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STRESS-ASSISTED, MICROBIAL-INDUCED CORROSION OF STAINLESS STEEL PRIMARY PIPING AND OTHER AGING ISSUES AT THE OMEGA WEST REACTOR

Author(s): **ANTONIO ANDRADE**

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A. Andrade
Los Alamos National Laboratory
Los Alamos, New Mexico, 87545 USA

1. INTRODUCTION

The Omega West Reactor (OWR) was shutdown in December, 1992 as a result of a scram. Shortly after the shutdown, during January 1993, it was discovered that the primary cooling system was having to be refilled with water at the same nominal rate expected during normal operations - about 284 liters per twenty-four (24) hour period. Upon this discovery, an immediate search for the cause of the water loss problem was initiated. Various major components of the reactor primary cooling system were isolated and tested for water loss rates consistent with the refill rate. Three of these major components first had to be drained (because of public concern for leakage of tritiated water into the ground) and then refilled with clean water for leak testing: the reactor tank, the surge tank, and the N-16 delay line. During early February 1993, it was determined that the stainless-steel (304) delay line was losing water at rates comparable to the refill rate and that no other portion of the reactor cooling systems showed signs of water loss.

Measurements of the rate of change of the leak rate in the 76.2-cm diameter, 33.5-m long delay line, from the time the line was full to the time that the rate approached zero, provided information regarding the probable location of the of the problem. Once this location was determined, an excavation effort was started to unearth the pipe. The pipe was buried at a depth of approximately 2.5 m under the reactor building and extended horizontally under the reactor room approximately 8.0 m. The remainder of the pipe inclined upwards and away from the reactor room at an angle of about 6 degrees until it connected with the surge tank stand pipe as partially depicted in Figure 1.

Excavation to uncover the delay line between the reactor room and the surge tank foundation was completed during February, 1994. When the line was uncovered, a cursory examination of the pipe revealed that a circumferential crack extending around the bottom half of the delay line pipe had developed at the previously-estimated location (at approximately 5.0 m from the surge tank end). This crack was approximately 0.0025 cm in width. The area comprised by this width and half the circumference of the pipe, along with the ambient static water pressure at this location, accounted for the water loss rate. In addition, other evidence of what appeared to be microcracking and pitting that originated at random nucleated sites around the pipe were also found. In all cases, it appeared that the cracking and pitting had developed from the outside in.

In this paper, the direct cause for the main crack and the other pitting, which was determined to be microbial-induced [1], is examined. The results of both destructive sample analysis and non-destructive testing methods are presented. These results indicate that microbial action from bacteria that are normally present in earth can be extremely harmful to stainless-steel piping under certain conditions. Because of the extent of known damage to the primary system piping by these bacteria, the OWR was permanently shut down during April, 1994.

Additionally, other potential problems that could have also eventually led to a permanent shutdown of the OWR are discussed. These problems, although never encountered nor associated with the current shutdown, were identified in aging studies [2,3] are associated with: (1) the water-cooled, bismuth gamma-ray shield and, (2) the aluminum TC head seal that prevents reactor vessel water from entering into the graphite-filled TC as shown in Fig. 2. However, before proceeding further with these topics, it is probably useful to provide the reader with a brief description of the OWR.

2. DESCRIPTION OF THE OMEGA WEST REACTOR

The Omega West Reactor is a thermal, heterogeneous, closed tank-type test and research reactor that is light-water moderated and cooled (Fig. 3). The core comprises a rectangular array of four rows (numbered 2-5) by nine columns (designated A-I) of fuel elements or in-core sample positions (Row 1 is a lead gamma-ray shield and Row 6 is a beryllium reflector). Normal operations are at a steady-state power of 8 MW utilizing either 31 or 33 fuel elements - allowing for up to five in-core sample positions. The reflector is made up of 21 beryllium blocks. In addition, two gamma ray shields, a 5.7-cm thick lead plate and a 12.7-cm thick bismuth shield (Fig. 2), are located on the opposite side of the core and allow for experiments with a minimum of gamma-ray or fast-neutron interference to be conducted in the thermal column.

