

**Charting and Analysis of Turbine Maintenance
Procedures for increased safety in a Nuclear Power Plant**

by

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Executive Summary

With the growing environmental crisis and the difficulties in fossil-fuel power generation it is expected that nuclear power will soon be the power source of choice in the world.

The Pebble Bed Modular Reactor (PBMR) in Centurion, Gauteng is an example of innovation in the nuclear power generation arena. They are striving to produce a nuclear power plant that is safe, efficient and effective.

PBMR uses nuclear fuel moulded into pebbles (*see figure 1*) which are cycled slowly through the reactor core. The PBMR technology is best known for its inherent inability to overheat and thus no reactor meltdown is possible. There is no risk of an accident such as Chernobyl.

In the nuclear reactor core helium gas is superheated by the nuclear radiation of the fuel pebbles. This heat is converted to electricity by the power turbine. The PBMR power turbine has been specially developed for this nuclear reactor system (*see figure 2*).

Figure 1: PBMR Fuel Pebbles

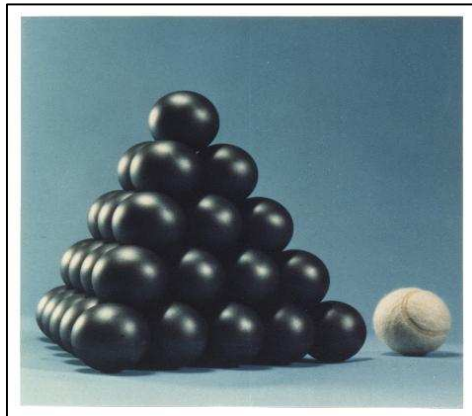
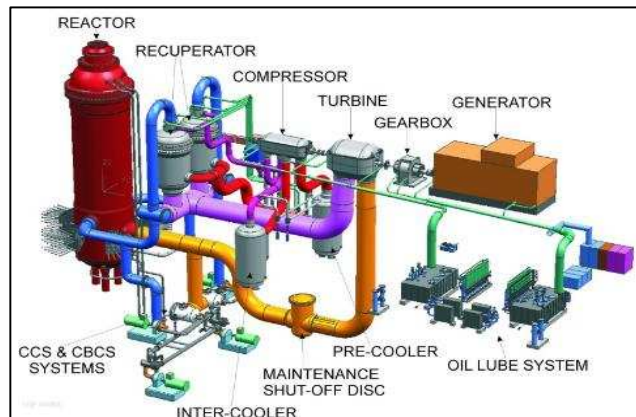


Figure 2: The PBMR Nuclear Power Plant System



During the production of energy the contact with the superheated helium exposes the interior workings of the power turbine to varying degrees and types of radiation. Computer modelling techniques are used to calculate the radiation levels that the various parts of the turbine will experience. These variations complicate the power turbine's maintenance processes.



This project focuses on the development and analysis of the maintenance procedures for the power turbine. A process flow diagram was developed to map the total process. This indicated where there were problem areas such as extremely high radiation exposure levels and tasks that may be impossible to complete by hand. The process flow diagram also assisted in determining parallel processes which can shorten working time.

Ergonomics and safety factors were also considered to identify problem tasks, assist in finding potential solutions and to increase the overall efficiency of the maintenance program. Through this process it was established that the “Cycle-Out” maintenance approach would be the only viable method.

With this knowledge in hand the remaining maintenance procedures were carefully checked to determine their inclusion in this approach. Eliminated procedures were not charted. The flow diagrams for the viable approach were completed and redrawn to include the parallel flows identified.

Upon inspection the original procedure list for the “Cycle-Out” approach was found to be incomplete. It was thus updated to include several missing procedures. The associated radiation calculations were made for the missing procedures to complete the data set. Radiation levels were mapped onto the additional flow diagram to clearly indicate radiation safety levels.

No changes were made to the safety equipment intended for use as no better alternatives could be found. Procedures where required protection measures prohibited effective working were identified and alternative methods suggested.



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1. Introduction & Background

1.1 Introduction

PBMR (Pebble Bed Modular Reactor) is a company aimed at the development, construction, commissioning and maintaining of PBMR nuclear power plants for South Africa. They are based primarily in Centurion, Gauteng.

PBMR's current goal is the development and construction of a DPP (Demonstration Power Plant) at Koeberg in the Cape. The PBMR DPP will be located adjacent to the current Koeberg Nuclear Power Station. Commissioning is scheduled for 2013.

Safety is paramount in working with nuclear technologies, especially in the application of such technologies for power generation aimed at being a safe, clean energy source for the people of South Africa.

A crucial part of the nuclear power generation process is the power turbine. Helium gas is superheated by radioactive materials in the core of the nuclear reactor and this heat is converted to electricity by the power turbine. This project focuses on the maintenance procedures of the power turbine.

1.2 Background

The power turbine is a large and specially designed piece of equipment housed inside two layers of protective casing and connected to the system through intakes and outlets. As with any other part of the system, it is both exposed to radioactive materials and requires maintenance to keep it operating efficiently and safely.



Maintenance for the power turbine is scheduled to occur at 6-year intervals. There are two approaches than can be used: overhaul or cycle-out. The overhaul approach entails the shut-down, disassembly, full servicing, reassembly and restarting of the power turbine unit. The single existing unit is maintained.

The cycle-out approach entails the rotation of two turbine units. During this procedure the entire existing unit is taken apart and the turbine is cycled out. A new or fully serviced turbine unit is put in place to operate for the next six years. The removed turbine unit is stored for a period to promote radioactive decay before servicing occurs. At the next service interval the two turbines are switched again.

In order to ensure that the maintenance is done safely and efficiently it is necessary for the entire maintenance procedure to be properly documented and analysed.

Analysis and proper documentation of this procedure will provide structure and detail which serves to assist in identification of problematic maintenance activities and dangerous radiation exposure periods.

Improved maintenance information could assist in determining which approach is best to use.



2. Project Aim

The aim of this project is to identify problem areas and research potential solutions for the maintenance procedures of the PBMR power turbine through the drawing and analysis of a process flow diagram.

PBMR has been provided with assembly and disassembly data for two differing maintenance approaches. This data needs to be broken down into manageable sections and charted with an appropriate process flow diagram (PFD) to allow problematic areas to be identified.

Construction of proper and detailed PFDs will also allow simultaneous tasks to be identified which will cut down on maintenance time. Individual task times can be allocated accordingly and the radiation dosages which maintenance personnel will experience can be calculated.

A list of problem tasks and processes can then be identified. This list will provide the groundwork for the research and development of safe and ergonomic specialised tooling or procedures that can be used to overcome obstacles for that particular maintenance approach.

Examples of maintenance obstacles that could arise from the PFD and analysis are:

- Operations which will be impossible for personnel to perform manually and should be mechanised through special tools, or done robotically.
- How carrying out a high radiation procedure is affected by wearing Personal Protective Equipment (PPE).
- What safety regulations and ergonomic issues a specific task could present.
- How these issues can be solved.



This information has great future potential value for PBMR. It can be used to appropriately schedule maintenance teams and working times to ensure radioactive safety and balanced dose periods. It can also be used to develop maintenance manuals and maintenance training materials.

Identification of problem tasks and researching potential solutions can be used in future to develop specialized tools or robotic solutions.

The PFD and the associated marked safety and ergonomic issues can be used to develop the detailed maintenance procedures that will be the standard practice for the power turbine. Detailed maintenance period information regarding the total downtimes for each maintenance approach could also be used to determine which approach is more viable.

3. Project Scope

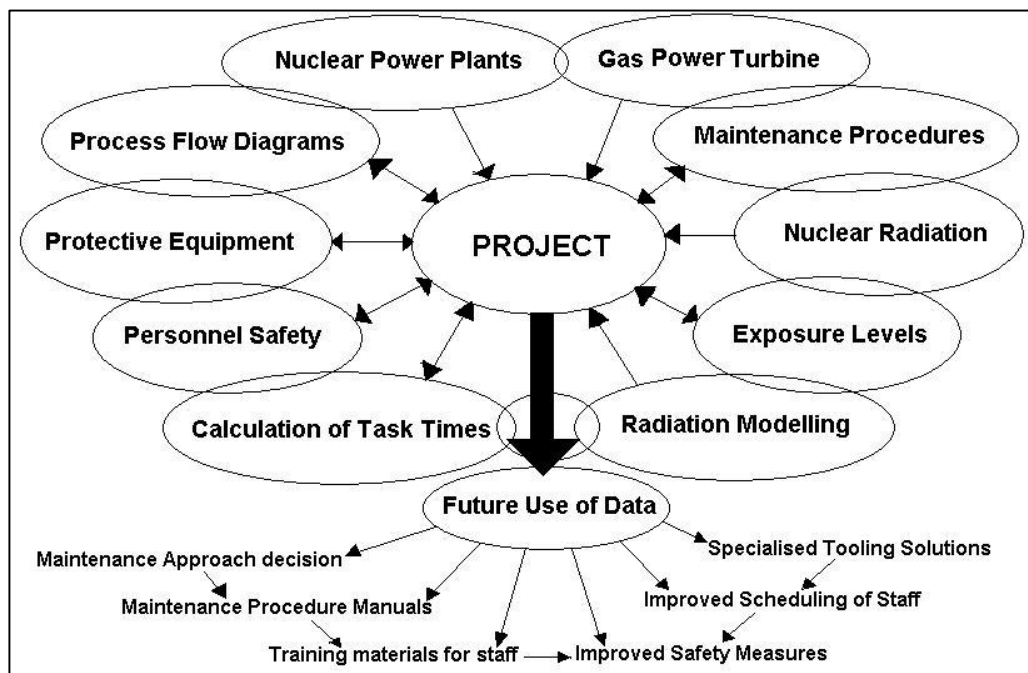
The Project includes:

- The breakdown of the entire maintenance procedure into categorised steps and charted using an appropriate process flow diagram,
- The identification of potential parallel tasks to reduce maintenance time,
- Charting of simulated task times and associated dosages based on manufacturer's data,
- Identification of problem tasks owing to radiation dosages and equipment,
- Identification of problem tasks based on Ergonomics and Safety concerns and
- Listing recommendations for solutions to problem areas with supporting research.

The Project **does not include**:

- The computer modelling of radiation dosages and body-distance radiation variations,
- The actual measuring/simulating of maintenance task times,
- The unique design and/or testing of the recommended solutions,
- The design of a maintenance procedure (only charting and analysis of existing process),
- Any alterations to the maintenance procedure (except equipment recommendations) or
- The development of a schedule for maintenance teams to reduce radiation exposure.

Figure 3: A visual overview of Project topics with information flow and future uses.





4. Literature Review & Selection of Methods, Tools & Techniques

4.1 Literature Study

4.1.1 Introduction

The nuclear power industry is still a relatively “young” field in the modern world. Although the technology has been around for more than 40 years a lot of the newer research and development occurring in this field is not public knowledge. Most projects in nuclear technology are not open learning environments and as such there is very limited reference material available that directly covers the specific topic of this project.

While it is true that nuclear energy is a widespread topic with much discussion and debate in today’s society it is the lack of (or secrecy of) research into the PBMR technology specifically which constrains this literature review to its fringe topics. As shown in figure 1 on the previous page there are numerous topics that together form this project.

While research into certain topics is either too vague or still very limited there are many reference articles which are related to this project. This research covers areas such as the building of safe nuclear reactors, the use of radioactive materials to generate energy, detection of radiation levels, human errors and the risks in nuclear power plants.



4.1.2 Nuclear Power Plants and Nuclear Energy

[10] Talamo, Alberto. (2006). *Advanced In-Core Fuel Cycles for the Gas Turbine-Modular Helium Reactor*. PhD Thesis. (KTH Royal Institute of Technology)

- Various generations of nuclear power have evolved, each focusing on improved safety and increased efficiency. This particular study focuses on testing 2 types of fuel in trying to reduce the decay of the core by increasing passive cooling.
- This project will also be designing a process for the maintenance of a gas power turbine but the fuel system is designed around pebble bed reactor technology rather than core fuel rods. This research shows the variety in the application of nuclear energy to power generation and the various ways that safety in general can be improved.

[6] Jones, Christopher Michael. (2003). *Nonproliferation Issues in the Nuclear Energy Future*. Double Master's Thesis. (Massachusetts Institute of Technology)

- In order to combat the continuing increases in greenhouse gas emissions it is necessary for less carbon-intensive energy technologies to be developed. The scale required to combat the environmental challenge will necessitate the development of nuclear power and a supporting infrastructure with workforce on a global growth scale, even in developing nations. The author questions not only the realisation of such a scenario but also the risks involved.
- The completion of this project forms part of the realisation of this scenario. PBMR is developing advanced nuclear energy technology which is inherently safe and environmentally friendly in design and in so doing is contributing towards meeting the global challenge. Future use of the materials developed in this project will also contribute to creating a workforce capable of maintaining this technology as a safe and reliable energy source. By improving the safety of the workforce and the technology the risks involved in moving towards a nuclear-powered future are greatly decreased.



4.1.3 Gas Power Turbine

[13] Zhao, Yongjun. (2005). *An Integrated Framework for Gas Turbine Based Power Plant Operational Modeling and Optimization*. Ph.D. Thesis. (Georgia Institute of Technology)

- This research encompasses the proposal of a framework which incorporates all the various major operational functions of a nuclear power plant that uses a gas turbine as its power conversion unit. By optimizing all the operational factors of the plant it enhances the strategic positioning in the electricity supply market for that specific power plant.
- It includes an optimized framework for maintenance scheduling and particularly looks at the sequential scheduling time intervals. The reality of ageing of the turbines and the influence it has on shorter periods between preventative maintenance are important to the profitability of the company.
- In nuclear power plants this operational situation is present with the added factor of the increased recurring periods of exposure to radiation that the maintenance personnel experience.
- This project thus acknowledges this operational aspect and introduces a PFD to clearly define the most effective and safe procedure for maintenance staff of the turbine to follow. This research also integrates with the concepts of turbine rotation or maintenance based upon the ageing effects of the radiation. By optimisation of the maintenance procedures the entire power plant benefits.

[11] Wang, Chunyun. (2003). *Design, Analysis and Optimization of the Power Conversion System for the Modular Pebble Bed Reactor System*. PhD Thesis. (Massachusetts Institute of Technology)

- This study deals with the development of a reference design for an indirect helium cycle in the power conversion system of a PBMR. The PBMR requires a gas turbine cycle to be used for its power conversion in order for the technology to achieve economic



competitiveness in the nuclear power generation industry. The author notes that the efficiency of the helium cycle (power conversion) is significantly affected by the performance of its individual conversion unit components.

- In analysing the maintenance procedures of the PBMR power turbine this project is contributing to the performance of the helium cycle as the turbine and compressor form the largest parts of the power conversion unit of the PBMR. The improved safety and the clarity of maintenance procedures through the development of the PFD are thus contributing to the economic competitiveness of the PBMR as a whole.

4.1.4 Radiation Modeling

[7] Ling, Xianbing. (2001). *Bayesian analysis for the site-specific dose modeling in nuclear power plant decommissioning*. Master's Thesis. (North Carolina State University)

- The author uses various modelling frameworks to determine the presence of radiation in various parts of the environment during and after decommissioning of a nuclear power plant. He provides information on the various radionuclides and their concentrations found around the nuclear power plants and then tests for them at those specific sites.
- The process flow diagram of this project takes into consideration the exposure of the various parts of the turbine to radionuclides which results in subsequent radiation exposure potential for the personnel handling them during maintenance procedures. Radiation dose modelling is the best way to judge the expected dosages for specific areas/items in order to improve safety.



[5] Jacobsson Svård, Staffan. (2004). *A Tomographic Measurement Technique for Irradiated Nuclear Fuel Assemblies*. PhD Thesis. (Uppsala University)

- This research designs a new measuring technique to measure the radiation of fuel rods without removing them from the assembly plant. It is also possible to apply the design to measure the radiation levels of spent fuel rods before removing them.
- Similar techniques are used in laboratory settings to model the exposure and absorption of radiation by the turbines to be used by PBMR. This data is used to ensure the least possible exposure to the various parts during maintenance as some parts are more radioactive than others. This influences the design of the PFD for the maintenance procedure.

4.1.5 Personnel Safety

[3] Delgado-Loperena, Dharma. (2004) *Human Error in Nuclear Power Plants: A Stochastic Dynamic Model*. Ph.D Thesis. (University of Missouri-Columbia)

- Chernobyl is an example of a nuclear disaster where failure was attributed to human error. This study researches the contributors to human performance errors and suggests a model to be used by nuclear power plant control room operators to ensure a safer environment.
- This study supports the current project by emphasizing the need to have clear and safe processes in a nuclear power plant. In this project the specific processes are limited to the maintenance of the power turbine and the safety of these procedures. Personnel operating in this particular environment should have well-defined maintenance procedures and processes which are easy to understand to provide the most efficient task plan with minimized radiation exposure.



