THE HEALTH PHYSICS ASPECTS OF THE FAILURE OF A PLUTONIUM-BERYLLIUM START-UP SOURCE IN THE SAFARI 1 REACTOR

D. K. CRAIG, B. C. WINKLER and J. R. COLLEY

National Nuclear Research Centre, Pelindaba, South Africa

Abstract—A neutron start-up source, containing 160 grams of plutonium, was supplied by the subcontractors for the Safari 1 reactor. During the start-up and commissioning period, for which the reactor was under the control of the subcontractors, the container for this source ruptured.

This allowed some of the plutonium and its fission products to escape into the various reactor systems.

The resulting increased levels of radioactivity were first indicated definitely on April 22, and after extensive investigations, the rupture of the source container was discovered on April 26, 1965. After removing the source from the reactor vessel and taking such other steps as were practical to control the increased radiation and contamination hazards, the reactor was brought back to power on April 28 and was operated at full power for seven consecutive days.

The events leading up to and surrounding the incident are described. The health physics aspects of the incident are presented and the consequences are discussed. It is shown that, while greatly increased radiation and contamination hazards arose, no personnel suffered injury, ingested radioactive material or received radiation exposures in excess of internationally recommended maximum permissible limits. Furthermore, no danger to the general public arose in any way as a consequence of the incident.

I. INTRODUCTION

It has become customary in the atomic energy industry to report reactor incidents in the open literature. This has been done in the hope that by revealing personnel errors, procedural inadequacies and instrumental failures, and by analysing the incidents and describing the methods used to combat them and prevent recurrences, others involved in this new and rapidly developing field might benefit. Examples of such reports are given in refs. 1 through 14. It is with this in mind that the present report is presented.

Safari 1 is a 90% enriched uranium fuelled, light-water cooled and moderated, tank-type research and materials testing reactor based on the ORR facility at Oak Ridge. It is located at the National Nuclear Research Centre at Pelindaba in South Africa. A general outline of the facility has been given by Roux,[15] and a more detailed description will be found in the "Engineering Design and Safeguards Report on the Safari 1 Research Reactor".[16]

II. BACKGROUND

On March 15, 1965, a 10 Ci Pu-Be start-up source (Fig. 1) was placed in the bottom of an aluminium basket 1.875 in. i.d. and inserted into a 2.00 in. i.d. hollow beryllium reflector element in the reactor core. Fuel element loading commenced next day and the reactor went critical with nine fuel elements and four control rods during the evening of March 18. Following control rod calibration, the source was moved to core location F7 (Fig. 2) on March 23, and on the following day, after loading more elements, the full operating core, as shown in Fig. 2, was attained. On March 25 the source was moved to reactor location E1 to increase the counting rate in the start-up channel, and low power runs were made up to

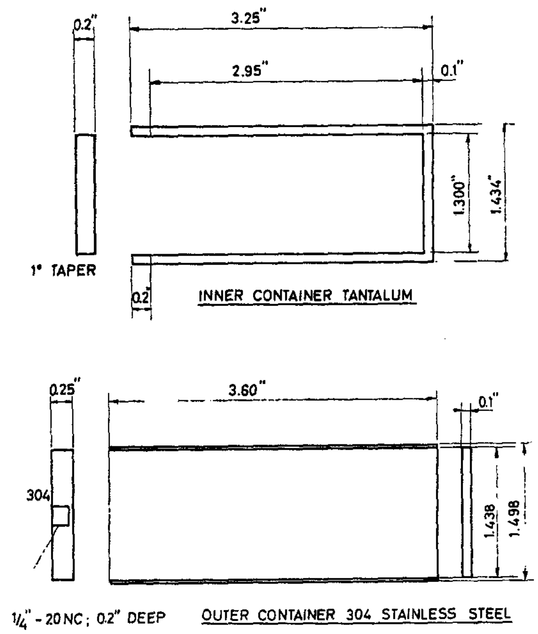

FIG. 1. Container of plutonium-beryllium source.

April 9 when the power was increased to 2.2 MW. At this time the reactor was run continuously, and power was brought up to the design maximum of 6.7 MW in the early morning hours of April 10, and maintained at this level through April 13. After this two days were spent performing Xenon build-up and decay tests at 60 W, and then all plant, including the ventilation system, was shut down for the Easter holidays, April 16–19 inclusive. When the ventilation system was started up on the morning of April 20 the stack particulate monitor readings increased by two orders of magnitude and returned to normal values of about 6×10^2 counts/min. Previously, increases by factors of up to five had been regularly observed under nocturnal inversion conditions, and as the much larger rise could be attributed to the build up of radon and thoron decay products, it had no disturbing effect upon the reactor operators.

III. THE INCIDENT

The reactor was started on April 21 but was shut down after a few hours due to an instrument fault. Some 10 hr after shutdown the reactor hall ventilation duct monitor, which was set at 30% above normal background, tripped the ventilation system from a 30,000 cfm unfiltered system to a 2000 cfm filtered system with stack discharge. The ventilation trips were reset and the reactor was started up again reaching full power at 00:43 hr on April 22.