The OWR has been operated by the Los Alamos National Laboratory without accident or major operational incident since August, 1956 and is, perhaps, one of the few remaining US reactors that was not built to a set of standards but was, instead, designed to the experience base of several reactors that had been operated during the late 1940's and early 1950's.

Materials Testing Reactor (MTR)-type fuel elements are utilized in the OWR core with each element being made up of 18 or 19 aluminum-clad plates that contain highly-enriched U_3O_8 in an aluminum matrix within a layer of cladding on each side. The active portion of each element is about 0.625 m in length. However, the overall length of each element, including the aluminum end caps is 1.1 m. The core is supported by an aluminum grid structure that is located inside a 7.3 m-high, 2.4-m diameter, stainless steel reactor tank vessel. A biological shield of high-density concrete in an irregular octagonal shape surrounds the tank and thermal column. This shape was chosen to maximize the number of experimental beam ports available for research.

Control is provided by eight blade-type poison rods. The rods are 3 meters in length and are made up of three sections: two aluminum end sections and a central 0.6-m long borated stainless steel section (1.2 wt% B_{nat}).

Cooling for the normal operation is provided by light water that is circulated downward through and around the core at a rate of 13,250 liters/min. More than half of this flow traverses directly through the core fuel elements while the remainder flows around the core. There is also a provision for operating the OWR, up to a power of 0.5 MW, in a natural convection mode. In this mode, the cooling water that is heated by the core, is forced upward by natural convection, and travels through a "flapper" valve that opens under its own weight whenever the normal coolant pump is secured (Fig. 1).

3. DELAY LINE TEST RESULTS

Nearly the entire length of the 304 stainless-steel delay line between the reactor room and the surge tank (approximately 20 m) was removed during the excavation mentioned above. As is well known, 304 stainless steel is made up of mostly iron with the following additional component elements in slightly-varying, actual chemical compositions:

C	0.08; (%)	Cr	18-20;
Ni	8-12;	Si	1.0;
Mn	2.0;	P	0.045.
S	0.03;		

Destructive samples of various sizes were cut away from the region near the pipe break and analyzed with a variety of techniques. After these tests were completed, an effort was mounted to non-destructively inspect the remaining sections of pipe. This latter testing required that a manned entry be made into the 76.2-cm diameter pipe sections that were left both under the reactor and in the surge tank. The results of these tests follow.

3.1 Destructive testing results

The outside of the uncleaned sample pipe was typically covered with rust-colored, nodular deposits (Fig. 4). Because this deposit had the appearance of a conglomerate of tubercles - the skeletal environment or by-product produced by certain microbes - this provided the first hint that a biological mechanism could be responsible for the corrosion. Samples cut from near the pipe break showing signs of pitting and cracking were cleaned, sectioned, and polished. These were then inspected to observe cracking patterns.

A typical cleaned pipe surface sample (no corrosion products left on the surface) is shown in Fig. 5. As can be seen, the cracking runs in many directions. Indeed, when the samples were sectioned and polished, micrographs showed the cracking to be both intergranular and transgranular and, also, running both perpendicular to and in-plane with the rolling direction. Note that energy dispersive X-ray spectroscopy (EDS) was utilized to confirm the elements ratio to positively identify the stainless steel as being type 304.

