RELIABILITY DATABASE OF IEA-R1 BRAZILIAN RESEARCH REACTOR: APPLICATIONS TO THE IMPROVEMENT OF INSTALLATION SAFETY

P.S.P. OLIVEIRA, J.B.M. TONDIN, M.O. MARTINS, M. YOVANOVICH, W. RICCI FILHO

Nuclear and Energy Research Institute, IPEN – CNEN/SP

Av. Prof. Lineu Prestes 2242 - CEP 05508-000, São Paulo – SP, Brasil

ABSTRACT

In this paper the main features of the reliability database being developed at Ipen-Cnen/SP for IEA-R1 reactor are briefly described. Besides that, the process for collection and updating of data regarding operation, failure and maintenance of IEA-R1 reactor components is presented. These activities have been conducted by the reactor personnel under the supervision of specialists in Probabilistic Safety Analysis (PSA). The compilation of data and subsequent calculation are based on the procedures defined during an IAEA Coordinated Research Project which Brazil took part in the period from 2001 to 2004. In addition to component reliability data, the database stores data on accident initiating events and human errors. Furthermore, this work discusses the experience acquired through the development of the reliability database covering aspects like improvements in the reactor records as well as the application of the results to the optimization of operation and maintenance procedures and to the PSA carried out for IEA-R1 reactor.

1. Introduction

The development of a reliability database for the research reactors located at Ipen-Cnen/SP started in 2001 when Brazil took part in an IAEA Co-ordinated Research Project (CRP). The IAEA CRP was entitled “CRP to Upgrade and Expand the IAEA Reliability Database for Research Reactor PSAs” and had participants from eleven Member States: Argentina, Australia, Austria, Brazil, Canada, Czech Republic, India, Indonesia, Republic of Korea, Romania and Vietnam. The main objective of this CRP was to generate a new version of IAEA reliability database to supersede IAEA-TECDOC-930 [1], since it had a broader scope providing guidance on a wider range of issues pertaining to reliability data for the Probabilistic Safety Analysis (PSA) of research reactors. However, this new version, which was concluded in 2005 and sent to the IAEA for a final review, has not been published yet.

In the case of Brazil, a specific reliability database for IEA-R1 reactor continued being updated and improved. IEA-R1 is a 5 MW pool type reactor, cooled and moderated by light water, and it uses graphite and beryllium as reflectors. First criticality was achieved on September 16, 1957 and the reactor has been operating regularly and safely for over 50 years. For this period, it has been intensively used for basic and applied research, training and production of radioisotopes.

In this work the current stage of IEA-R1 reliability database is presented, and the main results regarding the compilation of component failure data, accident initiating events and human errors are discussed. These results are based on the facility records from January 1999 to December 2007, which means a nine-year-observation period.

The main features of the reliability database are described in section 2. A brief explanation of the process for collection and updating of data regarding operation, failure and maintenance of IEA-R1 reactor is presented in section 3. The methods used for the compilation of data are explained in section 4. This work also covers the main applications of the reliability data in the safety analysis of IEA-R1 reactor as well as in the improvement of operating and maintenance procedures of the facility. These aspects will be discussed in section 5 followed by the conclusions in section 6.

2. Main Features of the Reliability Database of IEA-R1 Reactor

The reliability database of IEA-R1 reactor consists of a set of connected Microsoft Excel spreadsheets (input data and output/final data) with necessary information:

- to generate estimates of component failure rates/probabilities of failure on demand and accident initiating events frequencies; and
- to compile human error evidences related to reactor operation and maintenance.

The generation of these data aims to give support to several technical areas of Ipen-Cnen/SP for the development of reliability and safety analyses of the local research reactors or other similar facilities.