During the rise to power the stack particulate monitor readings rose steadily (Fig. 3) and by 02:00 hr the shift health physicist had to change the range from 10^4 to 10^6 counts/min. Neither the rate of increase of this reading nor that of the

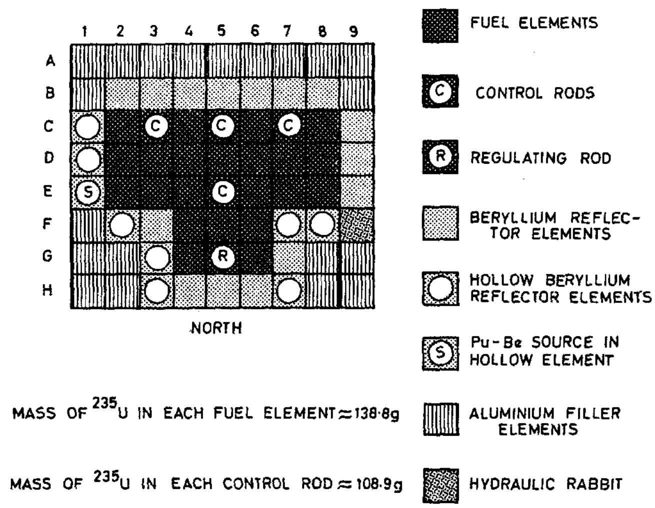

FIG. 2. Safari 1 core configuration at time of incident.

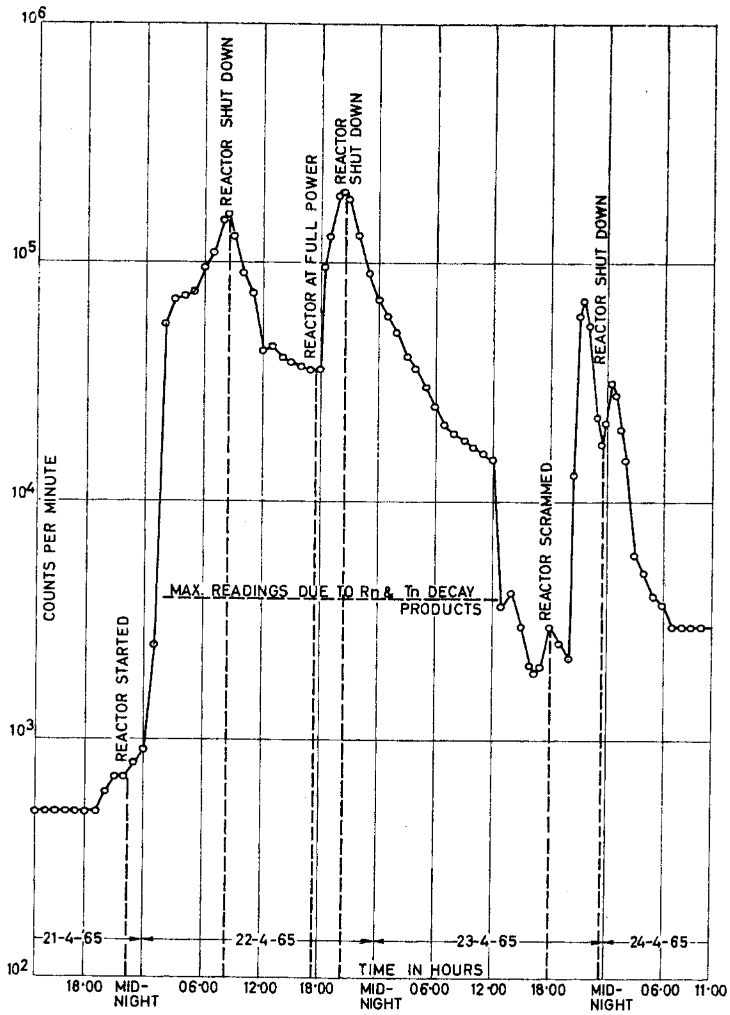

FIG. 3. Stack particulate monitor readings from 14:00 hr 21.4.65 to 09:00 hr on 24.4.65.

stack gaseous monitor reading (Fig. 4) was recognized as a serious abnormal condition. At 03:30 hr the duct monitor tripped the reactor hall ventilation system again and, although previous peaks in the duct monitor has been observed (Fig. 5), these were attributed to instrument behaviour. Routine smear tests and air samples taken at this time throughout the reactor area showed no increases above normal background. However, at 04:19 hr the secondary water monitor showed abnormally high readings, not due to contamination from the secondary water but to direct radiation from other equipment. Following high readings from the reactor fission products monitor at 05:10 hr a special survey was started. At 06:00 hr several areas of high exposure rate were identified (50 R hr^{-1} at the surface of the primary water demineraliser filter, 25 mR hr^{-1} at the entrance to the degasifier room) and at 07:54 hr the sub-pile room monitor tripped its alarm (Fig. 6). A few minutes later the senior health physicist arrived to take over the shift and on his advice the reactor was shut down at 08:34.