Further analysis (X-ray diffraction) of the deposit revealed it to be comprised of calcium sulfate hydrate (gypsum, $CaSO_4 \cdot 2H_2O$) and, to a lesser extent, calcium carbonate silicate hydrate (scawtite, $Ca_7(Si_6O_{18})(CO_3) \cdot (2H_2O)$) which are mineral forms that can also be produced by microbial processes [Ref. 1]. It is interesting to note that, historically, weak solutions of sulfuric acid may have been released at or near the site of the pipe break because this area was used to support resin bed regeneration processes. Although this practice was abandoned decades ago, some of the sulfuric acid could have been reduced by anaerobic bacteria that are typically found in soils such as desulfotomaculum, desulfomonas, and desulfovibrio. These bacteria will reduce the SO_4^{2-} in sulfuric acid to the more reactive forms S^{2-} and/or H_2S. These bacteria also live symbiotically with sulfur oxidizing bacteria. Therefore, one would expect to find sulfur present in multiple oxidation states in the deposits, possibly inside the cracks, and possibly in the soil just next to the pipe in this scenario.

Analysis using X-ray photoelectron spectroscopy (XPS) to scan the deposits, resulted in indications that sulfur was present in at least two oxidation states - SO_4^{2-} and S^{2-}. X-ray fluorescence was used to analyze samples of: soil from just under the pipe; deposits scraped from the pipe; and, both clean and uncleaned metal from the pipe - all of which were found to contain significantly elevated levels of sulfur. Electron microprobe analysis revealed that in polished cross-sections of the metal, the various corrosion cracks tended to originate and terminate from "inclusions" whose cores were made up of mostly oxygen and sulfur, among other elements. Finally, elemental maps of a small cross-section of the pipe at the location of the main crack were obtained using X-ray fluorescence. It was interesting to note that sulfur was heavily concentrated near the exterior of the pipe and that it became normally distributed as the mapping proceeded inward.

As these analyses were taking place, reactor personnel were also gathering data regarding the original construction of the primary system. We learned that the 0.635-cm thick, 76.2-cm diameter SS pipe had been cold rolled, on site, as construction had taken place. In addition, because 304 SS is difficult to heat treat, it was not treated in any form after the rolling process. Hence, it was placed in the ground and welded together in a pre-stressed condition that would make it susceptible to various forms of stress-corrosion cracking. In addition, because the bulk temperature of the primary water that flowed through it was normally about 120° F, the tensile stress and the temperature of the pipe would, together, make conditions ideal for stress corrosion cracking and the incubation of microbes.

Thus, these conditions, along with the results of the various analyses mentioned above, lead to the conclusion that the cracking and pitting of the delay line pipe had developed from the outside in and that the physical defects were the result of stress-assisted, microbial-induced corrosion of stainless steel.

3.2 Non-destructive testing results

As the destructive testing analyses described above was being completed, plans were being made to inspect the remaining portions of the delay line that had been left in place. These inspections were being considered because, given the indications of microbial-induced corrosion in the piping that had been exposed to the earth, the question arose regarding whether the remaining piping had been protected by the concrete foundations around it.

The sections of pipe that were to be inspected were the 76.2-cm diameter pipe stubs that existed at both the surge tank concrete foundation end and the foundation under the reactor (see Fig. 1). In addition, the 30.48-cm diameter pipes that attached to the delay line at both of these points were to also be inspected. It was decided that direct ultrasonic and visual inspections would be sufficient to determine the integrity of the piping. However, manned entries into the delay line pipe stubs would be necessary to obtain the most reliable inspection data.

The approximately 2.13-m long stub in the surge tank foundation was inspected first because of ease of access. The ultrasonic testing (UT) instrumentation used for these inspections was sensitive to changes in thickness on the order of 0.0025 cm. After calibrating the UT instrumentation to a known quality piece of SS tubing of the same nominal wall thickness (0.635 cm), the surge tank stub wall thicknesses were measured at approximately 100 locations. Both visual and UT inspection results indicated that the material in both the stub and the connecting piece of 30.48-cm diameter piping were in sound condition.

The delay line left underneath the reactor room and the reactor is about 8 m in length. Because of this, a specially designed cart was used to allow a manned entry into this pipe. The cart had a number of safety and convenience features such as lighting and two-way communications built onto it to make the inspection task as simple as practicable. The inspections were to proceed in the same fashion as with the other stub except that the visual data would be recorded on video. The inspection of the 30.48-cm diameter connecting pipe that went up and into the reactor was especially important because any signs of corrosion in this piping would have meant that the reactor was most probably irreparable.