[8] Mkhosi, Margaret Msongi. (2007). *Computational fluid dynamics analysis of aerosol deposition in pebble beds*. PhD Thesis. (Ohio State University)

- The essence of this research is to determine the transport by air of radioactive materials if they were to be released during an accident at a Pebble Bed Nuclear Reactor. Computational fluid dynamics is used to predict the dispersion of irradiated aerosol particles from the PBMR.
- This research strongly supports this project as active radionuclides are dispersed throughout the entire system of the PBMR by the inert helium from the reactor. These particles travel through the turbine and compressor and are deposited within the equipment either as plate-out or deposition radiation. Maintenance of the turbine thus has to take into account this radiation in order to maintain a safe working environment. Both the research and this project are important in proving the safety of the PBMR to allow for its subsequent licensing to operate in South Africa.

4.1.6 Task Times and Turbine Safety

[12] Yildiz, Bilge. (2003). *Development of a hybrid intelligent system for on-line real-time monitoring of nuclear power plant operations*. M.IT Thesis. (Massachusetts Institute of Technology)

- This research aimed at improving the monitoring of ongoing operations and productivity in a nuclear power plant and other environments with complex systems by creating a monitoring system for early detection of errors. They specifically looked at monitoring various factors that affect the bearings in complex equipment. Turbines use shafts and complex bearing structures and which will benefit by such an early warning system as malfunctions and the resulting loss in production are very costly.
- This project will provide a process flow diagram used during routine maintenance of the turbine, which will also focus on parallel tasks to ensure that no unneeded time is wasted during maintenance, not only for the limitation of exposure to radiation, but also for the



minimizing of downtime of the turbine. Turbine downtime means no power generation which results in economic losses. A real-time monitoring system such as the research describes will continue to operate through maintenance and improves the safety of the working environment.

4.1.7 Maintenance Procedures

[9] Smith, Curtis Lee. (2002). *Risk-informed incident management for nuclear power plants*. Ph.D Thesis. (Massachusetts Institute of Technology)

- In this research the author examines various factors that influence decision making in the operations of a nuclear power plant then develops a methodology and tests it in two case studies requiring informed decisions during incidents in the plant. He provides a tool with which managers can defend their decisions as it is based on sound scientific principles and includes all factors relevant to the specific environment.
- The methodology eliminates personal preferences and ensures that various groups who give input to the decisions all consider similar factors, which if not guided by a given methodology for decision making, can result in increased risk affecting efficiency and economics.
- This project proposes to achieve a similar result, thus providing the maintenance team with a clear and scientific process to approach the maintenance of the turbine. Radiation exposure specifics and parallel tasks have been predetermined and translated into procedure and safety regulations.

[4] Erguina, Vera. (2004). *Safety assured financial evaluation of maintenance*. Ph.D Thesis. (Texas A&M University)

- Continued economic success is the reason for this model, while balancing this with the safety and environmental factors influencing the maintenance scheduling. The study



looks at maintaining reliability and how to allocate funding to keep reliability optimal. The author acknowledges that the reliability of the operations at a nuclear power plant is based on the initial reliability of the plant and the subsequent reliability of maintenance procedures.

- Although this research and modelling is done in the traditional environment of radioactive cores which are prone to decay and cooling issues (with the possibility of meltdown as the extreme case of failure) the reliability factors of the nuclear power plants are similar in their effect on safety and profitability. The analysis of maintenance procedures from a safety perspective is the exact undertaking of this project.

4.1.8 Process Flow Diagrams

[1] Bandara, Wasana. (2007). *Process modelling success factors and measures*. PhD Thesis. (Queensland University of Technology)

- The author has researched the application of business process modelling as a process design technique with a focus on “how” to do this effectively. This research is the first study which has shown empirical evidence for the success of process modelling techniques. It also considers the proper identification of the process and the workflow as guidelines in effective management.
- While business and a turbine may be very different process scenarios the fact remains that processes need to be understood. While businesses require process models the turbine maintenance procedure requires an effective process flow diagram. Properly identifying and charting the workflow as a PFD will assist in effectively managing the maintenance procedure.

[2] Blomqvist, Peter & Wygler, Franz. (2006). *Analysing and Reengineering the Order Process at Noblessa Sverige AB: A Pre-Study for an ERP System Implementation*. Master’s Thesis’. (Linköping University)



- This research focuses on the analysis and re-engineering of an order process system at a sales company as preparation for the acquisition of an ERP system to increase order capacity. In order to understand the current order process the system was mapped so that improvement areas could be identified. This process mapping was then used to develop an improved process.
- This research supports the selection of process flow diagrams as the major tool for this project. In order to enhance the safety and improve the maintenance procedures it is necessary to understand the process. Mapping the process using process flow diagrams will result in the ability to identify problem areas so that improvements can be made.

4.2 Selection of Methods, Tools and Techniques

The major technique for the execution of this project will be the charting of the maintenance procedures using process flow diagrams.

The PFD will be detailed with other applicable collected data in order to create a comprehensive and detailed yet logical and understandable maintenance flow diagram. This PFD can then be used to identify problem areas in the maintenance procedures with regards to radiation dosages.

General research and ingenuity will be applied to discover potential solutions to problem areas. Ergonomics and general safety (in adherence with the Occupational Health and Safety Act) will be considered when identifying problems and potential solutions.



5. Project Environment and Data Analysis

5.1 The Project Environment

This project falls under the auspices of the Special Tooling Division of PBMR. Special Tooling is dedicated to the analysis and development of specialised equipment solutions for the PBMR. This stems from the lack of existing tools and machinery available to maintain and operate the very unique design of this PBMR.

Work done in this particular division is mostly in digital format however hard copies of all materials are maintained for reference purposes. Often scale models are built to assist in understanding and solving unique design problems. A large open-plan office with mid-height cubicles provides a good balance between interaction, communication, personal space and privacy.

PBMR has catered for this project by providing collections of data, support from its engineers in this division, a working space within the offices of the division and has offered internet connectivity as well as a computer with software on which to work. The offices provide all necessary amenities for a working environment. A prerequisite for the undertaking of this project is that all source data and work done on this project will remain the property of PBMR. All information forming part of this project will be governed by PBMR's intellectual property rights.

This project cannot be ranked as "vital" to the company however it is "necessary" that the work be done in order for the construction of the plant to go ahead. This can be said for almost any of the work taking place within PBMR. With commissioning of the DPP set for 2013 there is somewhat pressure to meet deadlines for approvals from the National Nuclear Regulator (NNR), a public entity reporting to the Department of Minerals and Energy.



The necessity for the completion of this work will still exist even if the work were not undertaken for the purposes of this project. The work is ideally suited for the Industrial Engineering discipline as it contains a great deal of process flow diagram creation and analysis as well as safety and ergonomics aspects.

For the purposes of this project stakeholders are defined as any party with an interest in the work of this project or any party who may benefit (even unknowingly) from the work done in the project.

The stakeholders of this project are:

- The candidate (this student),
- PBMR Special Tooling Division,
- PBMR Demonstration Power Plant (DPP) Division,
- Maintenance and training manual creators for turbine operations (PBMR),
- PBMR turbine maintenance workers,
- The Department of Industrial Engineering, UP,
- Eskom and
- The general electricity-consuming populace of South Africa.



5.2 Data Gathering and Analysis

The data for this project has been sourced by way of the Special Tooling division of PBMR. The data in its raw form consists of documentation from both the turbine manufacturer and the turbine systems design teams at PBMR. No actual documentation has been included in this report owing to the confidential nature of these documents. Examples and extracts are shown.

This data analysis does cover the purpose, organisation and quality of the data gathered. The data is divided into sets of which the content and use of the data are explained. The relationship between the gathered data as it relates to this project is also shown. The data only takes into account non-emergency and standard operational events. Emergency situations, such as breakages or penetrations are outside the scope of this project.

5.2.1 The purpose and risks of data gathering:

This project has significant practical application rather than theoretical formulation. Without the data gathered it would not be possible to do this project as it is, simply put, merely a logical consolidation and rearrangement of the various data sets into a simple, logical and useful form. This is then used to identify problems and research potential solutions in order to improve safety.

Without obtaining all the required data possible this project would be extremely risky. It is thus important to ensure that all the necessary data was gathered before proceeding with the task. Lack of data in any particular set could cause incorrect or incomplete results which, given the environment in which this project lies, could cause a very unsafe working environment.

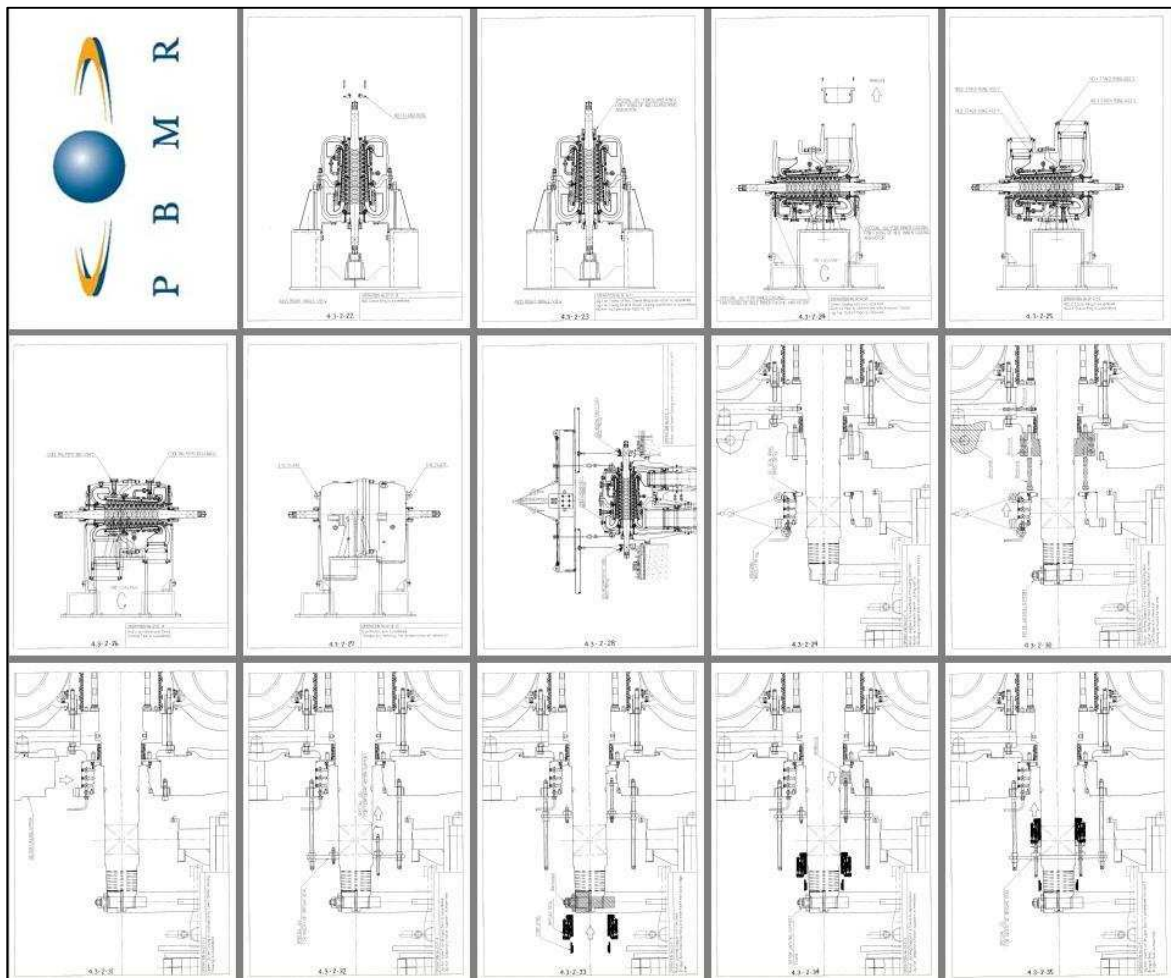
5.2.2 Turbine assembly/disassembly procedures

Detailed assembly/disassembly procedures for the entire turbine unit are documented in three formats:

- Textual – step by step written instructions (example not shown)
- Schematic – a series of machine design drawings (see Image 3)
- Graphic – a collection of 3D computer models (see Image 4)

It must be noted that the assembly and disassembly procedures for the turbine are identical but reversed. Also, assembly/disassembly should not be confused with maintenance. While maintenance does require disassembly and assembly of the turbine it also requires other tasks such as actual repair work which distinguishes it from normal assembly/disassembly procedures.

Figure 4: Example of machine design drawings for turbine assembly/disassembly





4.1 Outline

The maintenance outline is shown in fig.4.1-1 to fig.4.1-2

Fig.4.1-1 The Turbine maintenance outline
The T-Inner Casing ,T-Rotor Ass'y are used

Fig.4.1-2 The Turbine maintenance outline
T-Inner Casing ,T-Rotor Ass'y are new-replacement

The outline of the maintenance procedures is provided in a rough flow-diagram fashion (see Image 5). This flow diagram contains very little detail and excludes the effects of radiation.

The full details of the turbine maintenance procedure can be extracted (in spreadsheet format) from the working body distances and man-hours documentation (see section 5.2.7).

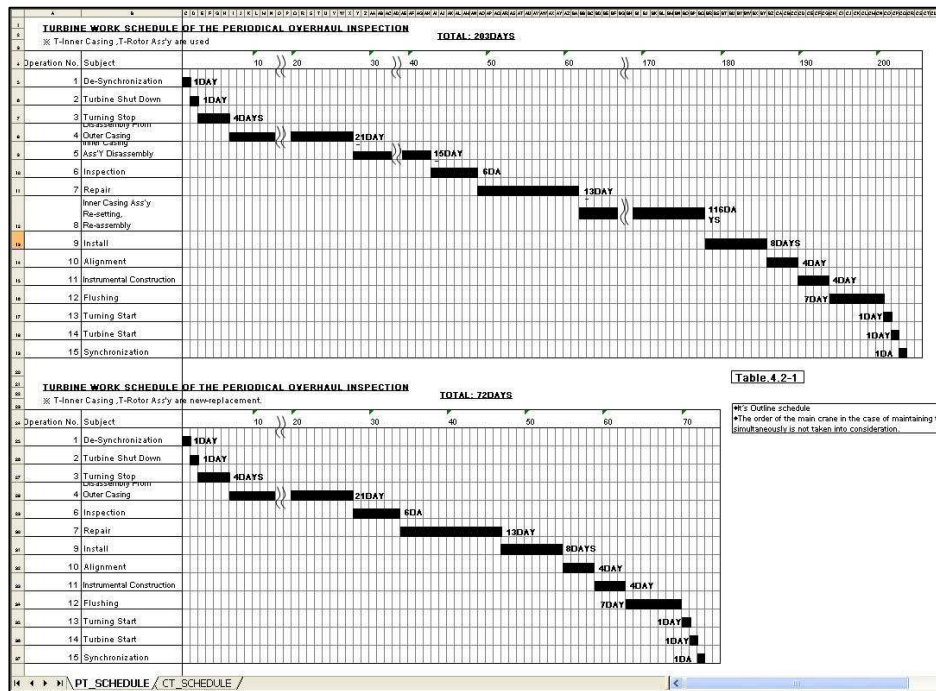


5.2.4 Work duration estimates

The turbine manufacturer has compiled a spreadsheet-based Gantt Chart to document the expected work duration estimates for the two maintenance approaches. (see Image 6)

These show the full time period estimated for disassembly, inspection, repair and reassembly of the power turbine. This data will be used to both generate and moderate the total process flow diagram that will be developed.

Figure 7: Spreadsheet-based Gantt Chart showing work duration estimates for full maintenance.



5.2.5 Radiation modelling

Atomic radionuclides generated in the core of the nuclear reactor are carried through the power plant system by the superheated helium gas. These radionuclides are deposited throughout the system in two manners: “plate out” or “dust deposition”. Most of the radioactivity present in the



turbine is due to the plate-out of the radionuclides on the inner surfaces. Radioactive dust also settles on these surfaces but their radioactivity is negligible to that of the plate-out deposits.

To assist in the planning of the maintenance tasks and especially in planning the appropriate radiation protection measures which may be required the radiation dose rates have been calculated at a number of locations around the turbine at various stages of disassembly, inspection and possibly repair.

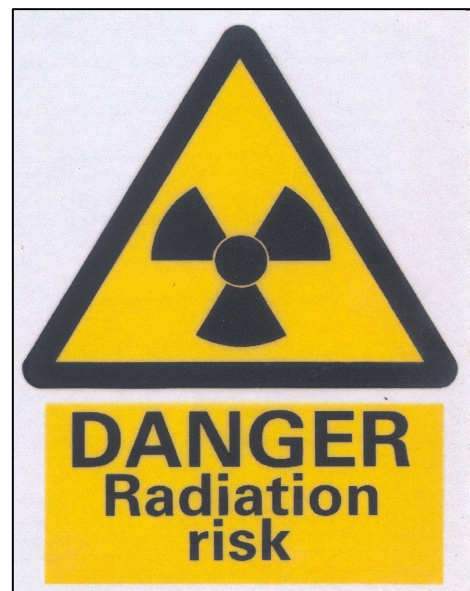
The computer modelling of the radiation levels has been done using specialised software. The comprehensive details of these models as well as explanatory text regarding the results have been provided. This data is mostly in text and table formats. Modelled dose rates which exceed the specified criteria for safe operating conditions have been highlighted.