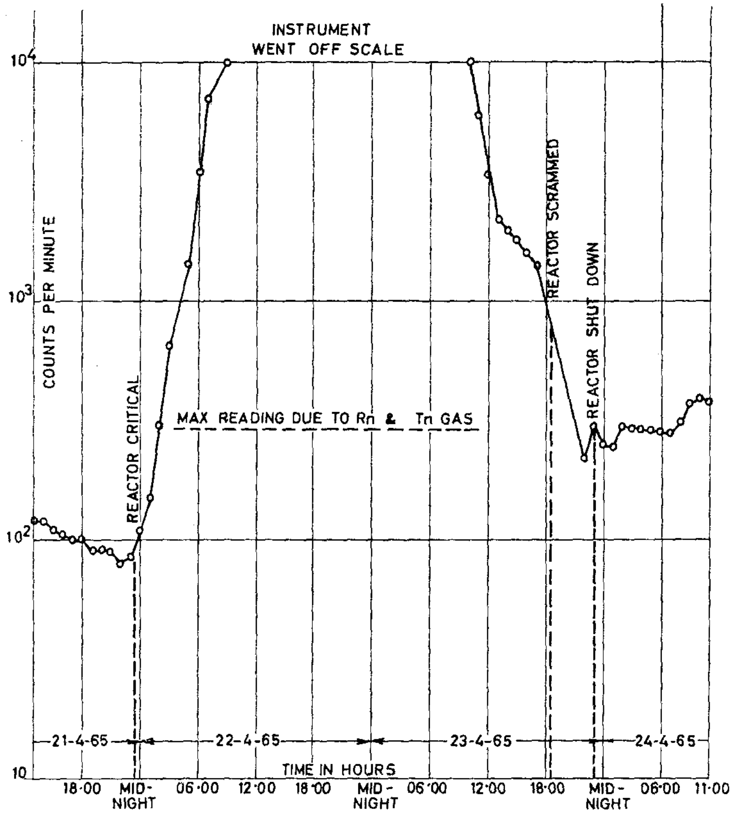

FIG. 4. Stack gaseous monitor readings from 14:00 hr on 21.4.65 to 09:00 hr on 24.4.65.

IV. INVESTIGATIONS AND SUBSEQUENT ACTION

Investigation into the cause of the high readings was commenced immediately, but fission products could not be identified in samples of primary water, or any filters. The fission product monitor filter contained a considerable quantity of ion exchange resin known to have been released from the demineralizer at an earlier date, and some consideration was given to the possibility that the high radiation levels were due to the accumulation of activated resin at obstructions in the primary water circuit. This did not explain high stack readings and therefore the reactor was brought up to full power between 17:02 and 17:40 hr in order to obtain further data (Figs. 3, 5, 6). Within five minutes the duct ventilation monitor tripped due to direct radiation. At 18:22 hr the pool water monitor gave a high level alarm, and at 20:54 hr the reactor was shut down because exposure rates around the primary coolant circuit were high and increasing. While the reactor was operating a gas sample was taken from the off-gas ventilation system, and by 08:30 hr on the following morning (April 23) it was confirmed that this contained fission products. The water level in the pool was lowered to just above the surface of the vessel, and a gas sample from the vessel showed a high Xenon content. The vessel access hatch was removed, and the water level lowered slightly to permit water sampling from each fuel channel. Initial results were indefinite, so sampling continued with the reactor operating at 5 kW, having refilled the pool and with all process systems shut off.

A Victoreen VMS-5/830 C continuous monitor responding to particulates in air was installed above the pool and after it had sounded an alarm at the 168 hr MPC level for radon all

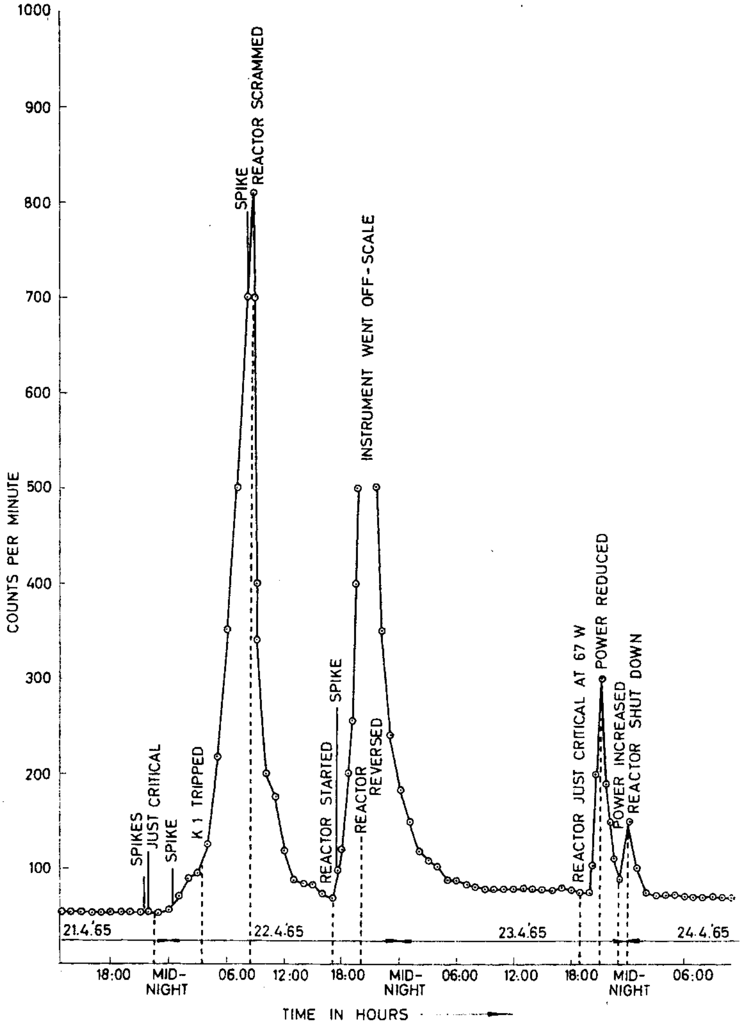

FIG. 5. Reactor hall ventilation duct (K1) monitor readings from 14:00 hr on 21.4.65 to 09:00 hr on 24.4.65.