Entry was made into this section of pipe on March 18, 1994 by non-destructive testing specialists. Their approach was to start at the furthermost endcap of the 76.2-cm diameter pipe and work back toward the stub entrance. The inspections of the smaller diameter pipe (which connects near to the end of the stub) included both visual assessment and UT testing extending up to approximately 2.1 m into the vertical pipe. The results indicated that this piping was intact and that there were no signs of corrosion.

The inspections of the larger diameter pipe also yielded no signs of corrosion up to a point at approximately 2 m from the endcap. At this point, pitting and small amounts of corrosion deposits were encountered. Upon review of construction drawings for the OWR, it was noted that the same concrete foundations that had been utilized for the Clementine fast reactor had also been used as part of the foundation structure for OWR. This condition resulted in the fact that the first two meters of delay line piping had been encased in concrete during construction. Hence, this concrete had apparently protected this last section of delay line piping from exposure to the earth. The remaining piping was not protected as such and was evidently subjected to the same microbial activity described above.

In summary, the results of the non-destructive testing support those derived from the analytical work mentioned above in that the corrosion is most likely microbial-induced. In addition, it is interesting to note that the opinions of both the analytical scientists and the non-destructive testing engineers is that the pipe can be easily fixed via sleeving and that the reactor, despite its age of 39 years, is still a viable machine.

4. OTHER AGING ISSUES AT OWR

In comprehensive studies of potential problems that could lead to extended shutdowns, a number of analytical and physical inspections of OWR components were completed. These components included: the control blades, the beryllium reflector blocks, the lead and bismuth gamma shields, the core support structure, the beam ports, the reactor vessel, the thermal column head, and other external primary system components (Refs. 2, 3). The analytical studies were for the purpose of estimating what type neutron and gamma irradiation damage could have occurred over time to some components. At the time of the compilation of the last aging study, the reactor had been operated for 27,300 MW-days over a period of 34 years.

The physical inspections that were performed included detailed visual inspections of the reflector (using a mirrored periscope) and other core components and dye-penetrant testing of a spare lead gamma shield. Two problems were identified in the course of these studies as so difficult to repair should they ever occur that permanent shutdown would probably result. These two failures, as described below, although repairable in principle, would involve unstacking the OWR thermal column which would be difficult, time consuming, and involve high radiation exposures. However, the same studies also conclude that, should no problems of the type described arise, there was no reason why the OWR should not continue to operate safely for at least another 10 years. Descriptions of the two major problems follow.

4.1 Leakage past the thermal column head

The end of the thermal column adjacent to the core is closed by a ribbed aluminum head that is 1.83 m in diameter and 15.24-cm thick (Fig. 2 & Fig. 6). The aluminum head is bolted to a stainless steel flange, and the seal is formed by a hollow stainless steel O-ring. The aluminum used for the head (Al-6061) has survived fluences up to 20 times the OWR fluence to date and, hence, there appears to be no likelihood of radiation failure under any conceivable future operations scenario.

When the OWR was first operated, intermittent water leakage past the O-ring seal was observed, but none has been observed since 1957 when the head bolts were tightened. However, because of it is possible that the original leak was caused by scrubbing of the O-ring resulting from differential expansion between the aluminum head and the stainless steel flange, it is possible that the leak could recur. Replacement of the O-ring would be a major undertaking. To gain access to the head bolts, it would be necessary to partially unstack the thermal column, which is accessible via a large shield door at its other end. In this operation, gamma-ray levels of a few hundred R/h would be encountered. Because most of the gammas are from Co-60 induced in stainless steel, the dose rate would decrease very slowly. Hence, there appears to be no way to perform the repair without significant exposure to personnel.