The information gathered in this database mainly covers:

Component Technical/Engineering Data. Technical characteristics of IEA-R1 reactor components are stored in the database (type, size, rating, fluid, manufacturer, model, location, etc.). For the definition of component boundaries, the criteria defined by the reactor personnel are followed. Also, the guidance given in IAEA-TECDOC-636 [2] and some definitions in OREDA Handbook [3] should be considered.
Component Operational Data. Records of continuous operating times between consecutive interruptions (either planned shutdowns or not) and the number of demands of the components per reactor operation are stored in the database. In addition, cumulative operating times and number of demands are also computed. In some special cases, the operating time is recorded using one of the installed "timers" and the number of demands is recorded by "counters".
Component Maintenance Data. Every maintenance activity (preventive, corrective or predictive), concerning each reactor component, is recorded in the database. Some details such as: description of the work done, execution time, and so on, are also registered. For IEA-R1, these data may be extracted directly from the maintenance database already developed by the Reactor Maintenance Division personnel.
Component Failure Data. All component failures are reported and verified in order to identify their causes, effects on system / subsystem, actions taken and recovery time. The database stores, whenever possible, the exact times of failure occurrence and detection as well as the time of component restoration to service. Component failure modes are identified and coded according to Table III of IAEA-TECDOC-930 [1].
Data Analysis. Part of the data stored in the database can be processed in order to generate estimates of component reliability parameters. The approach implemented in this database is based on the assumption that failure times are exponentially distributed. It generates an estimate of the constant failure rate (that is the inverse of the “mean time to failure”) associated to each time-related component failure mode. The analysis includes the calculation of a 90% confidence interval estimate (uncertainty limits) for each component failure rate or probability of failure on demand. The MLE (maximum likelihood estimator) for the failure rate / probability of failure on demand is calculated. The Chi-Square distribution is used to derive the confidence bounds for the mean of these parameters. The algorithms to calculate these estimates are implemented in a Microsoft Excel spreadsheet which was developed during the IAEA CRP.

Accident Initiating Events and Human Errors Data. Occurrences identified as accident initiating events precursors and/or human errors are stored in the database in order to be investigated and properly grouped.

3. Process for collection and updating of data related to operation, failure and maintenance of IEA-R1 Reactor

Although IEA-R1 reactor has been operating for over fifty years, it has not been possible to completely restore its operational experience since many records of the past history of this facility had information which was incomplete or dubious. Besides that, some important modifications occurred in IEA-R1 in the past. In 1976 the reactor cooling system was duplicated whereas in 1997 a few changes were accomplished in order to increase its power level from 2 MW to 5 MW and to extend its operating cycle to continuous 64 hours per week. Therefore, it was agreed with the reactor personnel to consider the restoration of the records from the year of 1999.

The process for collection and updating of data regarding IEA-R1 reactor will be described below. These tasks have been conducted by the reactor personnel under the supervision of specialists in reliability engineering and PSA. Data on abnormal / unusual occurrences are extracted from the following sources: logbooks, reactor start-up checklist, reactor shutdown checklist, reactor operation datasheets, corrective maintenance datasheets, etc.

Considering the proposed content of IEA-R1 reliability database, two different forms have been introduced to collect input data: (1) Form-1 used for the identification and analysis of abnormal / unusual occurrences during reactor operation and maintenance; (2) Form-2 used to record operating times and number of demands of the main reactor components.

3.1. Identification and analysis of abnormal/unusual occurrences during IEA-R1 reactor operation and maintenance

To fill in the spreadsheet used for the identification and analysis of abnormal / unusual occurrences, the following procedures and criteria are adopted:

- Data on abnormal / unusual occurrences extracted from logbooks or from other documents are first assessed and then classified according to the event type: component failure, accident initiating event, human error, common cause failure and maintenance activity.
- Occurrences related to inadvertent reactor shutdown (SCRAM) are taken into consideration in order to record the number of demands of the Reactor Protection System.
- Occurrences related to inadvertent reactor shutdown (SCRAM) due to loss of offsite power (LOSP) are recorded so as to estimate the number of demands of the emergency power supply systems.
- Failures detected upon preventive maintenance or in a shutdown state of the reactor may be compiled if there is evidence that these failures will be revealed in the next operational phase of the component.
- Further screening can be done to exclude component failures that have no significant impact on reactor safety, and to include component failures related to safety systems and their support systems.
- Failures in which the direct cause is a human error are not taken into account for component failures rates, but are modelled separately.
- Occurrences classified as potential accident initiating events (or initating events precursors) are reproduced in a separate datasheet to verify their association with the events listed in IAEA Safety Standards Series No. NS-R-4 [4].
- Each item failed is assigned a component type code according to standardized codification set by IAEA [1]. Examples: fission counter - ACF; ionisation chamber - ACI; sensor pool water level - ALR; sensor pressure difference - APD; sensor conductivity - AQC; radiation monitoring alarm unit - ARU; sensor temperature - ATA; diesel generator,