personnel in the area wore full-face or half-face respirators. A 5 ml water sample from core location E2 (Fig. 2) gave over 90,000 counts/min compared with 6000–10,000 counts/min for similar samples from adjacent channels. This differential was confirmed during a short run at 50 kW and the reactor was shut down just before midnight in the belief that the high readings may have been due to a faulty fuel element. At 01:16 hr on the next morning (April 24) a new fuel element was fitted. On April 26 it was suggested that the Pu-Be might also be considered as a possible source of contamination. The ratio $^{140}La/^{140}Ba$ to $^{103}Ru/^{103}Rh$ in the spectrum of water from channel E2 was more consistent with a fission product release from ^{235}U than from ^{239}Pu. The reactor was therefore started up at 15:00 hr and operated at 30 kW to gather more data. Access to the reactor hall was, of course, restricted to essential personnel and respirators were worn. Even with the new fuel element in place water

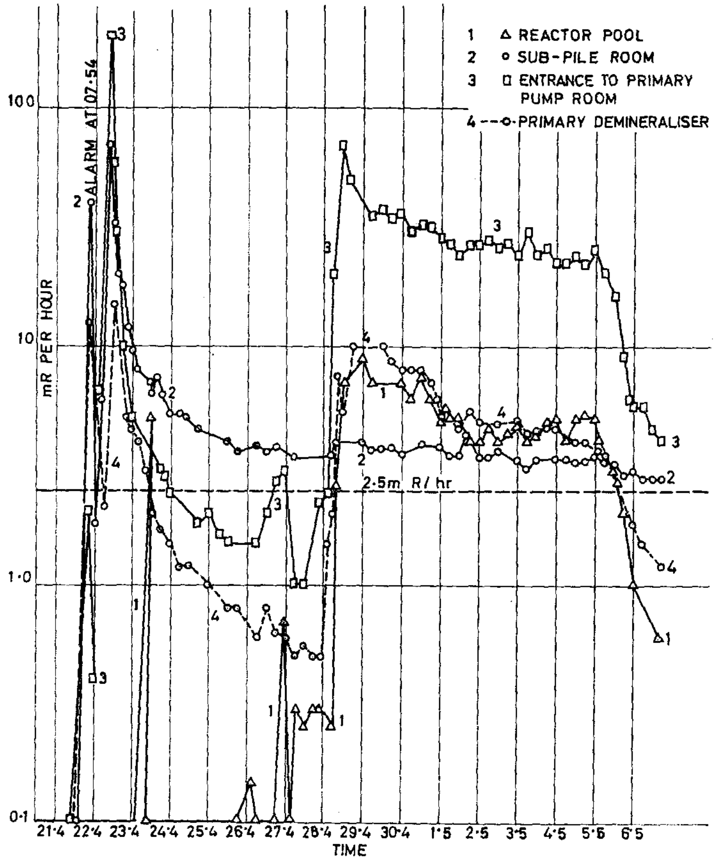

FIG. 6. Some area radiation monitor readings for the period April 21 through May 6, 1965.

samples from location E2 still showed very high readings and it was decided to remove the basket containing the source and nine beryllium plugs for visual examination. The source was removed with considerable difficulty late on April 26, and was seen to have split longitudinally (Fig. 7). Discoloration of the steel case indicated that very high temperatures had been reached. On the following morning activity and irradiation levels were seen to be decreasing, and the alpha activity in the pool water was about 5×10^{-6} μCi/ml. Two days were spent in cleaning up the reactor area and consideration was given to the safety of starting up the reactor again. Although some chips of the Pu-Be source were probably in the reactor vessel, primary coolant circuit and pool, and would release further fission products on start up, it was decided that these could best be disposed of by operating the plant and allowing the primary circuit and pool filters to remove the plutonium and fission products. With a close watch on activity and radiation levels the reactor was run up to 2.2 MW without a source in the afternoon of April 28 and kept steady for two hours during observations. At 18:00 hr power was increased to 4.4 MW, and the main source of stack activity was shown to be the degasifier. By 19:12 hrs the reactor was at full power and all monitor readings began to level off. Full power was maintained during a warranty run which lasted for the next 7 days. After this the reactor was shut down with the reactor and pool water purification systems still running continuously to clean up as much activity as possible.