4.2 Failure of cooling for the bismuth gamma shield

The most serious problem identified during the course of the aging studies was a failure of the cooling for the bismuth gamma shield (Figs. 2 & 6). The 1.53-m diameter, 12.7-cm thick bismuth shield is cast in a stainless steel rim. It is located between the inner end of the thermal column and the thermal column head. There have been no problems associated with the shield to date. However, failure of the bismuth shield cooling system could lead to overheating and possible melting. Note that the bismuth cooling temperature and flow are monitored during normal operation.

At normal 8-MW operation, approximately 12 kW of gamma heating is generated in the shield and removed by means of cooling water that is circulated through embedded stainless steel tubes.

Failure could result from blockage of the cooling tubes or from degradation of the bismuth sufficient to raise the temperature differential required for heat transfer to the cooling tubes by an unacceptable amount. Replacement of the shield would entail removal of the aluminum thermal column head, thereby presenting the same difficulties noted with the leakage problem above.

5. CONCLUSIONS

In this paper, it has been shown that after the discovery of cooling system leak of about 284 liters per twenty-four (24) hour period, an investigation determined that the 76.2-cm diameter, 33.5-m long stainless-steel (304) OWR delay line was losing water at the same nominal rate. An excavation effort revealed that a circumferential crack, approximately 0.0025 cm in width, extended around the bottom half of the delay line. In addition, other evidence of what appeared to be microcracking and pitting that originated at random nucleated sites around the pipe were also found.

The results of both destructive sample analysis and non-destructive testing methods allowed Los Alamos staff to conclude that the direct cause for the main crack and the other pitting resulted from stress-assisted, microbial-induced corrosion of the stainless steel primary piping. The results also indicated that microbial action from bacteria that are normally present in earth can be extremely harmful to stainless- steel piping under certain conditions.

Additionally, other potential problems that could have also eventually led to a permanent shutdown of the OWR were discussed. These problems, although never encountered nor associated with the current shutdown, were identified in aging studies and are associated with: (1) the water-cooled, bismuth gamma-ray shield and, (2) the aluminum thermal column head seal that prevents reactor vessel water from entering into the graphite-filled thermal column.

6. REFERENCES

1. BUTT, D. P., "Summary of Failure Analysis and Inspections of the Omega West Delay Line," Los Alamos Internal Memorandum MST-6, May 24, 1994.
2. YARNELL, J. L., "Assessment of the Probable Lifetime of the Omega West Reactor," Los Alamos Report LA-UR-87-682, 1987.
3. YARNELL, J. L., WILLIAMS, H. T., "Reassessment of the Probable Lifetime of the Omega West Reactor," Los Alamos Report LA-UR-90-3287, September, 1990.