emergency ac - DGA; etc. This task requires special attention to assure that the identified failure corresponds to an item within the component boundaries.

- Component boundaries are defined according to the guidelines provided in IAEA-TECDOC-636 [2]. Whenever the boundaries presented in reactor maintenance reports differ from the boundaries recommended in [2], specific definitions of reactor maintenance personnel are preferably adopted.
- Each failure record is assigned a failure mode code according to standardized codification set by IAEA [1]. Examples: failure to function - F; degraded failure - B; spurious function - K; failure to run - R; open circuit - I; erroneous signal - N; etc.
- All the results should be carefully checked before being incorporated into the database.

3.2. Recording the operating times and number of demands of the main IEA-R1 reactor components

The operating times of IEA-R1 components are mainly derived from the records found in the datasheets generated during each reactor operation. Timers and counters are installed in a few important components, which are: control console, primary and secondary circuits cooling pumps, cooling tower fans, Ventilation and Air Conditioning (VAC) system fans, diesel generator groups and instrument air compressor. As a whole seventeen timers and three counters are installed in IEA-R1 in order to record exact operating hours and number of demands of these main components. In the case of the other components the operating times and number of demands are estimated based on either the values recorded in the reactor operation datasheets or the timers and counters of the main components.

In Figure 1 some examples of tables summarizing the annual totals calculated from the collection of operating times and number of demands of the main IEA-R1 components.

Year	Reactor Operating Time (hours)	Reactor Operating Time (hours)	Number of Reactor Operations	Reactor Operations - High Power	Reactor Operations - Low Power	Number of SCRAMs	Loss of Off-Site Power (LOSP)
1999	2445:57:30	2445,96	65	49	16	26	9
2000	2705:06:00	2705,10	69	57	12	21	17
2001	1923:42:00	1923,70	55	49	6	23	7
2002	1767:15:30	1767,26	73	50	23	10	8
2003	1606:11:00	1606,18	54	44	10	35	4
2004	2491:48:00	2491,80	77	46	31	17	8
2005	2873:56:00	2873,93	57	49	8	22	14
2006	2735:07:00	2735,12	70	50	20	38	19
2007	1440:27:00	1440,45	42	30	12	20	3
Total	**19989:30:00**	**19989,50**	**562**	**424**	**138**	**212**	**89**

Mean Values			
Operating hours/ year	Operations/ year	SCRAM/ year	LOSP/ year
2.445,96	65,00	26,00	9,00
2.575,53	67,00	23,50	13,00
2.358,25	63,00	23,33	11,00
2.210,50	65,50	20,00	10,25
2.089,64	63,20	23,00	9,00
2.156,67	65,50	22,00	8,83
2.259,13	64,29	22,00	9,57
2.318,63	65,00	24,00	10,75
2.221,06	62,44	23,56	9,89