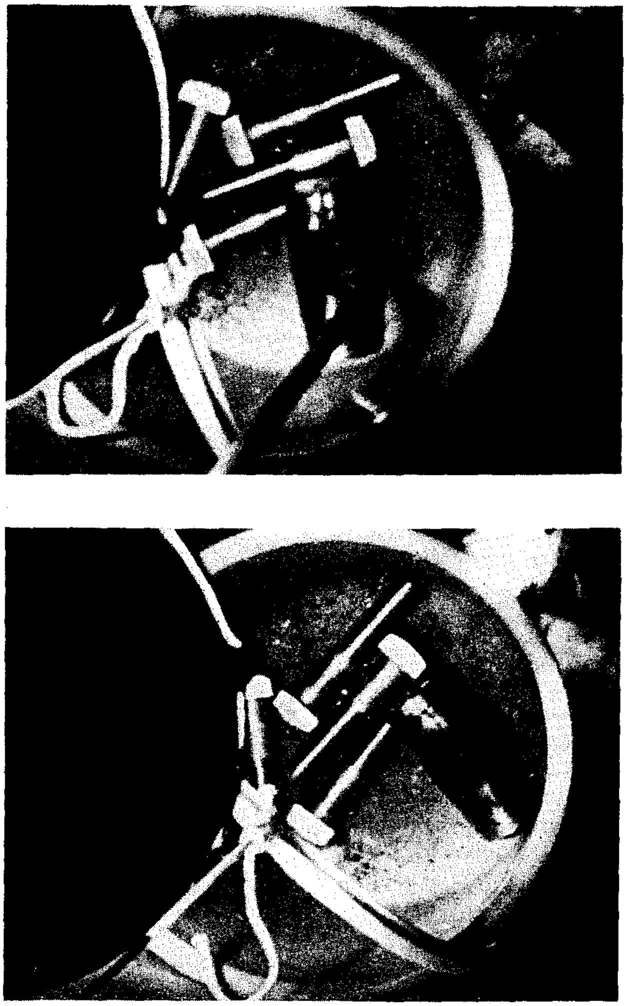

FIG. 7. Photographs of ruptured source container. These photographs were taken with the source in a plastic bucket, located under about 12 ft of water. The upper photograph shows the longitudinal rupture along the top of the container. The lower photograph was taken with the container rotated through 90°.

V. HEALTH PHYSICS ASPECTS OF THE INCIDENT

Table 1 shows the results of personal dosimeters worn by all people involved in the incident and who received more than 10 mR exposure. It will be noted that all results are well within ICRP Recommendations. Five people were selected for special examination, including whole body counting, urine analysis, and a complete medical examination. All tests showed that no person had suffered any injury whatever as a result of the incident.

VI. RELEASE OF AIRBORNE RADIOACTIVITY TO THE ENVIRONMENT

Figures 3 and 4 show that airborne radioactivity was released from the stack whenever the reactor was operated. The analysis of gas samples showed that the gaseous activity was almost entirely due to ^{133}Xe and ^{135}Xe, which

Table 1. *Integrated β–γ Exposure received by Personnel involved in Incident*

Person	Function	Total exposure in mR	
		Film badge 19.4.65–14.5.65	Pocket dosimeter 22.4.65–9.5.65
K.T.B.	Reactor operator	30	48
D.F.C.	Reactor engineer	35	75
J.R.C.	Reactor engineer	55	41
D.K.C.	Health physicist	565	603
G.P.D.	Health physicist	385	361
A.D.	Operations manager	293	326
T.E.	Reactor operator	160	91
D.J.F.	Plant engineer	30	48
R.D.G.	Electrician	10	21
N.G.	Chem. operations ass.	30	66
R.H.J.	Reactor operator	17	45
P.J.J.	Plant engineer	160	184
E.L.	Fitter	14	33
J.M.	Reactor operator	80	88
C.M.	Reactor supervisor	150	172
W.M.	Reactor operator	35	46
C.W.P.	Ass. operations manager	30	145
A.S.	Health physicist	80	78
A.M.V.	Reactor operator	10	28
R.V.	Reactor analyst	10	25
J.D.V.	Reactor analyst	200	185
D.J.W.	Health physicist	635	535
B.C.W.	Health physicist	260	231

Table 2. *Airborne Particulate Activity in the Stack at Various Times during and Subsequent to the Incident*

Date	Time	Reactor power	μCi/cc	
			α $\times 10^{10}$	β–γ $\times 10^{10}$
22.4.65	18:00–20:00	6.67 MW	0.8	780
24.4.65	23:01	Off	0.5	1.8
29.4.65	00:20	6.67 MW	1.9	410
29.4.65	22:38	6.67 MW	1.4	16
29.4.65	23:43	6.67 MW	1.4	40
30.4.65	04:30–06:30	6.67 MW	2.0	300
16.2.66	11:41	6.67 MW	1.2	21
23.2.66	10:54	Off	0.7	1.6
25.2.66	11:45	Off	0.2	0.3

Note: All measurements were made after allowing 30 min for decay.

of course passes unimpeded through the filtration banks. ^{88}Rb and ^{138}Cs, with half-lives of 18 and 32 min, were identified in the airborne particulate samples. These are the decay products of the fission product noble gases ^{88}Kr and ^{138}Xe. It is assumed that the decay nuclides rapidly attached themselves to the surfaces of dust particles,[17] which in turn were collected by the filter paper of the various monitors and samplers. The isotopes ^{88}Rb and ^{138}Cs are not listed in the report of Committee 2 of the I.C.R.P.[18] An $(MPC)_a$ value of 1×10^{-6} μCi/cm^3 has been calculated[19] for ^{88}Rb for a 40 hr week, i.e. approximately 2×10^{-7} μCi/cm^3 for a 168-hr week. Table 2 gives airborne particulate activity concentrations obtained from samples taken on GF/A filter paper from the stack, both at the time of the incident and more recently. The highest β-γ value observed was 7.8×10^{-8} μCi/cm^3, well below the $(MPC)_a$ value for the isotopes identified.