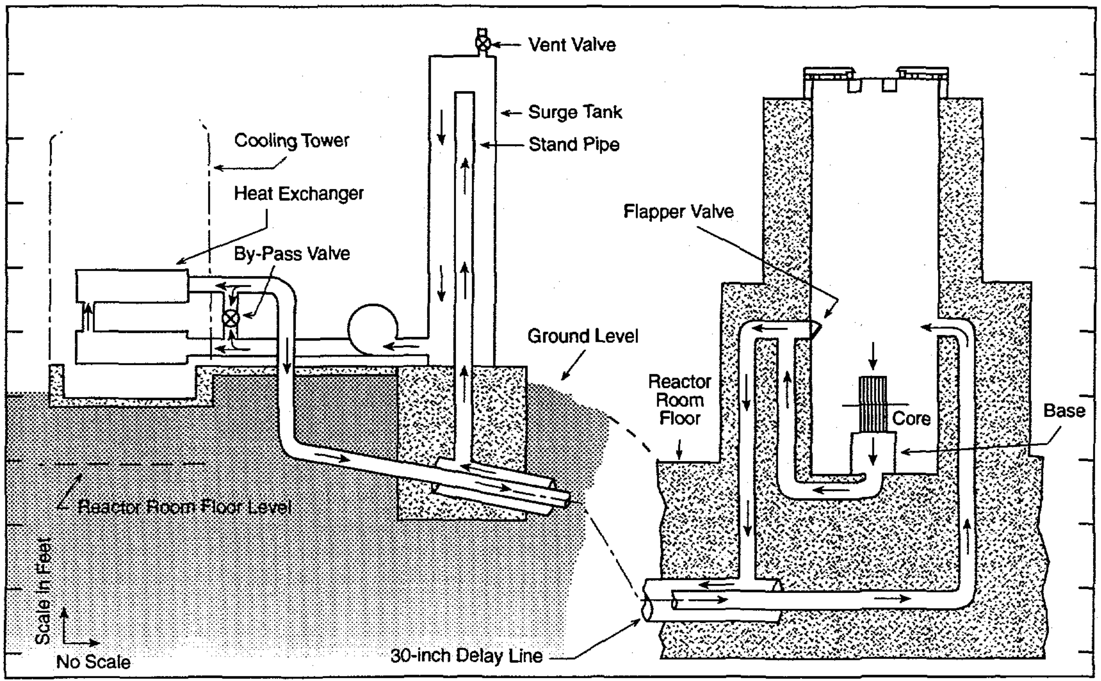

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Fig. 1. The OWR vessel and external cooling system elevations showing the ends of the N-16 delay line on both the surge tank and reactor ends.

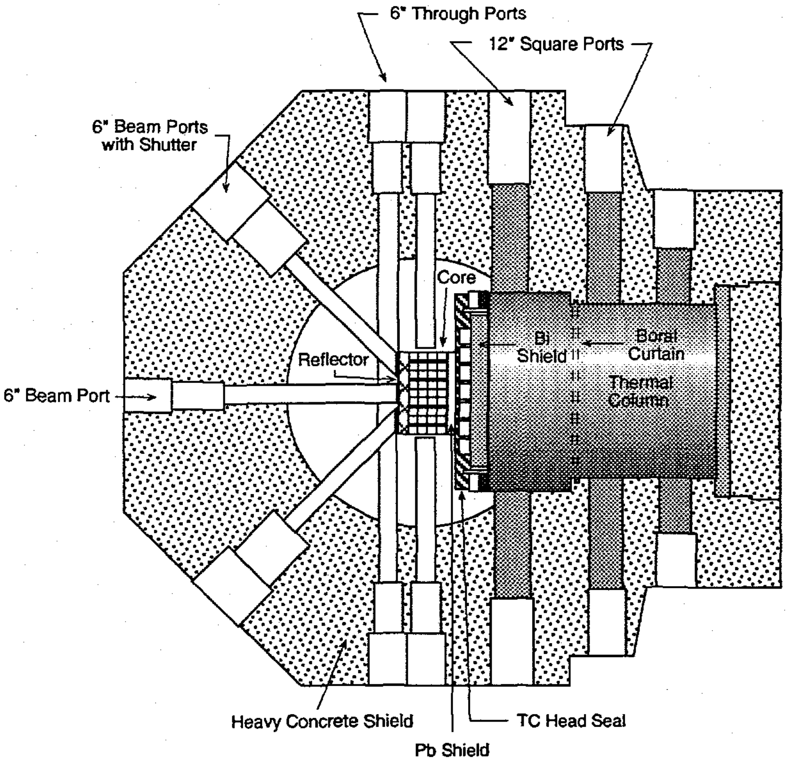

Fig. 2. A vertical cutaway drawing showing the OWR thermal column components and ports.