Year	Control Console			Primary Circuit Pump B101-A (CP-BOM-01)			Primary Circuit Pump B101-B (CP-BOM-02)			Heat Exchanger A		Heat Exchanger B	
	No. of Demands	Operation Data Sheet (hours)	Timer (hours)	No. of Demands	Operation Data Sheet (hours)	Timer (hours)	No. of Demands	Operation Data Sheet (hours)	Timer (hours)	No. of Demands	Operating Time (hours)	No. of Demands	Operating Time (hours)
1999	71	2544:03:00	2544,05	27	1101:49:00	1101,82	34	1327:00:00	1327,00	17	665,65	33	1739,79
2000	83	2834:37:00	2834,62	36	1284:35:00	1284,58	39	1477:03:00	1477,05	27	1219,55	29	1540,23
2001	71	2004:26:00	2004,43	59	1540:08:00	1540,13	16	378:15:00	378,25	21	834,65	28	1071,38
2002/b.t.	16	407:58:00	407,97	16	383:20:00	383,33	0	0:00:00	0,00	5	183,05	6	200,28
2002/t.	52	1419:32:00	1595,50	15	462:04:00	466,48	26	885:41:00	894,44	9	406,24	29	950,11
2003	58	1646:32:30	1930,58	8	282:17:00	286,65	38	1161:40:00	1275,69	9	557,94	35	1558,04
2004	94	2602:52:00	2725,50	58	1722:03:00	1746,71	23	711:23:00	727,80	8	485,49	39	2139,27
2005	63	2962:45:00	3058,67	19	1109:08:00	1057,34	114	1581:34:00	1872,78	6	356,05	43	2545,12
2006	85	2814:52:00	2939,04	42	1267:46:00	1314,91	83	1355:51:00	1307,99	0	0,00	49	2678,40
2007	45	1481:00:00	1567,49	19	272:44:00	282,69	44	1149:48:00	1177,41	2	0,15	33	1451,63
Total	**637**	**20718:37:30**	**21607,85**	**299**	**9425:54:00**	**9464,65**	**417**	**10028:15:00**	**10438,41**	**104**	**4708,77**	**324**	**15874,26**

Figure 1 - Operating times and Number of Demands of IEA-R1 Reactor Components

4. Compilation of collected data to estimate component reliability parameters and other failure event frequencies

The compilation of collected data is developed in a spreadsheet that is a calculation report to generate final data concerning component failure rates / probabilities of failure on demand. This calculation report (or intermediate spreadsheet) uses both data on abnormal / unusual occurrences mentioned in subsection 3.1 and data on operating times / number of demands described in subsection 3.2.

In this calculation report the components are codified according to their types based on the three letter coding system standardized in IAEA-TECDOC-930 [1]. Besides that, this calculation report contains detailed technical descriptions of the analyzed component types and can be cross-referenced with the reliability parameters data table.

The data collected and reported in this study cover major components of the following IEA-R1 reactor systems: Reactor Core; Reactor Cooling System – Primary and Secondary Circuits; Instrumentation and Control System; Electrical Power Supply System; Ventilation and Air Conditioning System; Instrument Air System; etc.

Considering the observation period from January 1999 to December 2007, 557 failures of 108 different component types were compiled. The total operating time of IEA-R1 reactor during that period was 19989,5 hours. Mean values of component failure rates / probabilities of failure on demand and respective confidence intervals are calculated using the algorithms developed during the IAEA CRP and are compiled in a spreadsheet which format is presented in Table 1. Examples of the technical descriptions of IEA-R1 components are shown in Table 2.

Data stored in the IEA-R1 database can also be used to estimate the frequencies of accident initiating events and to assess occurrences related to human errors during the operational and maintenance procedures. During the nine-year-observation period from 1999 to 2007, over 350 events were identified as initiating events precursors. Among these events, 82 occurrences might have evolved to the initiating event "fuel cooling channel blockage". Based on these evidences, the estimated initiating event frequency is $4{,}1 \times 10^{-3}$/hr, since the total operating time of the reactor during the observation period is 19989,5 hours. In addition, 38 human errors were identified and grouped according to event types: failure to follow procedures or maintenance error (26); error of commission (9); and design error (3). Among these 38 events related to human errors, at least 25 could also be classified as precursors of accident initiating events. The scope of this database does not include quantitative derivation of human error data.

5. Application of the results to safety aspects of IEA-R1 Reactor

It is important to mention that enhancement of accuracy and quality of reliability data has already been observed along these years at IEA-R1 reactor. In this sense, some factors presented a major contribution: more detailed descriptions of the abnormal/unusual occurrences or failures; more precise data on component failure times or failure detection times; records of exact operating times and number of demands obtained from timers and counters installed in the main reactor components; and more detailed descriptions of corrective maintenance activities including information on their durations. Besides that, there were changes in format and content of the records in logbooks and other operation datasheets aiming to include the information necessary to compose the reliability database.