5.2.6 Maximum safe radiation exposure levels

In order to maintain the safety of workers during maintenance it is necessary to understand the limits of the human body with relation to radiation exposure. Many years of medical testing and research into these fields have determined safe exposure levels. These dose rates are moderated and approved by nuclear authorities such as the NNR and are reviewed on an international level.

The maximum safe dose rates as approved for the PBMR have been tabulated and are included in the modelling documentation (see section 5.2.5).

Figure 8: Radiation warning symbol





5.2.7 Working body distances & man-hours

The distances between the body of the worker and the irradiated components are documented in a spreadsheet which also contains the detailed maintenance process. The man-hours required for certain processes are also tabulated in this document. These three data sets will play a vital role in the creation of the PFDs for this project. Below is a segment of the spreadsheet (see image 8).

Useful information derived from the spreadsheet regarding turbine (dis)assembly requirements:

- 11 523 man hours if the turbine inner casing and turbine rotor assembly are reused,
- 2 738 if the inner casing assembly is replaced with a pre-assembled inner casing,
- 3.3 workers minimum to complete the assembly in 345.9 days, or
- 18 workers maximum to perform the assembly in the shortest possible time (202.6 days).
- A dedicated maintenance area on the maintenance facility floor,
- 200mm approximate working distance from the worker's body.

Figure 9: Spreadsheet containing process, man-hours and working body distance details.

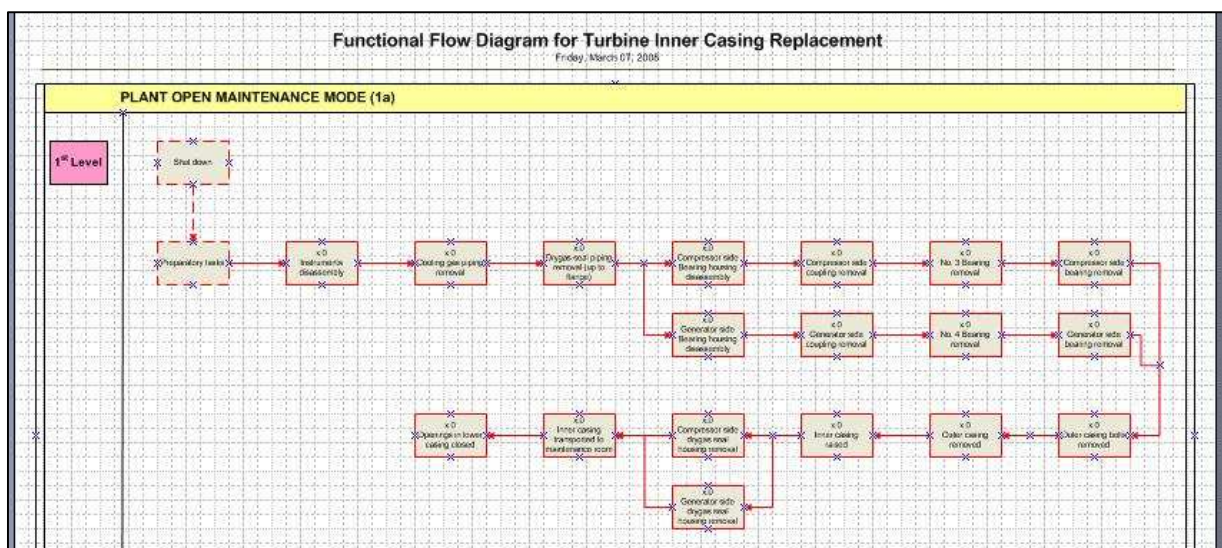
3	P B M R TURBINE MAINTENANCE PROCEDURE								
4	Operation	Subject	Detail	Min Worker	Work Hour	Man - Hour	Day	Working Distance from Worker's body (mm)	Drawing
119	5-7	No.3 Blade Ring Disassembly (Operation Side By Side)	#10 Isolation Ring, Lugs And Row 9 Stationary Blade Are Disassembled	3	4	12	0.4	~ 200	
120			#19,20 Isolation Rings And #9 Ring Segment Are Disassembled	3	3	9	0.3	~ 200	
121			Row 10 Stationary Blade Is Disassembled	3	2	6	0.2	~ 200	
122			#21,22 Isolation Rings And #10 Ring Segment Are Disassembled	3	3	9	0.3	~ 200	
123			Row 11 Stationary Blade Is Disassembled	3	2	6	0.2	~ 200	
124			#23,24 Isolation Rings And #11 Ring Segment Are Disassembled	3	3	9	0.3	~ 200	
125			Row 12 Stationary Blade Is Disassembled	3	2	6	0.2	~ 200	
126			#25,26 Isolation Rings, Lugs And #12 Ring Segment Are Disassembled	3	3	9	0.3	~ 200	
127			Ope No.5-7 Sub Total	3.0	33	99	3.3		
128			5-8	Inlet Dummig Ring Disassembly	The Seal Ring Is Disassembled(Leak Type)	3	3	9	0.3
129	Seal Rings Are Disassembled(Labyrinth Type)	3			2	6	0.2	~ 200	
130	Measurement Of Fin Height	3			8	24	0.8	~ 200	
131			Ope No.5-8 Sub Total	3.0	13	39	1.3		
132	5-9	Exhaust Dummig Ring Disassembly	Seal Rings Are Disassembled(Labyrinth Type)	3	2	6	0.2	~ 200	
133			Measurement Of Fin Height	3	8	24	0.8	~ 200	
134			Ope No.5-9 Sub Total	3.0	10	30	1		
135			Ope No.5 Sub Total (5-2*5-4,8-1 Parallel Work, Max Day Is 5-3 5-5*5-9 Parallel Work, Max Day Is 5-7)	3.4	248	833	14.6	~ MIN DAYS (Consideration of parallel work)	
136	6	Inspection	Ope No.6 Sub Total	6.0	60	360	6		
137	7	Repair	Ope No.7 Sub Total	6.0	130	780	13		
138	8	Parts Assembly							
139	8-1	Bearing Assembly (Operation Side By Side)	Fin Is Inserted In Oil Seal Ring	1	8	8	0.8	~ 200	
140			The Oil Seal Ring And Supports Are Assembled	2	8	8	0.2	~ 200	
141			The Bearing And The Support Ring Are Assembled	4	16	16	0.4	~ 200	
142			The Rotor Is Set On Bearings	4	20	20	0.4	~ 200	
143			Tough Face Of Bearing Is Confirmed	2	8	16	0.8	~ 200	
144			The Rotor Is Lifted Up	5	4	20	0.4	~ 200	
145			The Bearing Support Ring And Oil Seal Ring Support Are Disassembled	4	4	16	0.4	~ 200	
146			Bolts For Casing Support And Grease Injection Pipe Are Assembled	3	8	24	0.8	~ 200	
147			Trance Bolt Anchor Is Assembled	3	30	30	1	~ 200	
148			Oil Seal Ring Lower Is Assembled	3	4	8	0.4	~ 200	
149			Journal Bearing Lower Is Assembled	3	30	60	3	~ 200	
150			Ope No.8-1 Sub Total	4.0	26	96	2.6		
151	8-2	Row 1 Stationary Blade Assembly	Row 1 Stationary Blade Is Assembled	3	3	9	0.3	~ 200	
152			Row 1 Stationary Blade Support Ring Is Assembled	3	2	6	0.2	~ 200	
153			Ope No.8-2 Sub Total	3.0	5	15	0.5		
154	8-3	No.1 Blade Ring Assembly (Operation Side By Side)	No.1 Blade Ring Is Repaired And Inspected(Cooling Holes Are Checked)	3	2	6	0.2	~ 200	
155			#8 Isolation Ring And Lugs Are Assembled	3	4	12	0.4	~ 200	
156			#7 Isolation Ring And #4 Ring Segment Are Assembled	3	4	12	0.4	~ 200	
157			Row 4 Stationary Blade Is Assembled	3	3	9	0.3	~ 200	
158			#5,6 Isolation Rings And #3 Ring Segment Are Assembled	3	4	12	0.4	~ 200	
159			Row 3 Stationary Blade Is Assembled	3	3	9	0.3	~ 200	
160			#3,4 Isolation Rings And #2 Ring Segment Are Assembled	3	4	12	0.4	~ 200	
161			Row 2 Stationary Blade Is Assembled	3	3	9	0.3	~ 200	
162			#1,2 Isolation Rings And #1 Ring Segment Are Assembled	3	4	12	0.4	~ 200	
163			#2,4 Seal Housing Are Assembled	3	3	24	0.8	~ 200	
164			Seal Rings Are Assembled	3	4	12	0.4	~ 200	
165			No.1 Blade Ring Upper Half And Lower Half Are Assembled	4	3	12	0.3	~ 200	
166			Seal Housing Are Aligned	3	4	12	0.4	~ 200	

6. Development of Conceptual Design/Solution

As stated a process flow diagram will be created from the data gathered. The PFD is the first and largest step. The PFD will structure the data in a logical and complete manner. By combining all the various data sets it will be possible to detail the PFD with all the information necessary to properly analyse the maintenance procedure as a whole.

Shown below is a simple flow diagram example drawn in Visio. The flow diagrams for the entire project will be drawn in Visio and will contain more detail than the example below.

Figure 10: Basic process flow diagram example





The PFD will evolve through the following steps:

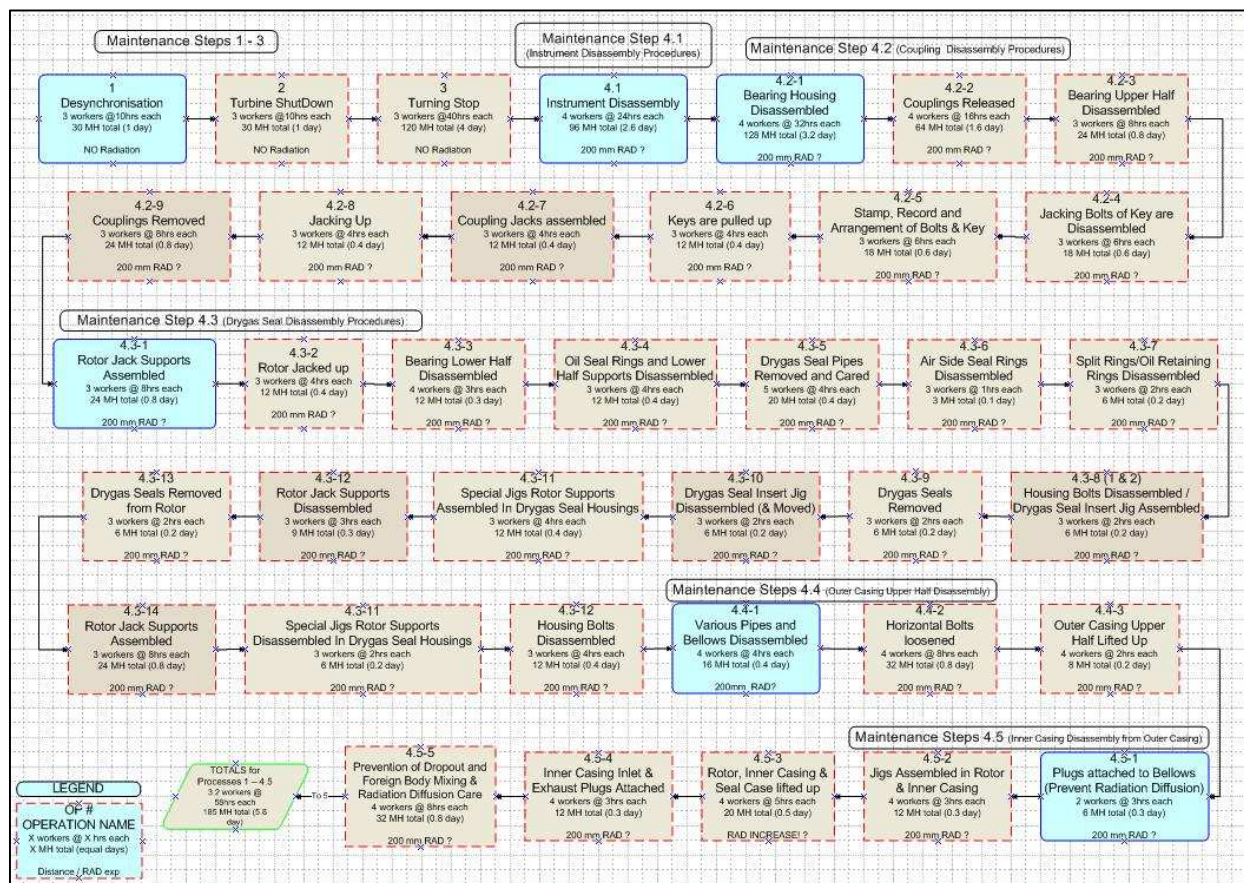
- Charting the entire maintenance procedure in sequence.
- Identify and name each individual task block.
- Identification of parallel streams.
- Populate tasks with information - task times, radiation measures, body distances, etc.
- Calculate task exposure values using detail information.
- Identify tasks in which maximum radiation dosages are exceeded and highlight these.
- Identify tasks in which ergonomic or other safety issues are present.
- Analyse the specific task/s to determine the exact cause of excess.
- Research available solutions and limitations based on specific task.
- Determine potential solution measures to overcome radiation or other problems.
- Summarise all useful information into a single project document.

7. The Charting Process: Development of the Process Flow Diagrams

7.1 Charting the Maintenance Procedure

The first step in the development of the Process Flow Diagrams was mapping the process fully in its original form. Microsoft Visio was used to draw up the process flow diagrams. Three examples of first-stage process flow diagrams are shown in Figures 11, 12 and 13 below.

Figure 11: First-stage PFD for Maintenance tasks 1 – 4.5



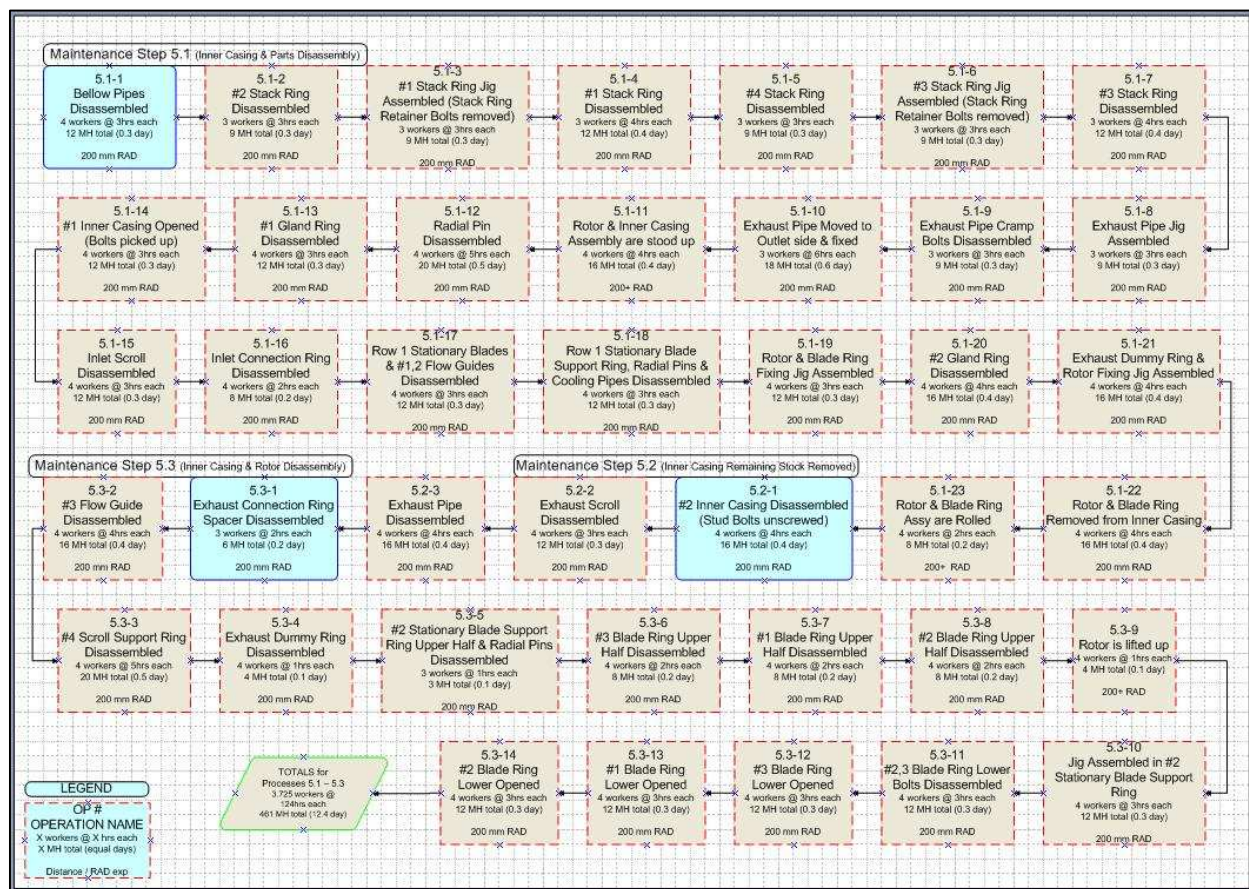
The tasks have been mapped in single file. The first task in a series is indicated in blue. Total process details are included at the end of each page in green. The PFD is structured in a basic zigzag pattern. No parallel tasks have been identified for this set and it remains as is.