It is estimated that, for the period April 21 through May 7, a total of 2.5 Ci of particulate-borne activity (mainly ^{88}Rb and ^{138}Cs) and of the order of 650 Ci of gaseous activity was discharged from the stack. On the basis of relative toxicities, this is equivalent to about 10 Ci of ^{131}I, which is within our accepted monthly release.

VII. DISCHARGE OF ACTIVE EFFLUENT ONTO THE SITE

During water sampling procedures on April 23 the active waste tanks became full due to normal drainage from the building. At this time the effluent treatment plant was incomplete and no other transfer tank was available. Approximately 1000 gallons of water with an activity of 0.14 μCi/ml were pumped out onto the ground resulting in a contaminated area about 60×30 yd which was fenced off. No contamination of any dam, river, or water supply resulted from this, and by May 11 the activity of the soil was normal for alpha activity (50 pCi/g) and only six times background for beta activity.

VIII. ENVIRONMENTAL SURVEY RESULTS

The normal levels of airborne activity around the plant were already well established before the incident.[20] These data enabled the high levels during the incident to be interpreted, and it appeared that the only observable fission product escape was of the noble gases Krypton and Xenon. Gamma surveys over a 500 yd radius on April 22 and over a 5 mile radius on April 29 showed no increase above normal levels.

IX. HEALTH PHYSICS COVERAGE OF OPERATIONS

The Reactor H.P. personnel consisted of two health physicists and three H.P. technicians, two of them untrained at the time of the incident. This was considered sufficient for normal reactor operation for one shift a day, five days a week. Prior to fuel loading operations, the building had been classified into zones on the basis of expected radiation and contamination hazards. Regulations governing entry to and exit from the zones had been issued. A comprehensive pre-start up survey of background radiation, air and surface contamination was conducted. This was repeated at various power levels.

Few of the operations personnel had previously had experience of working in high radiation fields and areas of gross contamination. Previously simple routine jobs now involved considerable risk of spreading contamination, of ingesting or inhaling radioactive material, and of receiving an excessive external radiation dose. All available H.P. personnel on the site were employed in providing 24-hr coverage of the numerous jobs that had to be performed in high radiation and/or contamination areas. This involved the demarcation of such areas by conducting radiation and smear surveys and taking air samples, controlling the access of personnel to the areas, deciding what protective clothing and respiratory equipment should be worn, etc.

The most serious problems that arose were:

(a) A shortage of trained health physics personnel, particularly those with sufficient knowledge and experience to make value judgements; and

(b) communications between operations personnel and health physicists. On several occasions, unnecessary exposure occurred or contamination was spread due to operations being carried out without first contacting health physics.

Table 3. Airborne Particulate Activity Levels under Normal Operating Conditions and at Various Times during Incident
(Readings after 30 min decay, except those followed by asterisk, which were after 5 min decay)

Date	Times	Reactor power MW	Overpool μCi/cc		Control room μCi/cc		Basement μCi/cc		Process wing μCi/cc	
			$\alpha \times 10^{10}$	$\beta\gamma \times 10^{10}$	$\alpha \times 10^{10}$	$\beta\gamma \times 10^{10}$	$\alpha \times 10^{10}$	$\beta\gamma \times 10^{10}$	$\alpha \times 10^{10}$	$\beta\gamma \times 10^{10}$
	Normal	0	0.6 to 2	3 to 8	0.9 to 3	4 to 20	0.8 to 2	4 to 7	0.3 to 2	2 to 8
	Normal	6.7	0.8 to 2	3 to 7	2 to 3	6 to 10	2 to 3	6 to 10	0.7 to 2	3 to 7
22.4	18:00–20:00	6.7	1	40	—	—	2	4	0.6	4
23.4	21:30	5.4 kW	—	700	—	—	—	—	—	—
	22:00	5.4 kW	—	100	—	20	—	—	—	—
24.4	00:21	Off	—	1000*	—	—	—	—	—	—
25.4	01:05	Off	—	200*	—	—	—	—	—	—
	09:00–10:30	Off	—	10*	0.4	20	—	—	—	—
28.4	12:00–15:30	Off	1	4	1	9	—	—	0.6	2
	20:22	6.7	1	300	—	—	—	—	—	—
	23:24	6.7	3	600	—	—	—	—	—	—
29.4	03:00–03:30	6.7	—	—	4	20	5	60	3	10
	15:20–18:00	6.7	—	900	2	10	—	—	—	—
	22:05	6.7	2	100	—	—	—	—	—	—
30.4	04:30–06:30	6.7	4	400	3	20	4	40	3	10
	22:17	6.7	—	200	—	—	—	—	—	—
1.5	02:00–05:00	6.7	6	300	5	20	5	30	4	10
	12:15	6.7	300†	5000†	—	—	—	—	—	—
2.5	01:00–02:30	6.7	5	400	—	—	4	40	3	20
	19:35	6.7	0.7	200	—	—	0.9	10	0.3	20

† Very large sample. After 5 hr decay, readings were 0.8 and 20 for α and β, respectively.