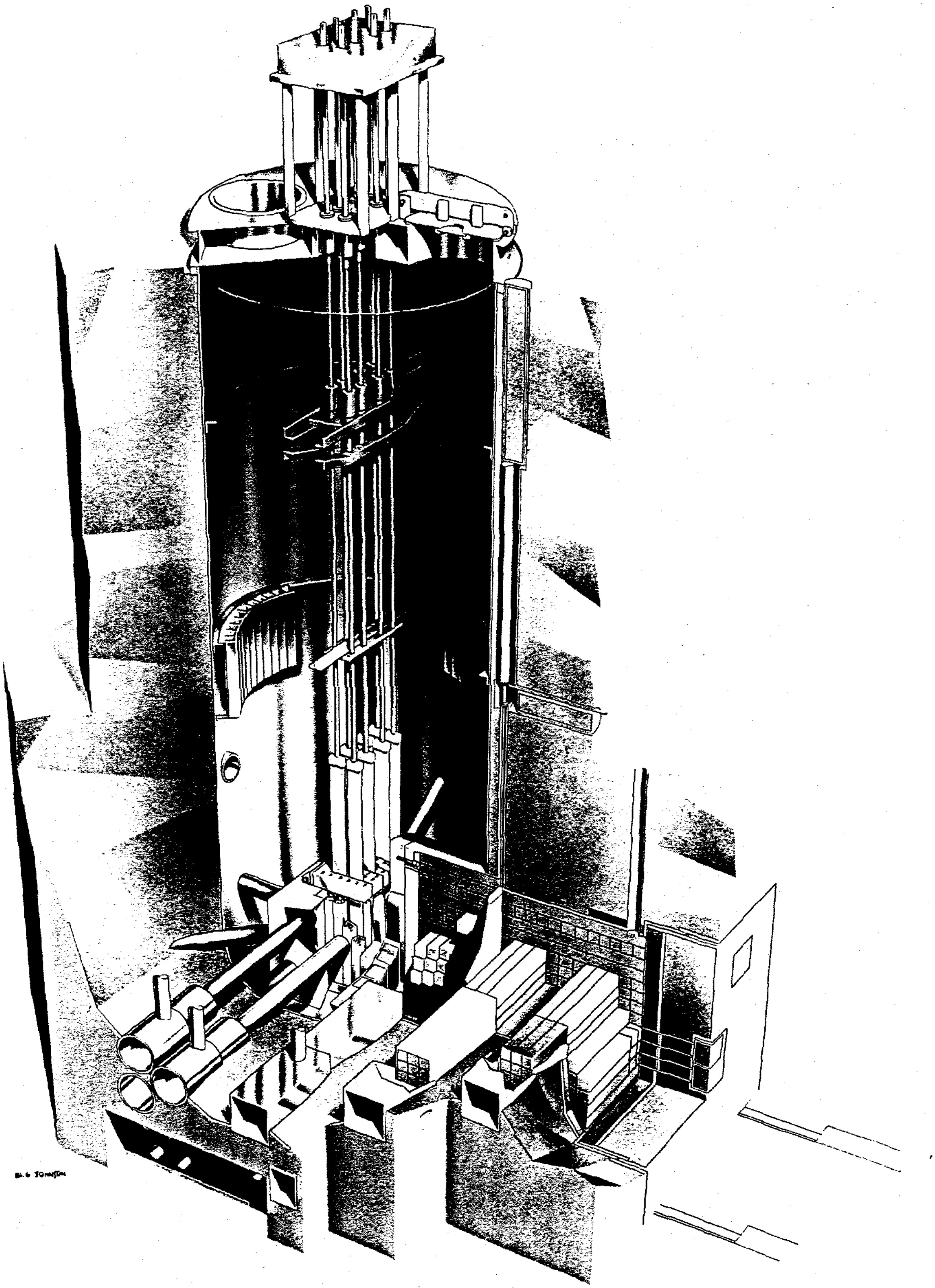

Fig. 3. A cutaway view of the Omega West Reactor.