A legend provides explanation of the contents of each task block, namely:

- Operation #
- Operation Name
- Number of workers required for each task
- The number of work-hours required per worker to complete the task
- The total number of man-hours (all workers)
- The number of days for a task, where a day is equal to 10 work-hours
- The working distance, in mm, from the body (Radiation Activity Distance)

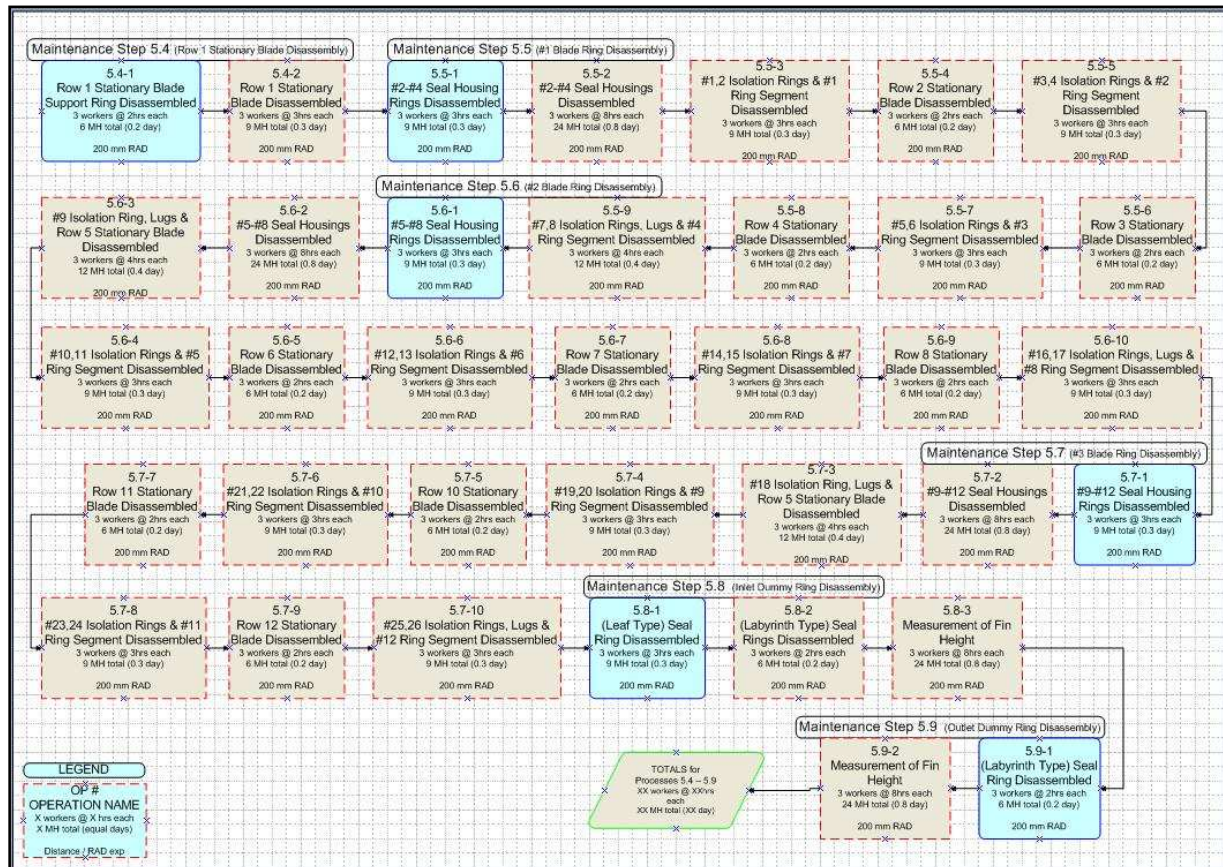
Individual Process Flow Diagram pages follow on from one another. Figure 12 shows the second page of the Process Flow Diagram.

Figure 12: First-stage PFD for Maintenance tasks 5.1 – 5.3



The Process Flow Diagrams are very cramped. The lack of parallel flows makes the maintenance process seem very linear. Below is the third example of a first-stage PFD.

Figure 13: First-stage PFD for Maintenance tasks 5.4 – 5.9

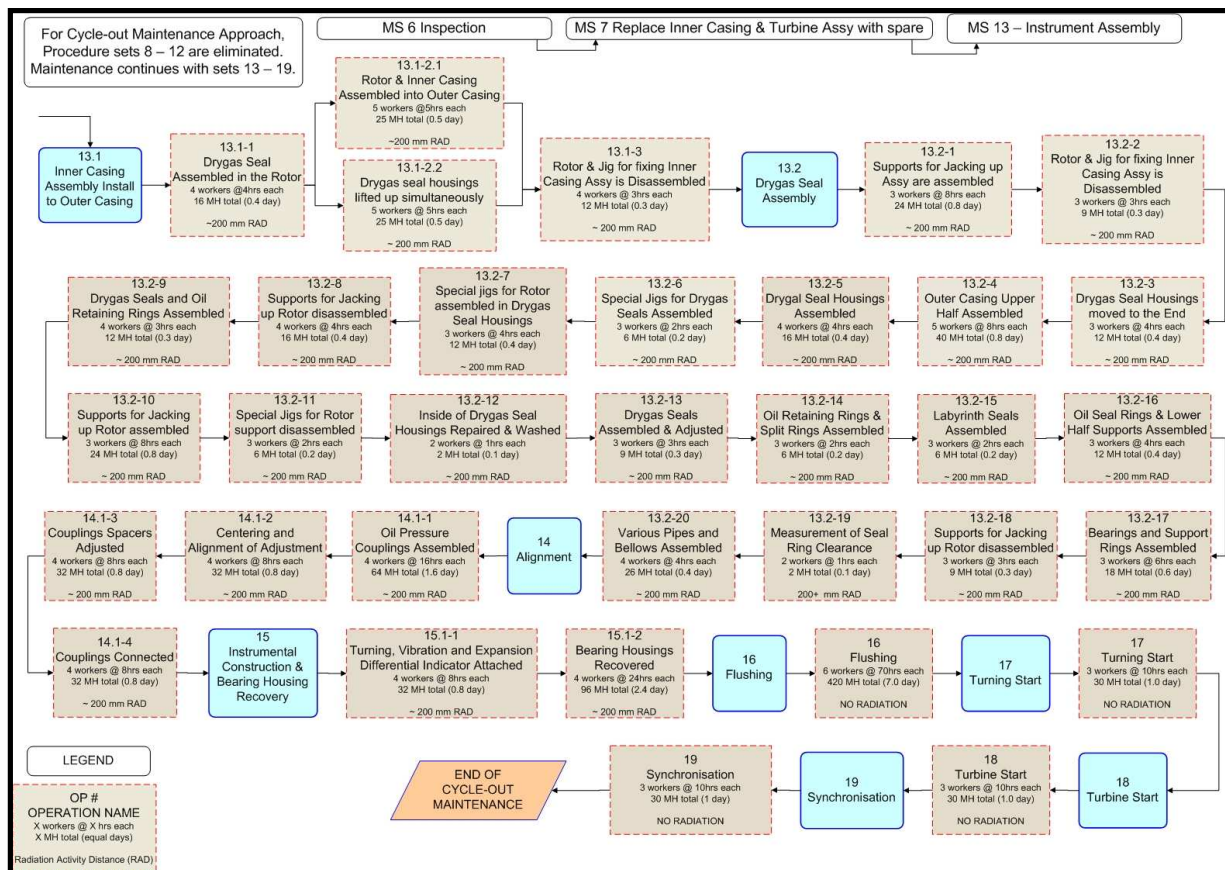


The Original maintenance tasks run from set 1 to set 19. The number of tasks within a set varies between 1 and 40. Later elimination of unnecessary procedures decreased the maintenance sets to 1 - 4, 6, 7 and 13-19 only. (Sets 5 and 8 – 12 eliminated).



Figure 14 shows the first-stage process flow diagram for tasks 13 – 19. Note that tasks 6 and 7 are single –step tasks and are included in this diagram as an aside.

Figure 14: First-stage PFD for Maintenance tasks 13 – 19.



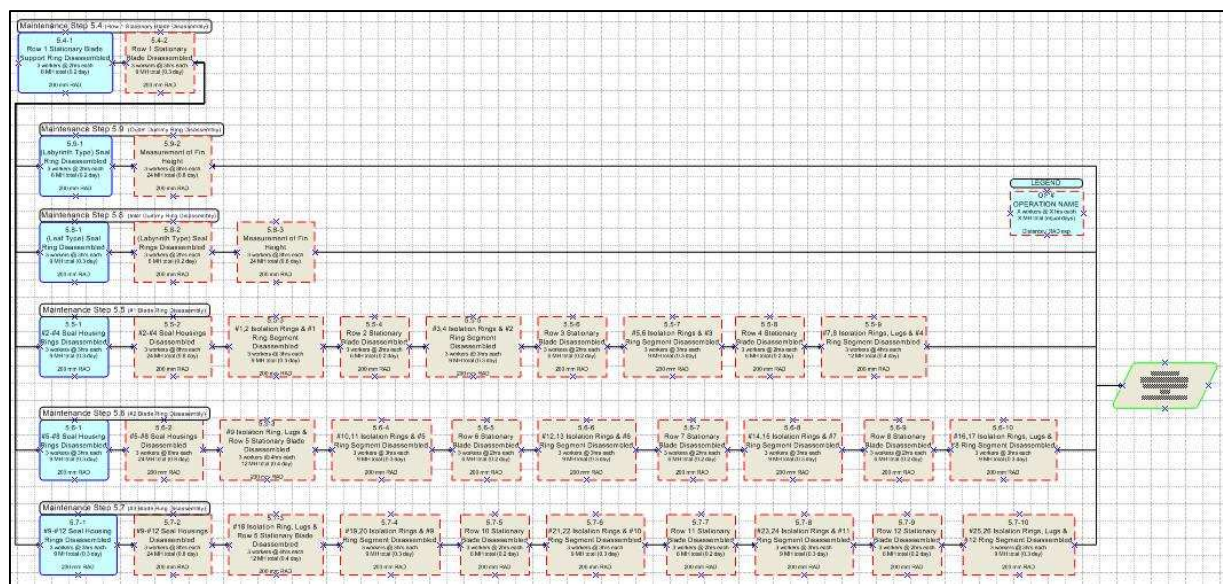
7.2 Identification of Parallel Streams

The second step in the development of the Process Flow Diagram is the identification of parallel tasks. Identifying parallel tasks reduces the overall down-time of the turbine and thus decreases the down-time of the power plant. The parallel tasks, once identified, required that the diagrams be rearranged to accommodate the new task flow structure.

The manpower-hours required are reduced from 372 to 183 hours (50.8% reduction).

Shown in figure 15 is a rearrangement of the tasks shown in figure 13, as this specific set of tasks was identified as having multiple parallel streams.

Figure 15: Second-stage PFD for Maintenance tasks 5.4 – 5.9



The process of identification of parallel tasks was repeated for all first-stage flow diagrams.

Parallel flow lines were checked to ensure correctness and compatibility with each other.

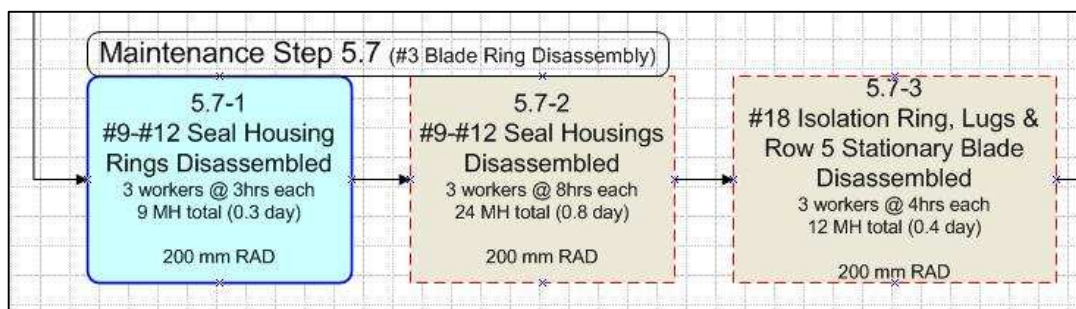
The general structure of the flow diagram is clearer and neater.

No additional parallel task flows were found.

7.3 Detail Task Analysis

Each task block in the new Process Flow Diagram contains detailed information about the task itself as described in Section 7.1. These details, coupled with the radiation modelling data for each task had to be analysed to determine where radiation levels exceeded safe levels or exposure times were too great.

Figure 16: Process Flow Diagram Block Detail



The safe radiation levels are based on the following data:

1. A maximum acceptable dose rate of **1.7mSv/h at 1 cm distance** from the outer shield or unshielded source surface.
2. A maximum acceptable rate of **60μSv/h at 20 cm distance**

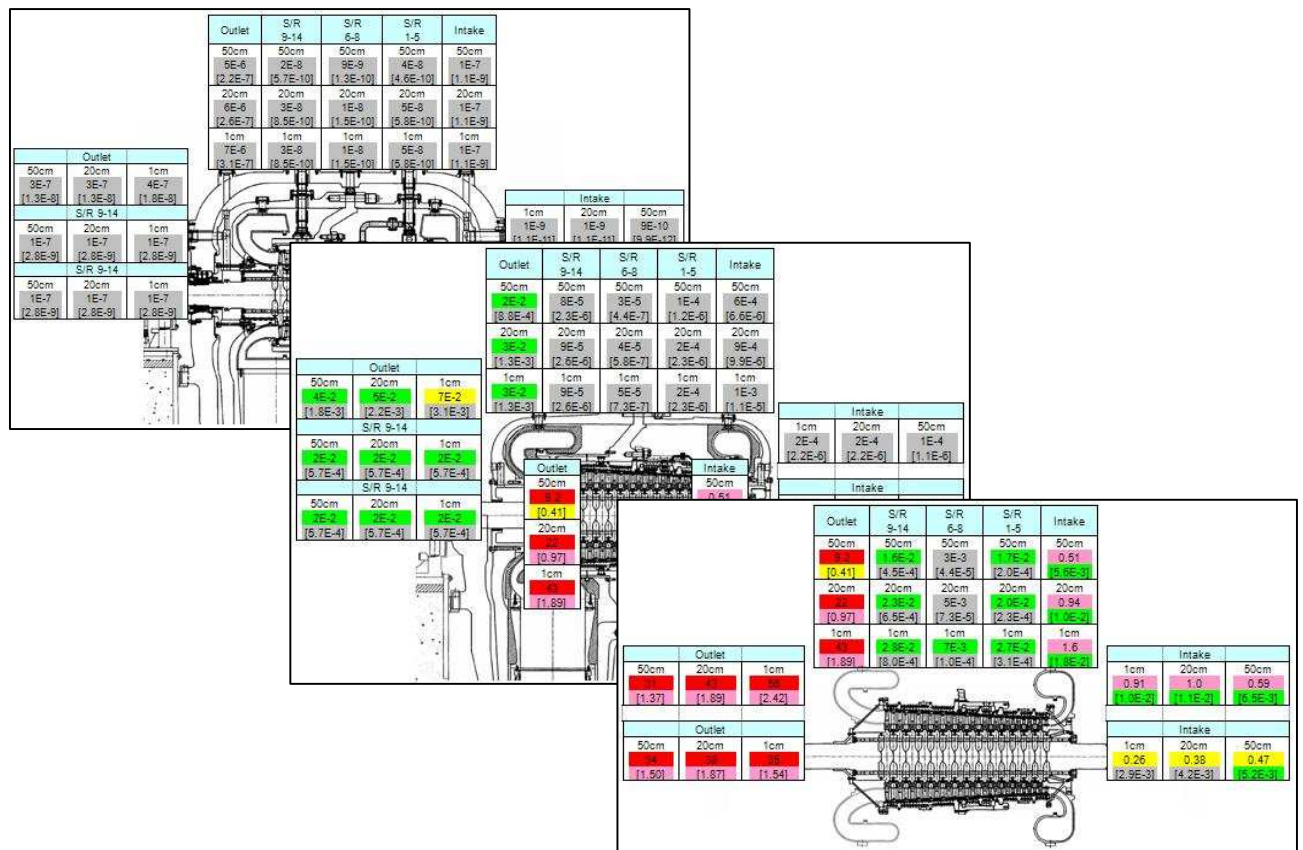
Following modelling, the radiation emissions have been zoned for clarity in distance and time exposure. Zones R1 (Gray) and R2 (Green) fall below the relevant criterion value while zones R3 (Yellow), R4 (Pink) and R5 (Red) are situations where the radiation exposure exceeds maximum safe levels.