Furthermore, component failure data resulting from this work was applied in the Probabilistic Safety Analysis (PSA) of IEA-R1 reactor. A master dissertation covering a partial PSA of IEA-R1 reactor was developed at Ipen-Cnen/SP and concluded in 2009 [5]. This work addressed the detailed analysis of the two main accident initiating events identified in the Safety Analysis Report of this facility, which are flow channel blockage and loss of coolant due to rupture of primary circuit boundary.

Code	Component type description	Reactor Code	Component Population #	Cummulative calendar time hs	Cummulative operating time hs	Demands #	Failure mode	Failures #	Failure rate 1/h	Failure probability 1/demand	90% Confidence bounds 5%	95%
ACF01	Fission Counter	BR01	2		2,16E+04		F	12	5,55E-04	-	3,20E-04	9,00E-04
ACF01	Fission Counter	BR01	2		2,16E+04		B	7	3,24E-04	-	1,52E-04	6,08E-04
ACF01	Fission Counter	BR01	2		2,16E+04		I	1	4,63E-05	-	2,37E-06	2,20E-04
ACI01	Ionisation Chamber - compensated	BR01	3		2,16E+04		F	3	1,39E-04	-	3,78E-05	3,59E-04
ACI01	Ionisation Chamber - compensated	BR01	3		2,16E+04		B	1	4,63E-05	-	2,37E-06	2,20E-04
ACI01	Ionisation Chamber - compensated	BR01	3		2,16E+04		N	1	4,63E-05	-	2,37E-06	2,20E-04
ACI02	Ionisation Chamber - non compensated	BR01	5		6,00E+04		F	2	3,34E-05	-	5,93E-06	1,05E-04
ALR01	Sensor - pool water level - float type	BR01	1	7,88E+04			K	4	5,07E-05	-	1,73E-05	1,16E-04
ALR02	Sensor - pool water level - ultrasonic type	BR01	3	2,37E+05			F	1	4,23E-06	-	2,17E-07	2,01E-05
ALR02	Sensor - pool water level - ultrasonic type	BR01	3	2,37E+05			N	3	1,27E-05	-	3,46E-06	3,28E-05
APD01	Sensor - pressure difference	BR01	4	3,15E+05			F	1	3,17E-06	-	1,63E-07	1,50E-05
AQC01	Sensor - conductivity (water re-treatment)	BR01	2	1,58E+05			N	1	6,34E-06	-	3,25E-07	3,01E-05
AQC02	Sensor - conductivity (water treatment)	BR01	4		1,58E+05		B	1	6,33E-06	-	3,25E-07	3,00E-05