Table 3 gives some typical airborne concentrations of β-γ particulate activity observed during the period under discussion. The high β-γ value observed at 21:30 hr on April 23 occurred while water samples were being drawn from each fuel element in turn in the search for the source of the fission products in the primary cooling system.

Table 4 presents the results obtained from some of the numerous smear samples taken during the incident in the search for abnormal surface contamination. The major cause for concern in the results shown in Tables 3 and 4 was the long-lived alpha values. All smear tests before the incident had yielded zero values for alpha contamination, so the positive results were presumably due to plutonium. The fact that the contamination was transferable indicated the possibility that it could become airborne.

The 40-hr week $(MPC)_a$ for ^{239}Pu is 2×10^{-12} $\mu Ci/cm^3$ = 4.44 d.p.m./m^3 of air. The last value in Table 4, 1.4×10^{-5} $\mu Ci/cm^2$, is equal to 3108 d.p.m./100 cm^2. The dispersion of just 2% of this activity into the air would be sufficient to give an $(MPC)_a$ value for 14m^3 of air. For the above reasons, all areas where transferable surface contamination was found to be present were carefully decontaminated as soon as possible.

Table 4. Some Typical Smear Sample Results obtained during Incident

Date	Location of smear	$\mu Ci/cm^2$ α $\times 10^5$	β $\times 10^4$
27.4	Upper portion of pool gate: West side	—	11.2
	Upper portion of pool gate: North side	6.6	5.6
	Upper portion of pool gate: South (partly washed)	—	6.5
28.4	Entrance to overpool area, west	—	0.03
	Floor in front of elevator entrance, overpool level	—	0.17
	Elevator floor	—	0.03
	Gallery floor, in front of steps	—	0.26
	Beam port floor, in front of steps	0.124	0.51
	Handling tool storage floor	7.72	18.1
29.4	Overpool floor, blue side of change room	—	0.06
	Overpool floor, red side of change room	—	0.38
	Overpool level, north wall above crane	0.001	0.001
	Beam port floor, door out of reactor hall to main entrance	0.007	0.018
	Beam port floor, south of handling tool storage	0.20	2.8
1.5	Overpool floor, east, next to steel stairs	0.082	0.68
	Overpool floor, south-west corner of storage rack	0.245	0.12
	Overpool floor, between storage rack and pool	0.015	0.12
	Overpool floor, between storage rack and pool	1.4	1.10

Note: The maximum values for blue contamination zones are 1×10^{-5} $\mu Ci/cm^2$ = 2220 dis/min/100 cm^2 for alphas and 1×10^{-4} $\mu Ci/cm^2$ = 22200 dis/min/100 cm^2 for betas.

Table 5. *Radiation Levels at Various Points inside the Process Wing*

Date	Time	Reactor MW	Shut down pump pipe	Primary pump pipe	Primary heat exchanger	Primary strainer		Primary demin. filters		Primary degasifier tank	Off-gas line	Pool system filters	
						On tank	On pipe	East	West			Full flow	Demineralizer
			mR/hr	mR/hr	R/hr	mR/hr	mR/hr	R/hr	R/hr	mR/hr	mR/hr	mR/hr	mR/hr
Before incident		6.7	3.2	8.2	4.4×10^{-3}	4.1	—	0.170	0.170	8.0	—	0.8	0.8
22.4	08:00	6.7	2000	2000–3000	5.0	—	—	—	150	—	—	—	—
22.4	20:49	6.5	5500	5000	16.0	—	—	16.0	—	—	—	—	—
23.4	10:15	Off	68	110	4.0	—	—	3.7	—	130	12.5	—	—
24.4	12:15	Off	28	42	2.3	—	—	21	12	35	2.6	—	—
25.4	12:10	Off	17	27	1.4	—	—	17	—	11	1.3	—	—
26.4	19:20	Off	12.5	20	1.6	40	45	15	8.5	8.0	0.9	—	—
28.4	16:15	Off	70	12	1.9	25	47	16	8.0	7.0	1.0	60	200
28.4	16:35	Started	60	10	1.4	20	35	15	6.0	4.3	0.7	56	135
28.4	17:15	0.277	70	36	1.4	60	57	15	6.0	11.0	1.3	85	150
28.4	17:35	2.2	160	230	1.5	350	220	16.5	6.2	60	6.0	110	160
28.4	18:25	4.4	430	750	1.65	1000	620	21	6.6	300	27	175	175
28.4	19:40	6.7	680	1200	2.15	1300	950	26	7.3	410	45	300	180
29.4	18:30	6.48	450	720	2.2	800	550	26	7.0	380	33	900	270
1.5	15:30	6.53	360	500	1.9	600	390	23.5	5.2	250	21	780	195
3.5	20:50	6.48	340	460	2.0	510	375	21.0	6.0	260	21	900	185
5.5	16:29	6.5	255	350	1.6	—	—	18.0	—	200	—	750	160
6.5	19:45	0.020	110	42	1.5	50	68	15.0	4.0	19	1.8	500	100
End of year		6.7	95	200	0.170	—	—	8.0	—	200	—	60	48
Similar reactor			—										
after 6 days at		20	—	400	0.180	—	—	0.5	—	—	—	—	10

Note: The west primary demin. filter was on line at the time of the incident. The east one was placed on line during the day of 22.4.65.

