
			D_e	D_i	$D_{fs} = D_e \times D_i$	D_f, (Highest value of D_{fs})
Item	Sub-elements	Degradation Mode	Degradation Extent	Impact Factor	Degradation Factors	Degradation Factor
	Containment Building					
1	Base slab	Re-bar Corrosion	2	8	16	16
		Chemical Attack	2	7	14	
		Leaching	2	4	8	
2	Gallery at level 238' 6"	Re-bar Corrosion	2	8	16	16
		Chemical Attack	2	7	14	
		Leaching	2	4	8	
3	Perimeter wall (to spring line), inside surface	Drying Shrinkage	3	6	18	18
		Thermal Exposure	3	6	18	
		Re-bar Corrosion	2	8	16	
4	Perimeter wall (to spring line), outside surface	Re-bar Corrosion	6	8	48	48
		Freeze/Thaw Cycling	6	5	30	
		Thermal Exposure	4	6	24	
		Chemical Attack	3	7	21	
	Dome					
5	Dome - inside	Drying Shrinkage	5	6	30	30
		Thermal Exposure	4	6	24	
		Re-bar Corrosion	2	8	16	
6	Dome - outside	Re-bar Corrosion	7	8	56	56
		Thermal Exposure	7	6	42	
		Leaching	4	4	16	
		Chemical Attack	3	7	21	
7	Dome centre Plug	Re-bar Corrosion	7	8	56	56
		Thermal Exposure	7	6	42	
		Leaching	4	4	16	
		Chemical Attack	3	7	21	
8	Pressure relief duct stub	Re-bar Corrosion	3	8	24	24
		Freeze/Thaw	3	5	15	
		Thermal Exposure	3	6	18	
9	Calandria, concrete	Radiation/Chemical	5	7	35	35
		Thermal Exposure	4	6	24	
		Re-bar Corrosion	2	8	16	

continued . . .

Table 2 (continued)

10	Calandria support	Radiation/Chemical	5	7	35	35
		Thermal Exposure	4	6	24	
		Re-bar Corrosion	2	8	16	
11	Closure plug	Chemical	5	7	35	35
		Thermal	4	6	24	
12	REM plug	Chemical attack	5	7	35	35
		Thermal	4	6	24	
		Radiation/Chemical	2	7	14	
13	Roof hatch 1,2,3,4	Chemical attack	5	7	35	35
		Thermal	4	6	24	
		Radiation/Chemical	2	7	14	
14	South cross wall	Chemical attack	5	7	35	35
		Thermal	4	6	24	
		Radiation	2	7	14	
15	North cross walls	Chemical attack	5	7	35	35
		Thermal	4	6	24	
		Radiation	2	7	14	
16	North Area walls	Chemical attack	5	7	35	35
	1-East	Thermal	4	6	24	
	2- West	Radiation	2	7	14	
17	Control Area walls	Chemical attack	5	7	35	35
	1- East	Thermal	4	6	24	
	2- West	Radiation	2	7	14	
18	Elevation 274	Chemical attack	5	7	35	35
	Room 216	Thermal	4	6	24	
	Room 217	Radiation	2	7	14	
	Room 202					
	Room 203					
19	Shield wall R-208	Chemical attack	5	6	30	30
	R-209	Thermal	4	7	28	
		Radiation	2	6	12	
20	Floor at level 274'	Chemical attack	5	6	30	30
		Thermal	4	7	28	
		Re-bar Corrosion	2	6	12	
21	Floor at level 289'	Chemical attack	5	6	30	30
		Thermal	4	7	28	
		Re-bar Corrosion	2	6	12	

continued . . .

Table 2 (concluded)

22	Floor at level 311' 6"	Chemical attack	5	6	30	30
		Thermal	4	7	28	
		Re-bar Corrosion	2	6	12	
23	Floor at level 317' 6"	Chemical attack	5	6	30	30
		Thermal	4	7	28	
		Re-bar Corrosion	2	6	12	
24	Boiler support beams	Thermal	9	7	63	63
		Re-bar Corrosion	2	8	16	
25	Fuel machine support	Chemical attack	5	6	30	30
		Thermal	4	7	28	
		Radiation	2	6	12	

Table 3: Ranking Values of sub-elements based on the highest Degradation Factors (D_f) from Table 2 (see Note, next page)

1	2	3	4	5	6	7
Item *	Sub Elements	Degradation Factor D_f	Safety Function S_f	Component Significance C_s	Safety Significance Factor (Ss) $S_s = S_f \times C_s/10$	Ranking $S_R = D_f \times S_s$
1	Dome - outside	56	10	8	8	448
2	Dome centre plug	56	10	8	8	448
3	Perimeter wall (to spring line, outside face)	48	10	9	9	432
4	Boiler support beams	63	8	6	4.8	302
5	Calandria, concrete	35	9	8	7.2	252
6	Calendria support	35	9	8	7.2	252
7	Dome - inside	30	10	8	8	240
8	Closure plug	35	8	8	6.4	224
9	REM plug	35	8	7	5.6	196
10	Roof hatch 1,2,3,4	35	8	7	5.6	196
11	Pressure relief duct stub	24	10	8	8	192
12	Fuel machine support	30	8	7	5.6	168
13	Perimeter wall (to spring line), Inside surface	18	10	9	9	162
14	Base slab	16	10	10	10	160
15	South cross wall	35	6	7	4.2	147
16	North cross walls	35	6	7	4.2	147
17	North Area walls, East, West	35	6	7	4.2	147
18	Control Area walls, East, West	35	6	7	4.2	147

continued. . .

1	2	3	4	5	6	7
Item	Sub Elements	Degradation Factor D_f	Safety Function of the Structure S_f	Component Significance C_s	Safety Significance Factor (Ss) $S_s = S_f \times C_s /10$	Ranking $SR = D_f \times S_s$
19	Elevation 274, Room 216,217,202,203	35	6	7	4.2	147
20	Shield wall R-208, R 208	30	6	7	4.2	126
21	Floor at level 274'	30	5	6	3	90
22	Floor at level 289'	30	5	6	3	90
23	Floor at level 311' 6"	30	5	6	3	90
24	Floor at level 317' 6"	30	5	6	3	90
25	Gallery at level 238' 6"	16	7	8	5.6	90

* **Note:** The item numbers in Table 2 are re-arranged to present the numerical ranking of sub-elements given in column 7 in a descending order.