Table 1: Allowable access times for radioactive zones

Zone	Mean Access Requirement [h/y]	Maximum Access Requirement [h/y]	Dose rate limits for zone [μSv/h]
R1	500	2000	<5
R2	50	500	$5 < X < 50$
R3	10	50	$50 < X < 500$
R4	1	10	$500 < X < 5000$
R5	<1		>5000

The radiation modelling results were presented in a series of tables and images which are colour-coded to match the Radiation Zones described. Examples of these are shown in Figure 17.

Figure 17: Radiation Modelling Data Example – Expected Dosages for various distances & stages



7.4 Identification of Problem Tasks

The initial radiation modelling suggested that the inner casing radiation dosages would be beyond safe levels even after a five-year radioactive decay period. This implied that all such tasks would automatically exceed the safe dose and would thus require safety equipment.

Safety standards indicate that the resulting radiation exposure from maintenance tasks should be less than **2mSv** per person per year. Radiation calculations were provided for both maintenance approaches.



7.5 Maintenance Approach Analysis

The Maintenance Approach was the first and largest problem encountered. As shown in Figures 18 and 19 the radiation dosages vary greatly between the two approaches. The resulting manpower required for the tasks (taking into account worker rotations due to radiation) in overhaul also bordered on the ridiculous. Shown in table 2 is a comparison between the requirements for Overhaul and Cycle-Out.

Table 2: Maintenance Approach comparison in radiation dosages and required manpower

Task	Min Worker [a]	Dose Rate [c] (μSv/h)	Total Dose Rate per worker (μSv/h x h)	Zone	Required min worker based on dose rate limit	Dose Rate [c'] (μSv/h)	Total Dose Rate per worker (μSv/h x h)	Zone	Required min worker based on dose rate limit
5.5-1	3	2000	6000	R4	180	11	33	R2	4
5.5-2	3	2000	16000	R4	180	11	88	R2	4
5.5-3	3	2000	6000	R4	180	11	33	R2	4
5.5-4	3	2000	4000	R4	180	11	22	R2	4
5.5-5	3	2000	6000	R4	180	11	33	R2	4
5.5-6	3	2000	4000	R4	180	11	22	R2	4
5.5-7	3	2000	6000	R4	180	11	33	R2	4
5.5-8	3	2000	4000	R4	180	11	22	R2	4
5.5-9	3	2000	8000	R4	180	11	44	R2	4
5.6-1	3	2700	8100	R4	243	11	33	R2	4
5.6-2	3	2700	21600	R4	243	11	88	R2	4
5.6-3	3	2700	10800	R4	243	11	44	R2	4
5.6-4	3	2700	8100	R4	243	11	33	R2	4
5.6-5	3	2700	5400	R4	243	11	22	R2	4
5.6-6	3	2700	8100	R4	243	11	33	R2	4
5.6-7	3	2700	5400	R4	243	11	22	R2	4
5.6-8	3	2700	8100	R4	243	11	33	R2	4
5.6-9	3	2700	5400	R4	243	11	22	R2	4
5.6-10	3	2700	8100	R4	243	11	33	R2	4
5.7-1	3	170000	510000	R5	15300	52	156	R3	9
5.7-2	3	170000	1360000	R5	15300	52	416	R3	9
5.7-3	3	170000	680000	R5	15300	52	208	R3	9
5.7-4	3	170000	510000	R5	15300	52	156	R3	9
5.7-5	3	170000	340000	R5	15300	52	104	R3	9
5.7-6	3	170000	510000	R5	15300	52	156	R3	9
5.7-7	3	170000	340000	R5	15300	52	104	R3	9
5.7-8	3	170000	510000	R5	15300	52	156	R3	9
5.7-9	3	170000	340000	R5	15300	52	104	R3	9
5.7-10	3	170000	510000	R5	15300	52	156	R3	9



After analysis of the range of problem tasks, specifically those of the overhaul-procedure maintenance of the inner casing assembly it was obvious that on-the-spot maintenance of the inner casing was unfeasible. Overhaul of the inner casing assembly would require

- large amounts of cumbersome and expensive protective equipment,
- more personnel to place into maintenance rotations in order to reduce radiation exposure per person to safe levels, which increases labour costs
- longer downtime to overhaul on the spot, reducing capacity and decreasing income
- extra manpower would require extra training of personnel for work under time pressure in an extremely dangerous environment, which would be economically unviable

The actual economic effects of these factors have yet to be quantified, however it is generally accepted that the economic shortcomings of the overhaul approach would greatly outweigh the costs involved in maintaining a replacement assembly and allowing radioactive decay before maintenance occurs.

The overhaul maintenance approach is thus not recommended. The cycle-out maintenance approach was therefore decided upon. The remaining process flow diagrams were drawn based on this information.

The elimination of procedures belonging to the overhaul maintenance approach decreased the total maintenance sets to 1 - 4, 6, 7 and 13-19 only. Sets 5 and 8 – 12 were removed. The diagrams for set 5 are still included in this report as their radiation levels were the critical factor in determining the feasibility of the approaches.

The final complete process flow diagrams for the cycle-out approach are shown in Appendix A.



7.6 Task and Radiation Zone Limitations

The following guidelines are specified for required protective measures for maintenance tasks performed in the radiation zones:

Table 3: Radiation Protection Guidelines

Zone	Required Protection	Dose Rate Limit ($\mu\text{Sv/h}$)
R1	• Wear protection mask to prevent internal exposure • Wear film badge to monitor external exposure • Shielding suit is preferable to prevent external exposure of β radiation • Allowable working time shall be less than 10 hours per day	<5
R2	• Wear protection mask to prevent internal exposure • Wear film badge and alarm meter to monitor external exposure • Wear shielding suits to prevent external exposure of β radiation • Allowable working time shall be less than 10 hours per day	$5 < \chi < 50$
R3	• Wear protection mask to prevent internal exposure • Wear film badge and alarm meter to monitor external exposure • Wear shielding suits to prevent external exposure of β radiation • Suitable shielding objects are required to prevent radiation • Allowable working time shall be less than 10 hours per day	$50 < \chi < 500$

As is shown, radiation guidelines only cover the zones 1 to 3. R4 and R5 zones are so highly irradiated that very few protective measures are capable of reducing the exposure levels. R3 exposure already requires bulky shielding suits as well as shielding objects.

R4 and R5 are thus highly unviable working conditions especially when coupled with the severe time restrictions placed on such levels of exposure, resulting in very high labour figures.



7.7 Potential Solution Identification

Several basic radiation contamination prevention procedures have been identified by PBMR. These include pre-maintenance preparation of the room as well as the preparation for workers.

Two types of radiation suits have been identified by PBMR as potential protective measures. These are the basic airtight “Tyvex Suit” and the heavier perfectly airtight “Air Line Suit” with an oxygen cylinder. Workers will also be required, on occasion, to use radiation shields for additional protection. Both the suits and the shields will decrease working efficiency but this has been factored into the maintenance plan already.

Additionally, jigs for lifting larger objects have been designed along with the machinery they were created for. These jigs thus fall outside the scope of this project. Additional specialised tooling for specific tasks are being developed by application to the first turbine prototype model as well as through advanced simulation modelling.

No additional information was available on potential alternatives as none currently exist in the marketplace. Until such time as improved protective equipment is internationally available at feasible prices the Tyvex suits and radiation shields will be used.

As explained in section 7.6 the radiation protection guidelines for R3 already require the use of shielding objects. Shielding objects are heavy, bulky and reduce worker capability as well as taking up at least one hand. Working under such conditions would greatly hamper productivity.

In order to recommend alternatives for these specific tasks, all tasks with radiation zone classifications of R3 or higher had to be identified. The data was incomplete, however, and had to be corrected before this could occur.

8. Correction of Incomplete Data Set & Radiation Calculations

As stated before, the radiation-based maintenance procedure set was incomplete and required the addition of the procedures 13 – 19. In order to identify any R3 classified tasks the radiation zone calculations for these added tasks had to be calculated. These can be seen in Figure 21 on the following page.

Only two of the added tasks were identified as R3. In existing charts only task set 4.5 was identified as R3. The radiation zones were mapped onto the process flow diagram, as seen in Figure 20 below. All zones identified are still feasible for work.

Figure 20: Maintenance PFD for sets 13 – 19, with radiation zones.

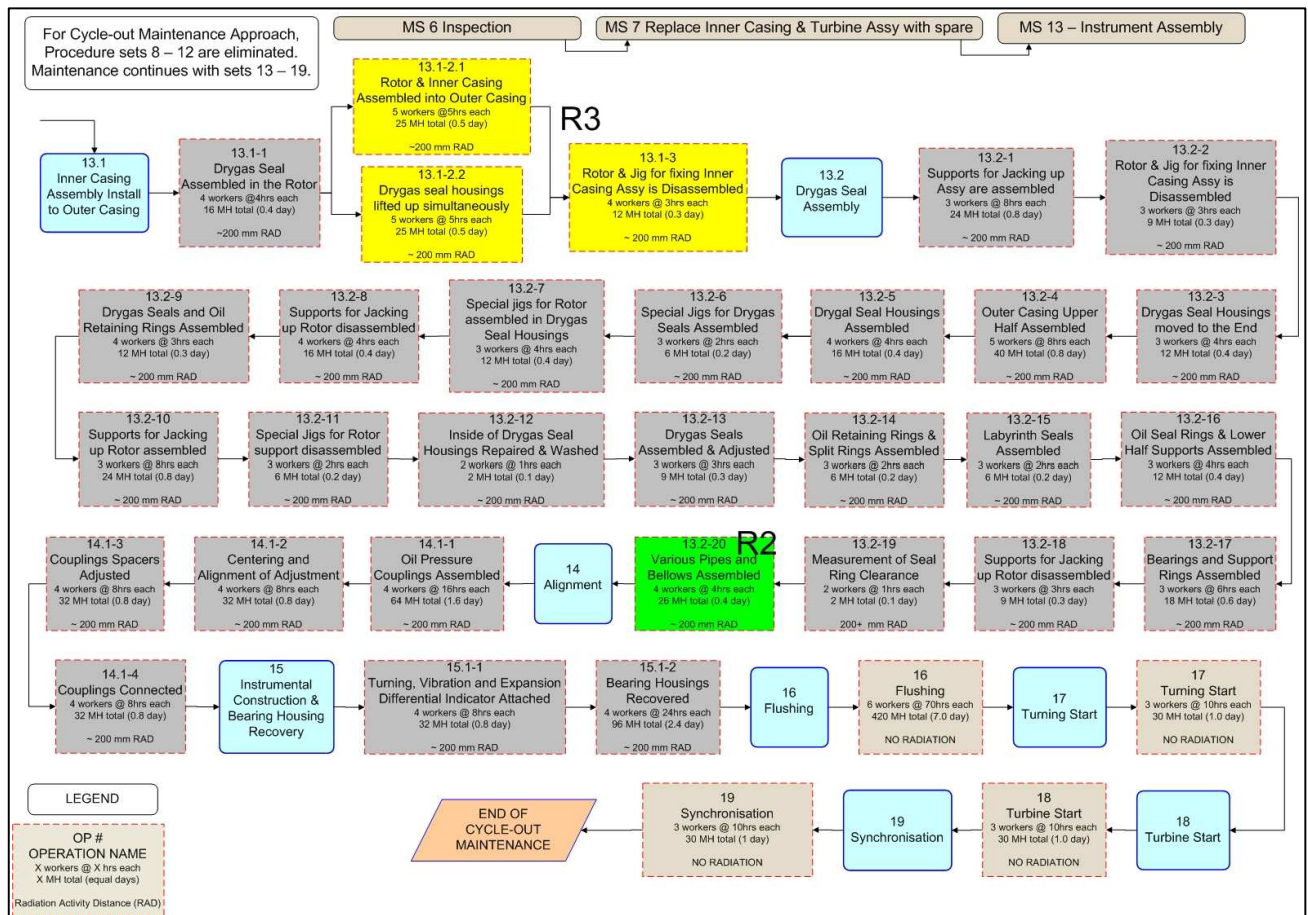


Figure 21: Additional procedures and radiation calculations

	B	C	D	E	F	H	I	J	K	
1										
2	P B M R Turbine Maintenance Procedure considering radiation exposure		1							Dose Rate L
3										Design Value
4	Subject	Detail	Min Worker [a]	Work Hour [b]	Man-Hour	Working Distance from worker's body (mm)	Dose Rate [c] (uSv/h)	Total Dose Rate per worker [d]=[b][c] (uSv/h x h)	Zone	wg effe prod
162	Instruments Assembly	The Drygas Seals Assembled In The Rotor	4	4	16	~500	0.007	0.028	R1	
163		The Rotor And The Inner Casing Assy Are Assembled Into The Outer Casing	5	5	25	1000~	92	460	R3	
164	Inner Casing Assy Install To Outer Casing	(Drygas Seal Housings Are Lifted Up At The Same Time)	4	3	12	~500	70	210	R3	
165		The Rotor And The Jig For Filing Of The Inner Casing Are Disassembled	4.3	12	53					
166		Ope No.13-1 Sub Total								
167		Supports For Jacking Up The Rotor Are Assembled	3	8	24	~500	0.007	0.056	R1	
168		The Rotor And Jigs For Filing Of The Inner Casing Are Disassembled	3	3	9	~500	0.007	0.021	R1	
169		Drygas Seal Housings Are Moved To The End	3	4	12	~500	0.007	0.028	R1	
170		The Outer Casing Upper Half Is Assembled	5	8	40	~500	0.7	5.6	R1	
171		Drygas Seal Housings Are Assembled	4	4	16	~500	0.007	0.028	R1	
172		Special Jigs For Drygas Seals Are Assembled	3	2	6	~500	0.007	0.014	R1	
173		Special Jigs For The Rotor Are Assembled In Drygas Seal Housings	3	4	12	~500	0.007	0.028	R1	
174		Supports For Jacking Up The Rotor Are Disassembled	4	4	16	~500	0.007	0.028	R1	
175		Drygas Seals And Oil Retaining Rings Are Assembled	4	3	12	~500	0.007	0.021	R1	
176		Supports For Jacking Up The Rotor Are Assembled	3	8	24	~500	0.007	0.056	R1	
177		Special Jigs For Rotor Supports Are Disassembled	3	2	6	~500	0.007	0.014	R1	
178		Inside Of Drygas Seal Housings Are Repaired And Washed	2	1	2	~500	0.007	0.007	R1	
179		Drygas Seals Are Assembled (Include Adjustment)	3	3	9	~500	0.007	0.021	R1	
180		Oil Retaining Rings And Split Rings Are Assembled	3	2	6	~500	0.007	0.014	R1	
181		Labirinth Seals Are Assembled	3	2	6	~500	0.007	0.014	R1	
182		Oil Seal Rings And Lower Half Supports Are Assembled	3	4	12	~500	0.007	0.028	R1	
183		Bearings And Support Rings Are Assembled	3	6	18	~500	0.007	0.042	R1	
184		Supports For Jacking Up The Rotor Are Disassembled	3	3	9	~500	0.007	0.021	R1	
185		Measurement Of Seal Rings Clearance	2	1	2	~500	0.007	0.007	R1	
186		Various Pipes And Bellows Are Assembled	4	4	16	~500	50	200	R2	
187										
188		Ope No.13-2 Sub Total	3.2	72	241					
189		Ope No.13 Sub Total	3.5	84	294					
189		Oil Pressure Couplings Are Assembled	4	16	64	~500	0.007	0.112	R1	
190		Centering And Alignment Of Adjustment	4	8	32	~500	0.007	0.056	R1	
191		Spacers Of Coupling Are Adjusted	4	8	32	~500	0.007	0.056	R1	
192		Couplings Are Connected	4	8	32	~500	0.007	0.056	R1	
193		Ope No.14 Sub Total	4.0	40	160					
194		Turning, Vibration, And Differential Expansion Indicator Are Attached	4	8	32	~500	0.007	0.056	R1	
195		Bearing Housings Are Recovered	4	24	96	~500	0.007	0.168	R1	
196		Ope No.15 Sub Total	4.0	32	128					
197		FLUSHING	6	70	420	-				
198		TURBINE START	3	10	30	-				
199		TURBINE START	3	10	30	-				
200		SYNCHRONIZATION	3	10	30	-				
201										
202		Total	4.3	256.0	1092.0					



9. Recommendations for Future work

This project has created several opportunities for further work related to the turbine maintenance procedures at PBMR. These topics include:

- Full charting of the maintenance procedures for the stored turbine unit after 5 years
- Investigation of alternative protection equipment and measures, with the possibility of development of new and improved items to cater to the needs of the workers
- Financial analysis (break-even analysis) of alternate maintenance approaches
- Creation of maintenance manuals and training materials for turbine maintenance
- Development of personnel rotation schedules for maintenance work
- Development of automation for tasks with high radiation levels or which require additional shielding to reduce task inefficiency and increase safety.

In particular, one large potential future development announced at PBMR which may be impacted by the results of this project is the recent idea to change the power generation plant to a water-based system. In this proposal, the super-heated helium will, through a heat exchange system, heat water to create steam which would drive the turbine.