No method for the biological monitoring of ingested or inhaled plutonium was available at this time. A method for analysing the amount of plutonium excreted in the urine was subsequently developed and none has been detected in the urine of operations personnel since tested.

Apart from the known presence of plutonium and fission product contamination in the reactor water systems, a major concern was the high radiation levels in the process wing, particularly on the primary filters. Table 5 gives a selection of radiation readings, during and after the incident. Some comparable data from a similar reactor are also given.

Table 5 shows how dramatically the radiation dose rates rose when the Pu-Be source was ruptured and, also, the effect of subsequent reactor operation on the levels. In most cases the year-end values, while considerably lower than at the height of the incident, were still very significantly higher than those obtained prior to the rupture.

The effect has been to demand much stricter health physics control over maintenance work in the process wing, particularly when such work involved breaking into the primary or pool water systems. It was nevertheless possible to prevent any of the operations personnel from acquiring any radioactive body burden or from receiving greater than the permissible quarterly radiation dose of 3 rem.

X. DISCUSSION AND CONCLUSION

Calculations that were carried out subsequent to the rupture indicate that the cooling for the source, in the core location chosen, was probably inadequate for operation at 6.7 MW.

The incident emphasised the following essential requirements for the construction and operation of a reactor:

(i) checking of design, materials and construction of every part of the reactor system;
(ii) checking of all reactor operations;
(iii) planning for accident conditions;
(iv) provision of adequate H.P. coverage;
(v) provision of sufficient protective clothing;
(vi) provision of adequate waste disposal facilities;
(vii) provision of a radiological training programme for all radiation workers.

Although the resources of the reactor health physics group have been taxed to the limit, a great deal of invaluable experience has been gained in a fairly short period.

XI. ACKNOWLEDGEMENTS

Thanks are due to Mr. D. van As who, with his colleagues, provided the data for sections VII and VIII. The paper is published by permission of the South African Atomic Energy Board.

REFERENCES

1. W. B. Lewis. The accident to the NRX reactor on December 12, 1952. Report DR-32, AECL 232 (1953).
2. D. G. Hurst. The accident to the NRX reactor Part II. Report GPI-14, AECL 233 (1953).
3. M.W. Kellogg Co. radiation incident on March 13, 1957, *Nucleonics* **15,** 42 (1957).
4. Accident at Windscale No. 1 Pile on October 10, 1957, *Nucleonics* **15,** 43 (1957).
5. Oak Ridge Y-12 accidental excursion, June 16, 1958, *Nucleonics* **16,** 138 (1958).
6. D. Callihan and J. T. Thomas. Accidental radiation excursion at the Oak Ridge Y-12 Plant. I. Description and physics of the accident, *Health Physics* **1,** 363 (1959).
7. J. D. McLendon. Accidental radiation excursion at the Oak Ridge Y-12 Plant. II. Health physics aspects of the accident, *Health Physics* **2,** 21 (1959).
8. G. S. Hurst, R. H. Ritchie and L. C. Emerson. Accidental radiation excursion at the Oak Ridge Y-12 Plant. III. Determination of radiation doses, *Health Physics* **2,** 121 (1960).
9. G. A. Andrews, B. W. Sitterson, A. L. Kretchmar and M. Brucer. Accidental radiation excursion at the Oak Ridge Y-12 Plant. IV. Preliminary report on clinical and laboratory effects in the irradiated employees, *Health Physics* **2,** 134 (1960).
10. Yugoslavian criticality accident, October 15, 1958, *Nucleonics* **17,** 106 (1959).
11. H. C. Paxton, R. D. Baker, W. J. Maraman and R. Reider. Los Alamos criticality accident, December 30, 1958, *Nucleonics* **17,** 107 (1959).
12. E. C. Hughes and J. W. Greenwood. Contamination and cleanup of NRU, *Nucleonics* **18,** 76 (1960).
13. J. R. Horan and W. P. Gammill. The health physics aspects of the SL-1 accident, *Health Physics* **9,** 177 (1963).
14. W. L. Marter. Radioiodine release incident at the Savannah River Plant, *Health Physics* **9,** 1105 (1963).

15. A. J. A. Roux. The first reactor installation of the Republic of South Africa, *S. Afr. Mech. Engr.* **12,** 29 (1962).

16. D. F. Carroll, J. R. Colley, C. Möller and P. J. Joubert. Engineering design and safeguards report on the Safari I Research Reactor. Report PEL 75 (Pelindaba, Dec. 1965).

17. D. K. Craig. An investigation of the interactions that occur between I_2 radionuclides and an iron oxide aerosol in the respirable size range, *Health Physics* **12,** 1047 (1966).

18. Report of ICRP Committee II on permissible dose for internal radiation (1959), with Bibliography for Biological, Mathematical and Physical Data, *Health Physics* **3** (June 1960).

19. A. Diaz. Personal communication.

20. D. Van As. Omgewingsradioaktiwiteit te Pelindaba. Halfjaarverslag: Januarie–Junie 1965. Report PEL 105 (Mar. 1966).