Table 1 - Example of the IEA-R1 Component Reliability Database

Component Code		Description
ACF 01	Component Type / Name:	**Fission chamber**
	System:	Instrumentation and Control System
	Component "Tag":	IC-CAF-01; IC-CAF-02; IC-CAF-03; IC-CAF-04
	Population:	4
	Location:	reactor core
	Manufacturer:	IPEN / IST Imaging & Sensity Tec
	Component characteristics:	model WL-6376A; 93% enriched U
	Operating duty:	1 fission chamber functioning (reactor core), 3 standby
	Component boundary:	sensor and cabling (excluding components installed in the control console)
	Linked components:	ICC02 (safety channels)
ACI 01	Component Type / Name:	**Ionisation chamber - compensated (linear channel)**
	System:	Instrumentation and Control System
	Component "Tag":	IC-CIC-01; IC-CIC-02; IC-CIC-03
	Population:	3
	Location:	reactor core
	Manufacturer:	Westinghouse / IST Imaging & Sensity Tec
	Component characteristics:	WL-7741 (CIC-01); WL-23084 (CIC-02/03)
	Operating duty:	1 ionisation chamber functioning (reactor core), 2 standby
	Component boundary:	sensor and cabling (excluding components installed in the control console)
	Linked components:	ICC01 (linear channel)
ACI02	Component Type / Name:	**Ionisation chamber - non compensated (safety channel)**
	System:	Instrumentation and Control System
	Component "Tag":	IC-CNC-01; IC-CNC-02; IC-CNC-03; IC-CNC-04; IC-CNC-05
	Population:	5
	Location:	reactor core (CNC-01/02/04/05); basement (CNC-03)
	Manufacturer:	Westinghouse (CNC-01/02/04); Ipen (CNC-03); IST Imaging & Sensity Tec (CNC-05)
	Component characteristics:	model WL-6937 (CNC-01/02/04/05); HOM-CARREI-N16 (CNC-03)
	Operating duty:	3 ionisation chamber functioning, 2 standby
	Component boundary:	sensor and cabling (excluding components installed in the control console)
	Linked components:	ICC02 (safety channels); N-16 channel ; EPH01 (high power voltage)
ALR 01	Component Type / Name:	**Sensor - pool water level - float type**
	System:	Instrumentation and Control System
	Component "Tag":	IC-MDS-01
	Population:	1
	Location:	reactor pool
	Manufacturer:	NIVETEC
	Component characteristics:	NPR-EXD; series 600-010-304
	Operating duty:	continuous functioning
	Component boundary:	sensor, transmitter and local power supply
	Linked components:	control room indicating instrument; URS01 (Scram circuit)
ALR 02	Component Type / Name:	**Sensor - pool water level - ultrasonic type**
	System:	Emergency Core Cooling System
	Component "Tag":	RE-MDS-01; RE-MDS-02; RE-MDS-03
	Population:	3
	Location:	reactor pool; retention tank
	Manufacturer:	CONTROL LEVEL / INCONTROL
	Component characteristics:	model ES-9063A4048AZ
	Operating duty:	2 sensors in continuous functioning; 1 stand-by
	Component boundary:	sensor, transmitter and local power supply - excluding indicators RE-INN-01 (emergency room), RE-INN-02 (control room) and RE-INN-03 (laboratory) installed in the control room
	Linked components:	UIE02 (indicating instrument); URS01 (Scram circuit)

Table 2 - Example of the IEA-R1 Component Technical Description Database

6. Conclusions

The reliability database being developed at Ipen-Cnen/SP has brought some benefits to IEA-R1 reactor besides arising the interest of the reactor management staff in subjects related to safety assessment and reliability analysis.

Prior to this database project, the operational and maintenance records found in the facility had not contained the necessary information to estimate failure rates or other reliability / availability parameters of the reactor components. Then, some effort was required to introduce new forms to be fulfilled by the reactor staff so as to serve to the purpose of generating plant specific reliability data. In fact, the involvement and commitment of supervisors and senior operators for the past nine years have been essential to obtain more reliable records to update the database. Actually, the research work being carried out at Ipen-Cnen/SP has shown that it is fundamental to promote an integration of data collection activities with the existing organizational features and administrative routines of the facility in order to minimize the efforts and to provide good quality data.

It is important to mention that the safety aspects concerning the observed component failures or human errors have been discussed more often in the periodical meetings held in the facility. In these debates, it has been possible to notice that few events could compromise the reactor safety. Even so, the results obtained may contribute significantly to the improvement of operational procedures as well as to the optimization of the maintenance programme of the reactor.

In this work the following important aspects were not addressed although they are being considered by the specialists involved in the reliability database:

- promotion of a practice in the facility to proceed a root cause analysis to investigate failures or to assess the effectiveness of the corrective actions. Some corrective maintenance records indicate that the symptoms of the failures rather than the causes have been addressed; and
- elaboration of a software to manage the database. In this case, a relational database is being planned by a specialist who will be in charge of implementing its future updates and making it available to local computer network users.

Finally, the database developed for IEA-R1 has to be specifically used in the applications of this reactor. However, some data may be applied to other facilities if the components are analogous or the operational conditions are alike. In this way, it is expected that all the experience acquired with this research work can be directed toward the project of a new multipurpose reactor being carried out in Brazil.

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