A steam-driven system will be slightly less inefficient overall owing to energy lost in the heat exchange but will significantly reduce the radiation levels passing through the turbine and compressor units. If radiation levels are reduced far enough the overhaul maintenance approach may become feasible again.

With respect to the results of this project, the following actions are recommended to improve safety and decrease working time:

- Task sets 4.5 and 13.1 be automated if possible, or to as great an extent as is possible.
- If not possible, additional shielding objects be mechanised to some degree to free the worker from having to hold and move them around



10. Conclusion

This project has produced results which are of great value to PBMR. The development of the process flow diagrams and the association of the radiation measures have provided a visual tool in understanding the processes, the safety levels of the tasks and identification of problem areas.

The most valuable output of this project is the discovery of the infeasibility of the overhaul maintenance approach owing to the extremely high radiation levels and ridiculously high number of workers required to complete the tasks. This revelation will reduce the amount of work to be done in task and tool simulations, writing of manuals and training materials, and the analysis of the economics of running the plant.

In addition, by charting the flow diagrams a foundation has been established for further charting and detailed analysis of work, not only in the turbine maintenance field but also elsewhere. The success of combining process flow diagrams with radiation modelling figures and ergonomics can be applied to numerous radiation-exposed procedures throughout the plant to increase the levels of safety for all workers.

The identification of specific tasks that may require automation or partial mechanisation will also allow for focused research and development into solving only actual problems and thereby reducing the overall workload.

In conclusion, this project has not only achieved its intended goals but has exceeded them by exposing vital information critical to both the design and running of the PBMR nuclear plant.



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11.2 Tables and Figures

Figure 1: PBMR Fuel Pebbles, Web, www.pbmr.co.za

Figure 2: The PBMR Nuclear Power Plant System, Web, www.pbmr.co.za

Figure 3: A visual overview of Project topics with information flow and future uses,
Own work ©A Wheeler 2008

Figure 4: Example of machine design drawings for turbine assembly/disassembly,
PBMR, Project data collection



Figure 5: Example of 3D computer models for turbine assembly/disassembly,	PBMR,	Project data collection
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Figure 8: Radiation warning symbol,	Web,	http://www.basis-online.nl/index.cfm/1,100,325,0,html/Kwaliteit-van-arbeid-in-de-gehandicaptenzorg
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Figure 11: First-stage PFD for Maintenance tasks 1 – 4.5	Own work	©A Wheeler 2008
Figure 12: First-stage PFD for Maintenance tasks 5.1 – 5.3	Own work	©A Wheeler 2008
Figure 13: First-stage PFD for Maintenance tasks 5.4 – 5.9	Own work	©A Wheeler 2008
Figure 14: First-stage PFD for Maintenance tasks 13 – 19	Own work	©A. Wheeler 2008
Figure 15: Second-stage PFD for Maintenance tasks 4.5 – 5.9	Own	©A Wheeler 2008
Figure 16: Process Flow Diagram Block Detail	Own work	©A Wheeler 2008
Table 1: Allowable access times for radioactive zones	PBMR	Project data collection



Figure 17: Radiation Modelling Data Example – Expected Dosages for various distances and stages

PBMR

Project data collection

Figure 18: Maintenance PFD for tasks 5.4 – 5.9 with zone gradations (Overhaul Approach)

Own work

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Figure 19: Maintenance PFD for tasks 5.4 – 5.9 with zone gradations (Cycle-Out Approach)

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Figure 20: Maintenance PFD for sets 13 – 19, with radiation zones

Own

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Figure 21: Additional procedures and radiation calculations

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Table 2: Maintenance Approach comparison in radiation dosages and required manpower

Adapted from

PBMR

Project data collection

Table 3: Radiation Protection Guidelines

PBMR

Project data collection



11.3 General Web References

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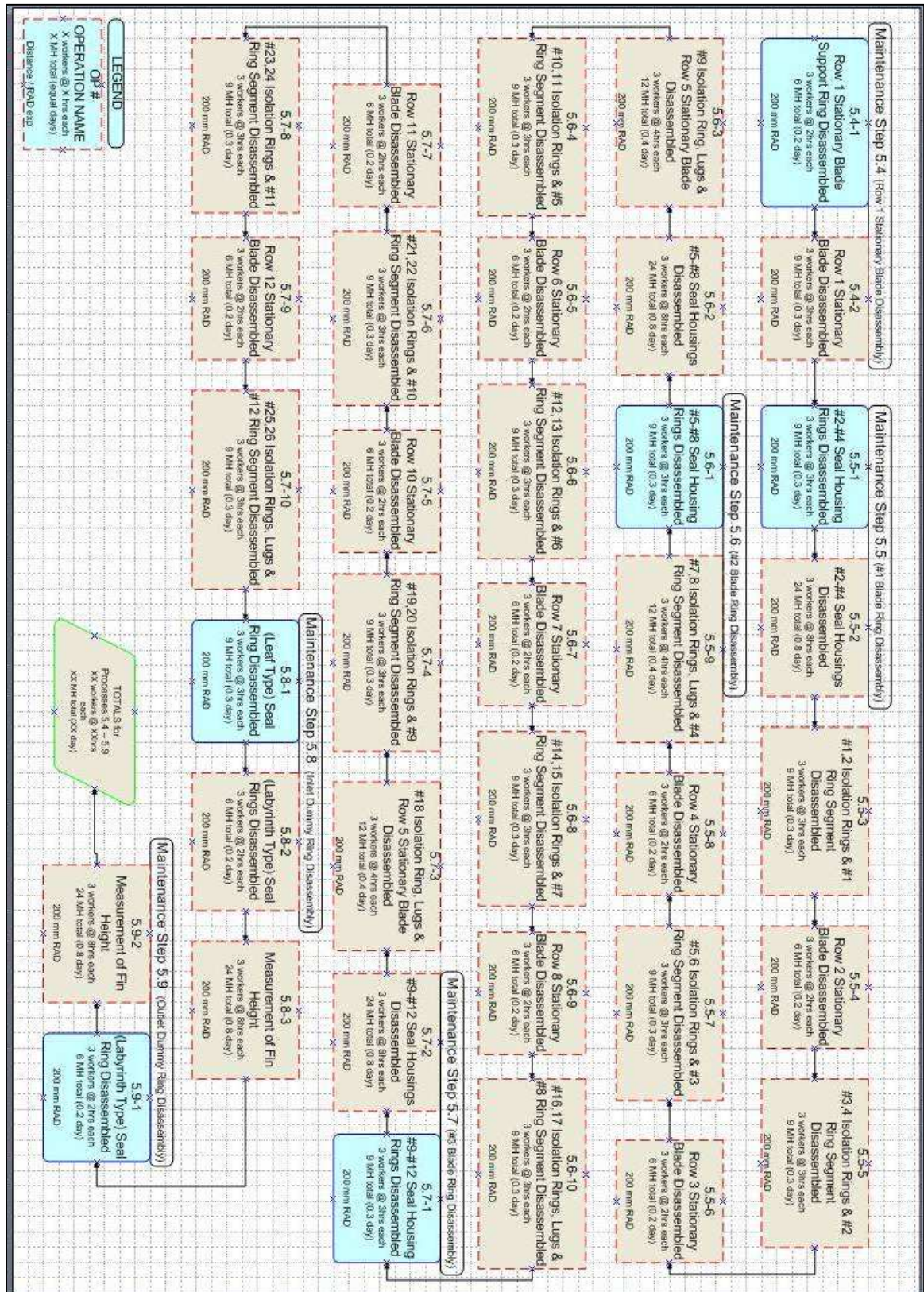
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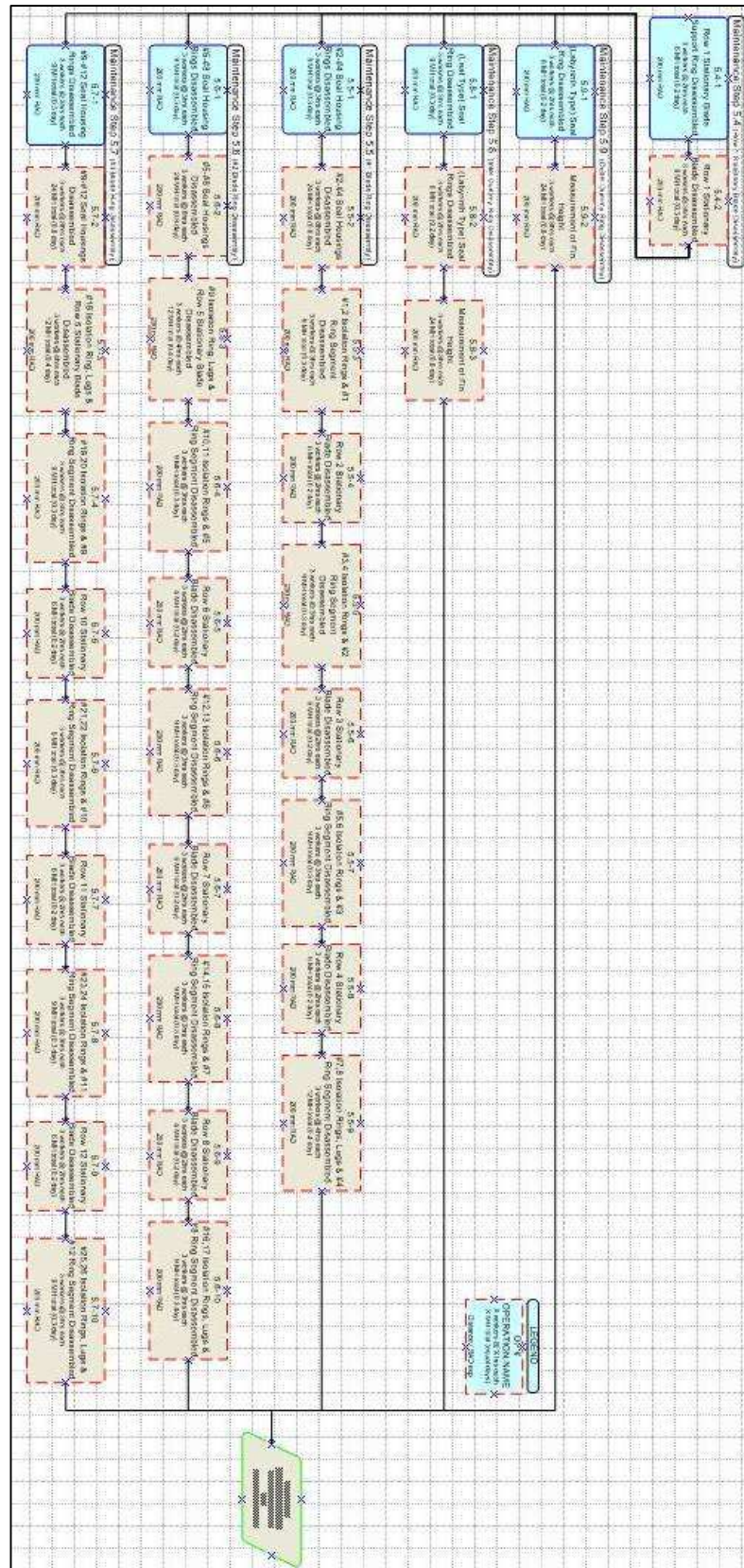
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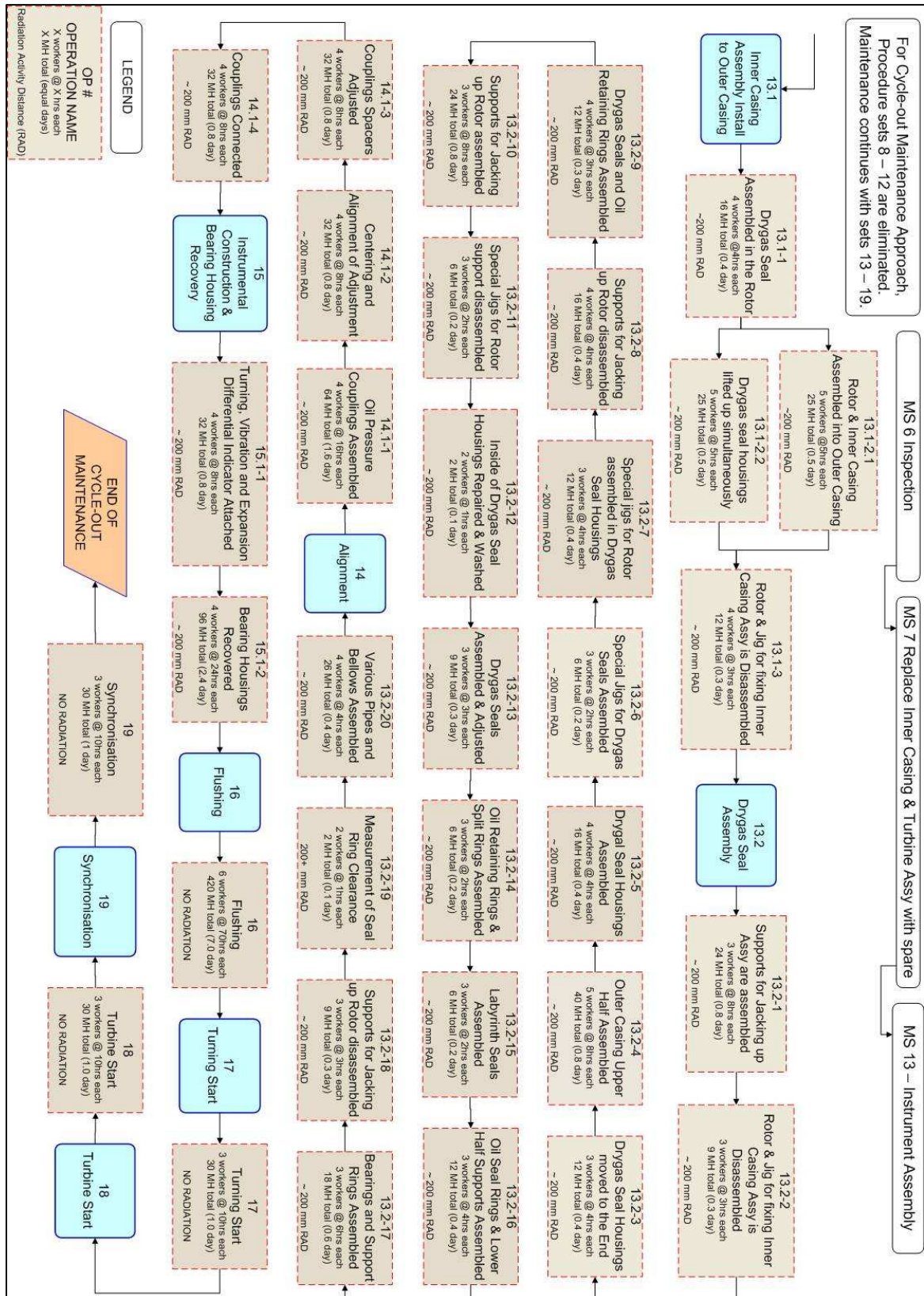
Turbine Maintenance Process Flow Diagram sets 5.4 – 5.9 (First-stage, no parallel tasks)



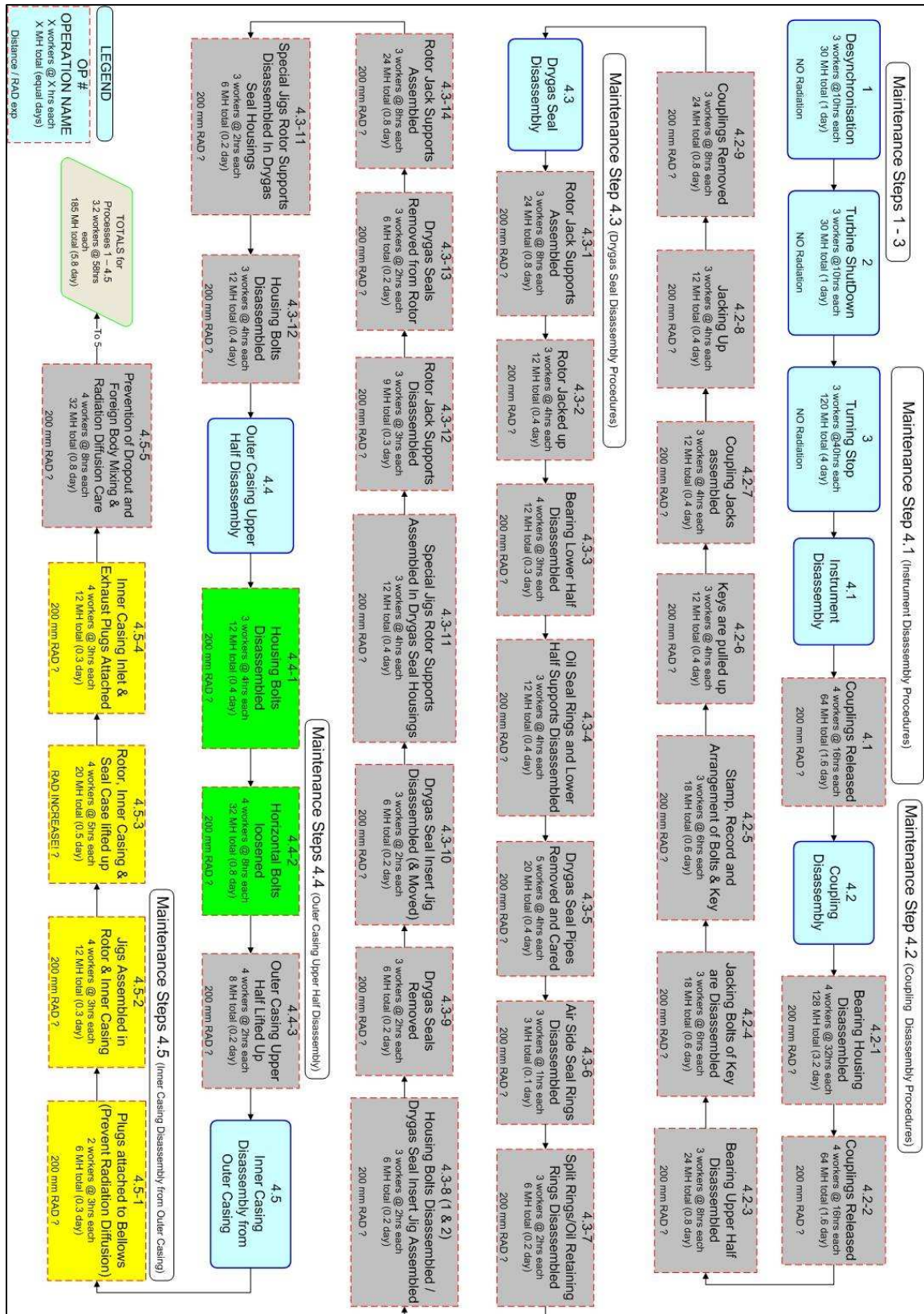
Turbine Maintenance Process Flow Diagram sets 5.4 – 5.9 (Second stage, parallel tasks)



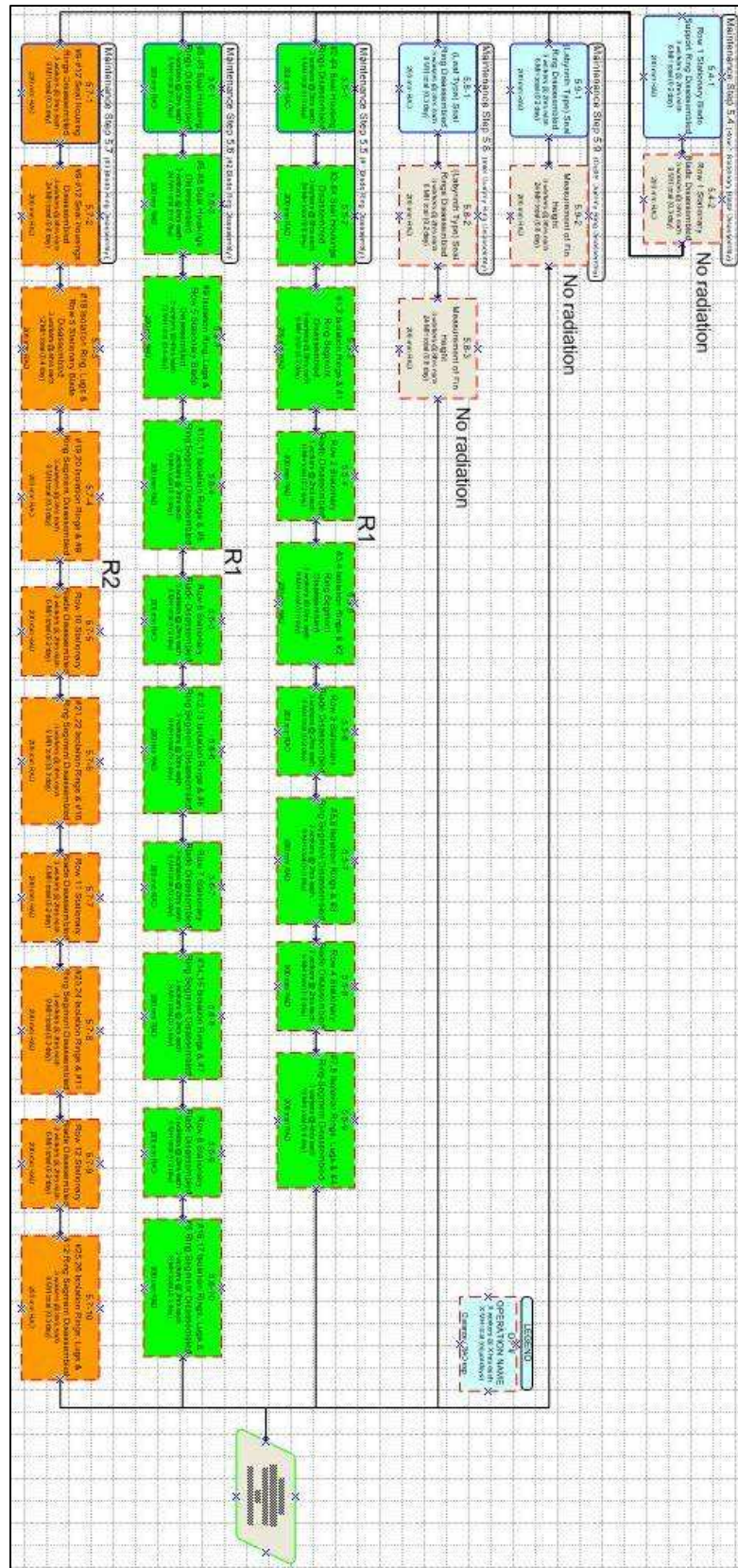
Turbine Maintenance Process Flow Diagram sets 13 – 19 (incl. 6 & 7)



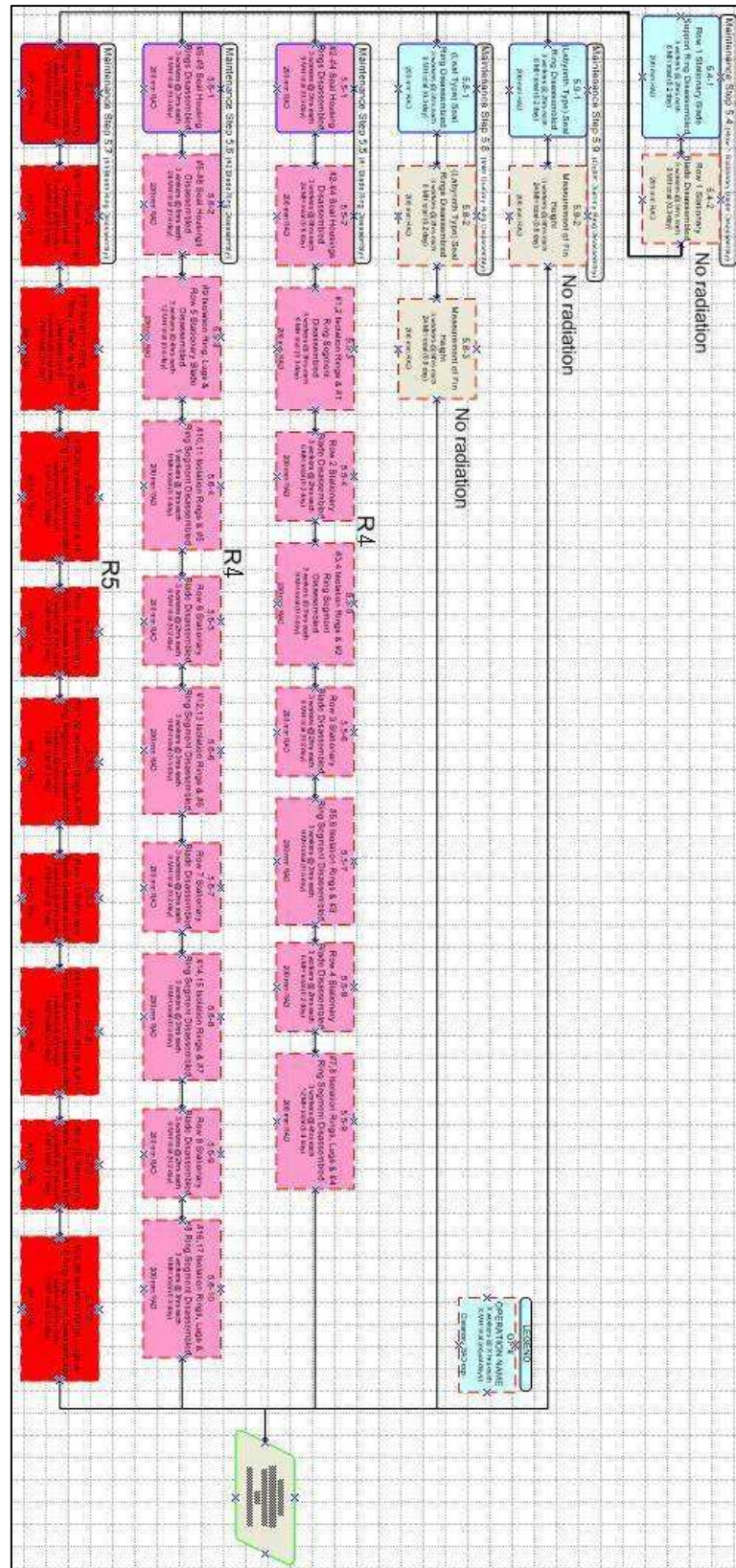
ZONED Maintenance PFD for sets 1 – 4 (colour coded)



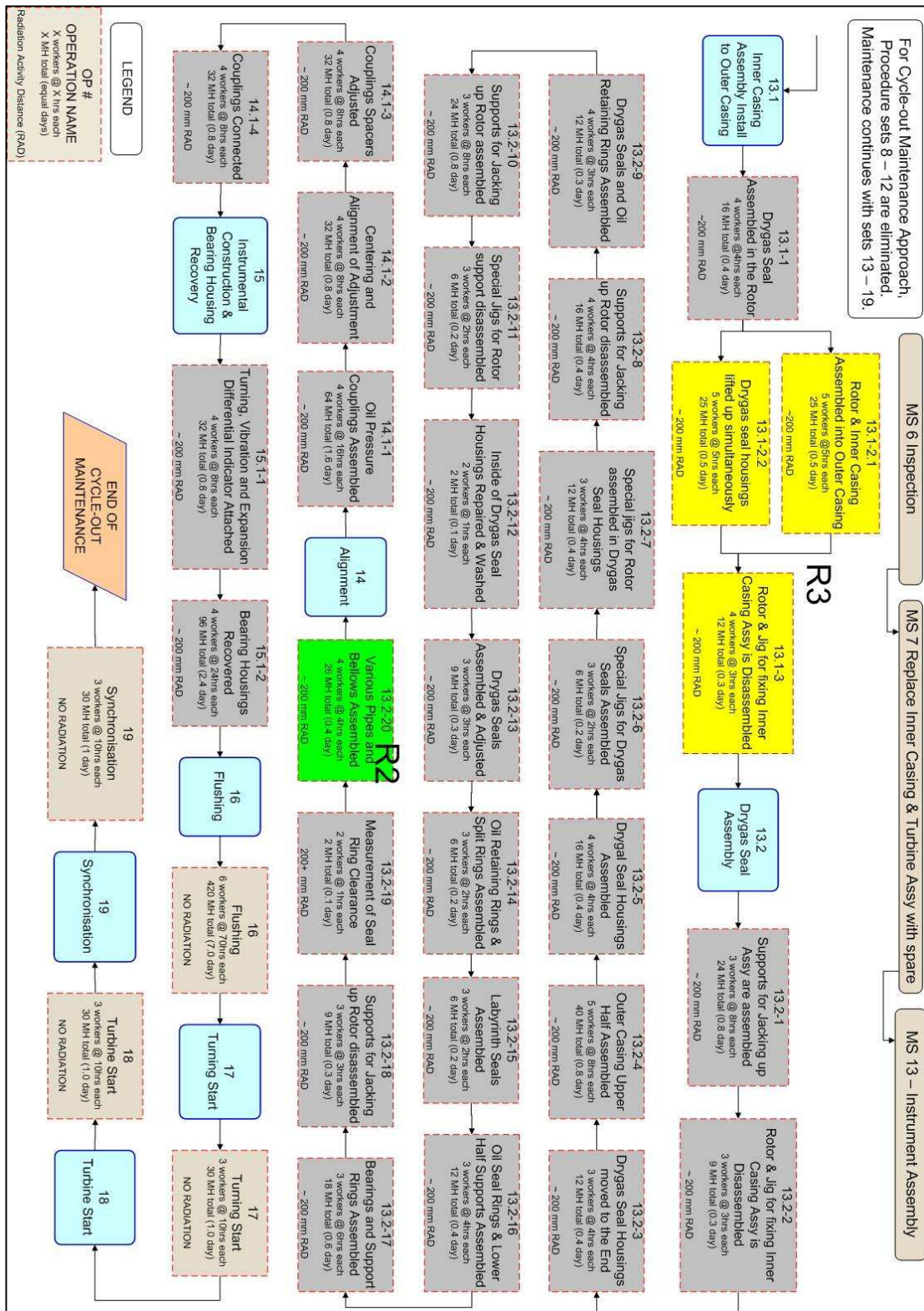
ZONED Maintenance PFD for sets 5.4 – 5.9 (Cycle-Out Approach, after 5 years decay)



ZONED Maintenance PFD for sets 5.4 – 5.9 (Overhaul approach, on-the-spot maintenance)



ZONED Maintenance PFD for sets 13 – 19 (incl. 6,7)



13. Appendix B

Example of original maintenance task list with worker radiation activity distances

P B M R TURBINE MAINTENANCE PROCEDURE									
3	Operation	Subject	Detail	Min Worker	Work Hour	Man - Hour	Dwg	Working Distance from Worker's body (mm)	Drawing
119	5-7	No.3 Blade Ring Disassembly (Operation Side By Side)	#18 Isolation Ring Lugs And Row 3 Stationary Blade Are Disassembled	3	4	12	0.4	~ 200	
120			#19,20 Isolation Rings And #9 Ring Segment Are Disassembled	3	3	9	0.3	~ 200	
121			Row 10 Stationary Blade Is Disassembled	3	2	6	0.2	~ 200	
122			#21,22 Isolation Rings And #10 Ring Segment Are Disassembled	3	3	9	0.3	~ 200	
123			Row 11 Stationary Blade Is Disassembled	3	2	6	0.2	~ 200	
124			#23,24 Isolation Rings And #11 Ring Segment Are Disassembled	3	3	9	0.3	~ 200	
125			Row 12 Stationary Blade Is Disassembled	3	2	6	0.2	~ 200	
126			#25,26 Isolation Rings, Lugs And #12 Ring Segment Are Disassembled	3	3	9	0.3	~ 200	
127			Ope No.5-7 Sub Total	3.0	33	39	3.3		
128			The Seal Ring Is Disassembled (Leak Type)	3	3	9	0.3	~ 200	
129	5-8	Inlet Durning Ring Disassembly	Seal Rings Are Disassembled (Leak Type)	3	2	6	0.2	~ 200	
130			Measurement Of Pin Height	3	8	24	0.8	~ 200	
131			Ope No.5-8 Sub Total	3.0	13	39	1.3		
132			Seal Rings Are Disassembled (Leak Type)	3	2	6	0.2	~ 200	
133	5-9	Exhaust Durning Ring Disassembly	Measurement Of Pin Height	3	8	24	0.8	~ 200	
134			Ope No.5-9 Sub Total	3.0	10	30	1		
135			Ope No.5 Sub Total (5-7-8-4-8-1 Parallel Work, Max Day Is 5-3 5-5-5-9 Parallel Work, Max Day Is 5-7)	3.4	248	833	14.6	~ MIN DAYS (Consideration of parallel work)	
136			Ope No.6 Sub Total	6.0	60	360	6		
137	8	Inspection Repair Parts Assembly	Ope No.7 Sub Total	6.0	130	780	13		
138			Final check of oil seal ring	4	8	24	0.8	~ 200	
139			The Oil Seal Ring And Supports Are Assembled	4	2	8	0.2	~ 200	
140			The Bearing And The Support Ring Are Assembled	4	4	16	0.4	~ 200	
141	8-1	Bearing Assembly (Operation Side By Side)	The Bolts Set On Bearings	4	4	16	0.4	~ 200	
142			Tough Face Of Bearing Is Confirmed	2	8	16	0.8	~ 200	
143			The Bolts Are Lined Up	5	4	20	0.4	~ 200	
144			The Bearing Support Ring And Oil Seal Ring Support Are Disassembled	4	4	16	0.4	~ 200	
145			Before For Casting Support And Release Injection Pipe Are Assembled	3	8	24	0.8	~ 200	
146			Frame-Bolt And Nut Is Assembled	3	40	240	1	~ 200	
147			Oil Seal Ring Bolts Are Assembled	3	4	12	0.4	~ 200	
148			Internal Bearing Cover Is Assembled	3	20	60	3	~ 200	
149			Ope No.8-1 Sub Total	4.0	26	36	2.6		
150	8-2	Row 1 Stationary Blade Assembly	Row 1 Stationary Blade Is Assembled	3	3	9	0.3	~ 200	
151			Row 1 Stationary Blade Support Ring Is Assembled	3	2	6	0.2	~ 200	
152			Ope No.8-2 Sub Total	3.0	5	15	0.5		
153			No.1 Blade Ring Is Repaired And Inspected (Cooling Holes Are Checked)	3	2	6	0.2	~ 200	
154			#6 Isolation Ring And Lugs Are Assembled	3	4	12	0.4	~ 200	
155			#7 Isolation Ring And #4 Ring Segment Are Assembled	3	4	12	0.4	~ 200	
156			Row 4 Stationary Blade Is Assembled	3	3	9	0.3	~ 200	
157			#6,5 Isolation Rings And #3 Ring Segment Are Assembled	3	4	12	0.4	~ 200	
158			Row 3 Stationary Blade Is Assembled	3	3	9	0.3	~ 200	
159			#3,4 Isolation Rings And #2 Ring Segment Are Assembled	3	4	12	0.4	~ 200	
160	8-3	No.1 Blade Ring Assembly (Operation Side By Side)	Row 2 Stationary Blade Is Assembled	3	3	9	0.3	~ 200	
161			#1,2 Isolation Rings And #1 Ring Segment Are Assembled	3	4	12	0.4	~ 200	
162			#2-4 Seal Housings Are Assembled	3	8	24	0.8	~ 200	
163			Seal Rings Are Assembled	3	4	12	0.4	~ 200	
164			No.1 Blade Ring Upper Half And Lower Half Are Assembled	4	3	12	0.3	~ 200	
165			Seal Housings Are Aligned	3	4	12	0.4	~ 200	
166									
167									
168									
169									

Task list with estimated exposures, radiation calculations and min worker requirements

	A	B	C	D	E	F	H	I	J	K	L	M
1												
2	Table 9 P B M R Turbine Maintenance Procedure considering radiation exposure											
3				1								50
	O p- No.	Subject	Detail	Min Worker [a]	Work Hour [b]	Man- Hour	Working Distance from Worker's body (mm)	Dose Rate [c] (μSv/h)	Total Dose Rate per worker [d]=[b]x[c] (μSv/h x h)	Zone	working effect due to protection [e]	min worker based on dose rate limit [h]= [c]/[g]x[a]x[e]
4												
35			Special Jigs For Rotor Supports Are Disassembled From Drygas Seal Housings	3	2	6	~500	0.007	0.014	R1	1.0	3
36			Housing Bolts Are Disassembled	3	4	12	~500	0.007	0.028	R1	1.0	3
37			Ope No.4.3 Sub Total	3.2	58	185			0.406			
38			1-1 Various Pipes And Bellows Are Disassembled	4	4	16	~500	50	200	R2	1.2	5
39			1-2 Plugs Are Attached On Bellows (Radioactive Diffusion Prevention)	2	8	16	~500	50	400	R2	1.2	3
40			2-1 Horizontal Bolts Are Loosened	4	8	32	~500	5	40	R1	1.0	4
41			2-2 The Outer Casing Upper Half Is Lifted Up	4	2	8	~500	0.7	1.4	R1	1.0	4
42			Ope No.4.4 Sub Total	3.5	22	72			641			
43			3) Plugs Are Attached On Bellows (Radioactive Diffusion Prevention)	2	5	10	~500	70	350	R3	1.5	6
44			4) Jig Is Assembled In Rotor And Inner Casing	4	3	12	~500	70	210	R3	1.5	12
45			5) The Rotor, The Inner Casing Assy And The Seal Case Are Lifted Up	4	5	20	1000~	92	460	R3	1.5	12
46			6-1 Plugs Are Attached On Inlet And Exhaust Of Inner Casing (Radioactive Diffu	4	3	12	1000~	430	1290	R3	1.5	54
47			6-2 Prevention Of Dropout And Mixing Foreign Body,									
48			And Care For Prevention Of Radioactive Diffusion	4	8	32			189.52			12
49			(1) Preparation	4	1	4	1000~	92	92	R3	1.5	12
50			(2) Plug on main pipe	4	4	16	1000~	0.92	3.68	R1	1.0	4
51			(3) Preparation and setting safety plate for prevention of dropout	4	2	8	1000~	0.92	1.84	R1	1.0	4
52			(4) Aftercare of safety plate	4	1	4	~500	92	92	R3	1.5	12
53			Ope No.4.5 Sub Total	3.6	32	86			2500			
54			Ope No.4 Sub Total	3.4	224	751			3142			
55			1-1 Remove pipe plug and prepare for Bellow Pipes disassembling	4	2	8	~500	430	860	R3	1.5	54
56			1-2 Bellow Pipes Are Disassembled	4	1	4	~500	4.3	4.3	R1	1.0	4
57			2) No.2 Stacking Is Disassembled	3	3	9	~500	1600	4800	R4	1.5	144
58			3) The Special Jig For Taking Out No.1 Stack Ring Is Assembled	3	3	9	~500	1600	4800	R4	1.5	144
59			(Several Stack Ring Retaining Bolts Are Taken Out)	3	4	12	~500	1600	6400	R4	1.5	144
60			4) No.1 Stack Ring Is Disassembled	3	3	9	~500	4300	12900	R5	1.5	3870
61			5) No.4 Stack Ring Is Disassembled	3	3	9	~500	4300	12900	R5	1.5	3870
62			6) The Special Jig For Disassembly No.3 Stack Ring Is Assembled	3	3	9	~500	4300	12900	R5	1.5	3870
63			(Several Stack Ring Retaining Bolts Are Disassembled)	3	4	12	~500	4300	172000	R5	1.5	3870
64			7) No.3 Stack Ring Is Disassembled	3	4	12	~500	4300	172000	R5	1.5	3870
65			8) The Jig For Fixing Of The Exhaust Pipe Is Assembled	3	3	9	~500	4300	129000	R5	1.5	3870
66			9) Bolts To Clamp The Exhaust Pipe Are Disassembled(For The Scroll)	3	3	9	~500	4300	129000	R5	1.5	3870
67			10) The Exhaust Pipe Is Moved To Outlet Side And Fixed	3	6	18	~500	4300	258000	R5	1.5	3870
68			11) The Rotor And The Inner Casing Assy Are Standed Up				1000~	92	368	R3	1.5	12
69			12) The Radial Pin Is Disassembled				~500	9200	46000	R5	1.5	1104
70			13) No.1 Gland Ring Is Disassembled				~500	9200	27600	R5	1.5	1104
71			14-1 Remove Bolts of No.1 Inner Casing and prepare for lifting up	4	2	8	~500	9200	18400	R5	1.5	1104
72												

Added maintenance tasks in the cycle-out approach task list with extra radiation calculations

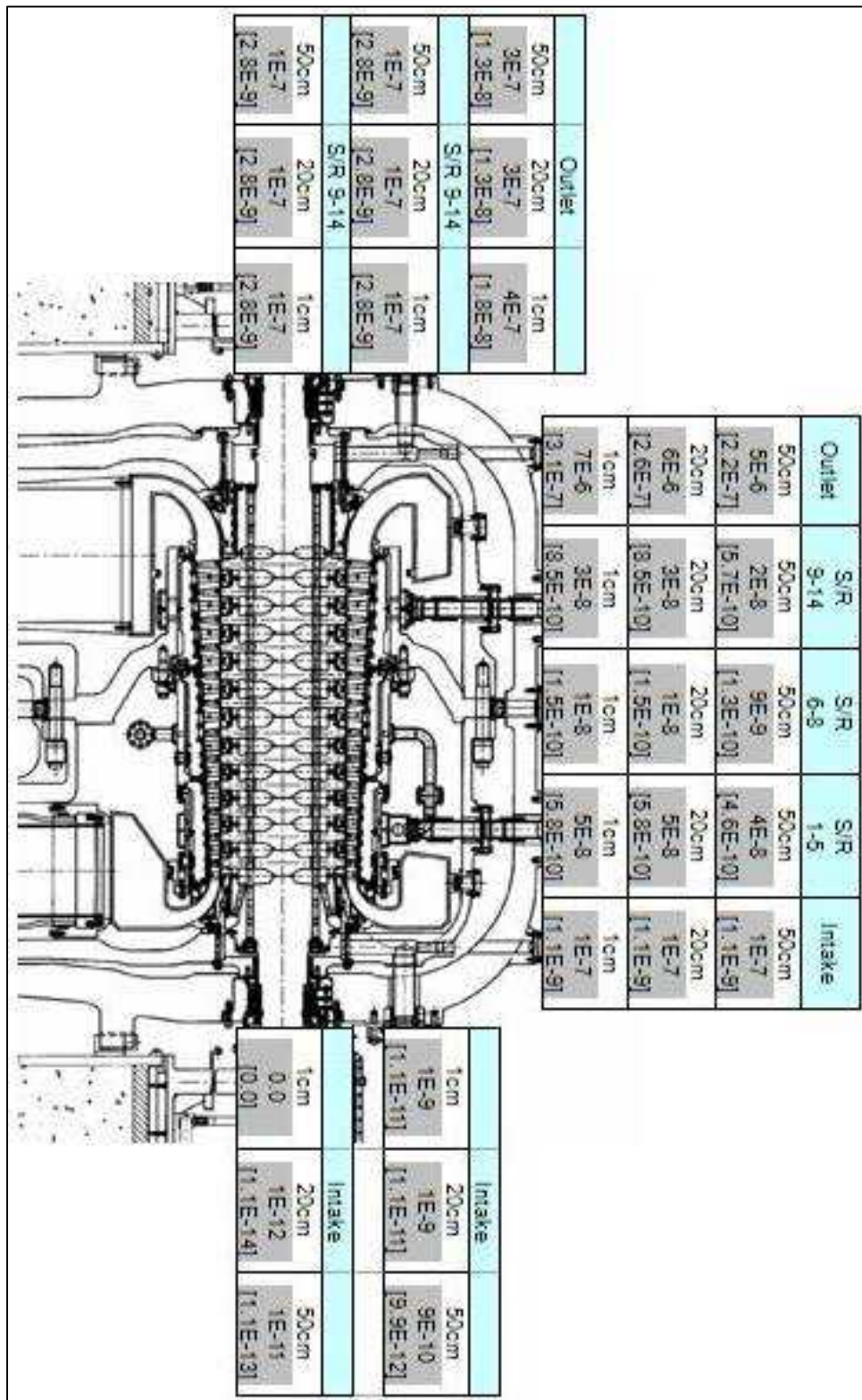
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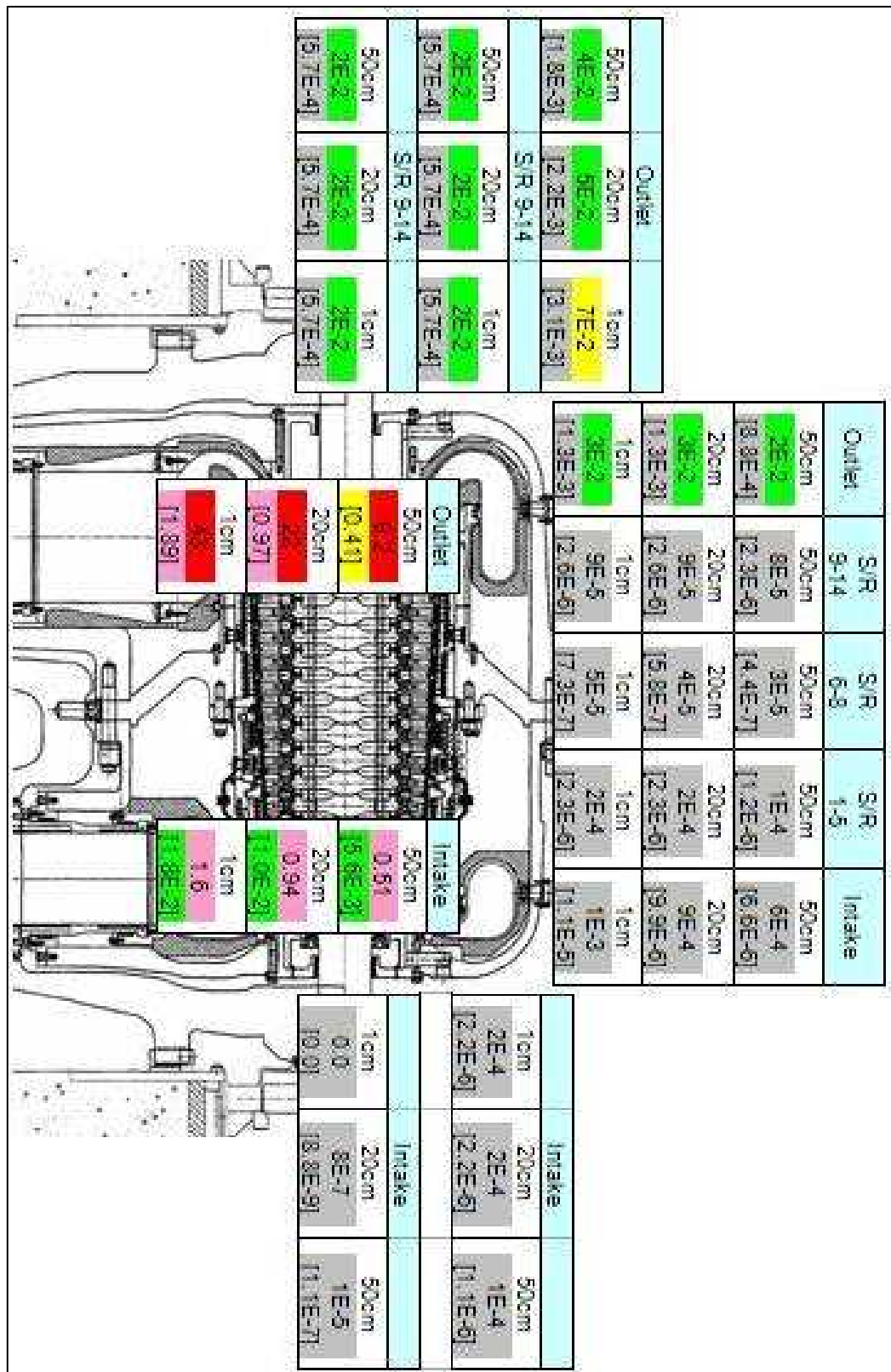
The Overhaul (left colouring) vs. Cycle-Out (right colouring) radiation and worker calculations which proved the infeasibility of the overhaul approach

Task	Min Worker [a]	Dose Rate [c] (μSv/h)	Total Dose Rate per worker (μSv/h x h)	Zone	Required min worker based on dose rate limit	Dose Rate [c'] (μSv/h)	Total Dose Rate per worker (μSv/h x h)	Zone	Required min worker based on dose rate limit
5.5-1	3	2000	6000	R4	180	11	33	R2	4
5.5-2	3	2000	16000	R4	180	11	88	R2	4
5.5-3	3	2000	6000	R4	180	11	33	R2	4
5.5-4	3	2000	4000	R4	180	11	22	R2	4
5.5-5	3	2000	6000	R4	180	11	33	R2	4
5.5-6	3	2000	4000	R4	180	11	22	R2	4
5.5-7	3	2000	6000	R4	180	11	33	R2	4
5.5-8	3	2000	4000	R4	180	11	22	R2	4
5.5-9	3	2000	8000	R4	180	11	44	R2	4
5.6-1	3	2700	8100	R4	243	11	33	R2	4
5.6-2	3	2700	21600	R4	243	11	88	R2	4
5.6-3	3	2700	10800	R4	243	11	44	R2	4
5.6-4	3	2700	8100	R4	243	11	33	R2	4
5.6-5	3	2700	5400	R4	243	11	22	R2	4
5.6-6	3	2700	8100	R4	243	11	33	R2	4
5.6-7	3	2700	5400	R4	243	11	22	R2	4
5.6-8	3	2700	8100	R4	243	11	33	R2	4
5.6-9	3	2700	5400	R4	243	11	22	R2	4
5.6-10	3	2700	8100	R4	243	11	33	R2	4
5.7-1	3	170000	510000	R5	15300	52	156	R3	9
5.7-2	3	170000	1360000	R5	15300	52	416	R3	9
5.7-3	3	170000	680000	R5	15300	52	208	R3	9
5.7-4	3	170000	510000	R5	15300	52	156	R3	9
5.7-5	3	170000	340000	R5	15300	52	104	R3	9
5.7-6	3	170000	510000	R5	15300	52	156	R3	9
5.7-7	3	170000	340000	R5	15300	52	104	R3	9
5.7-8	3	170000	510000	R5	15300	52	156	R3	9
5.7-9	3	170000	340000	R5	15300	52	104	R3	9
5.7-10	3	170000	510000	R5	15300	52	156	R3	9

Example 1 of modelled dose rate calculations (colour-coded by zone) for stages of maintenance



Example 2 of modelled radiation dose rates for various stages of maintenance (colour-coded)



Example 3 of modelled radiation dose rates for various stages of turbine maintenance