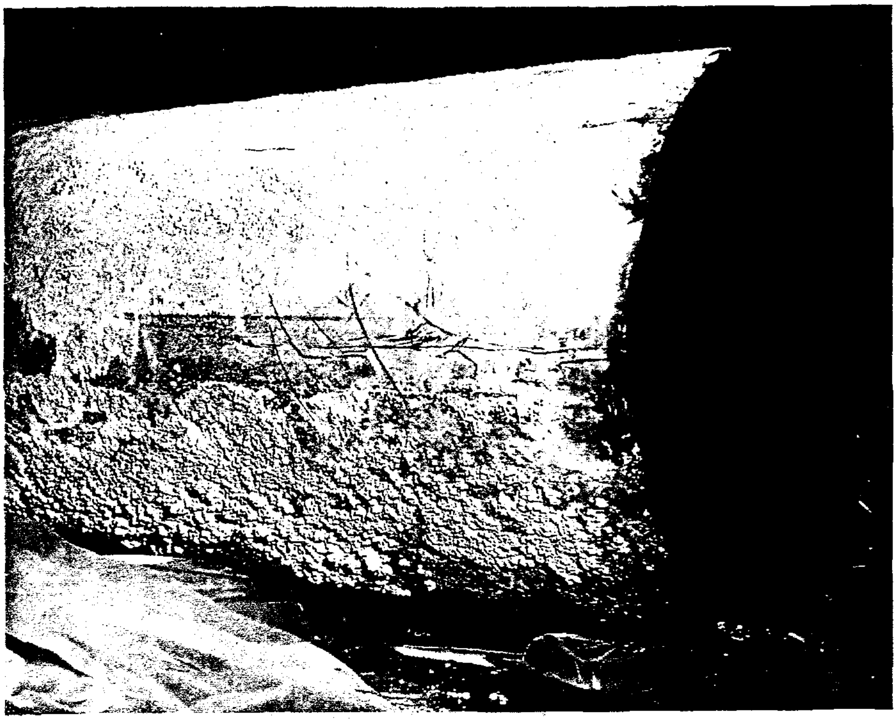

Fig. 4. The outside of the delay line pipe, cut near the surge tank, as found after excavation with the typical covering of rust-colored, nodular deposits.

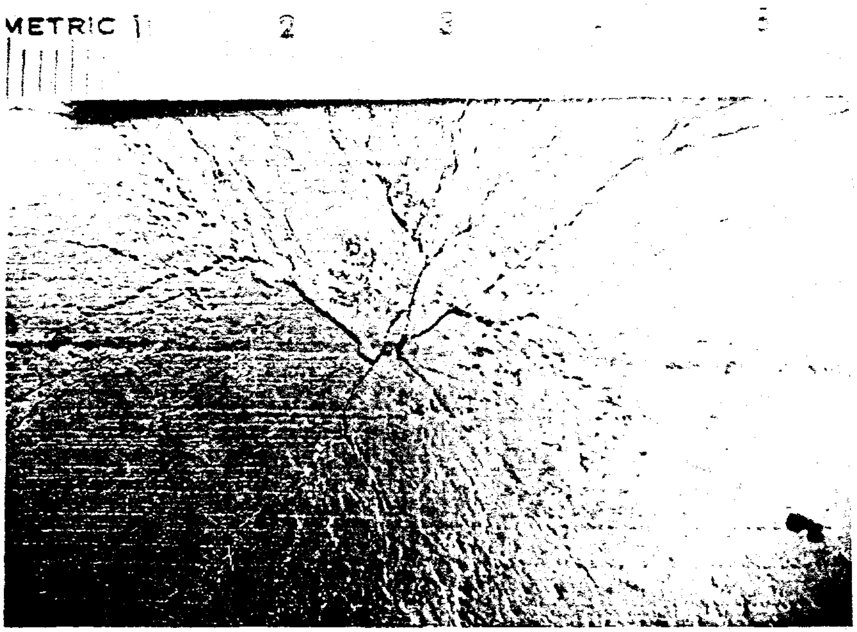

Fig. 5. A micrograph of a clean pipe surface sample (no corrosion products left).

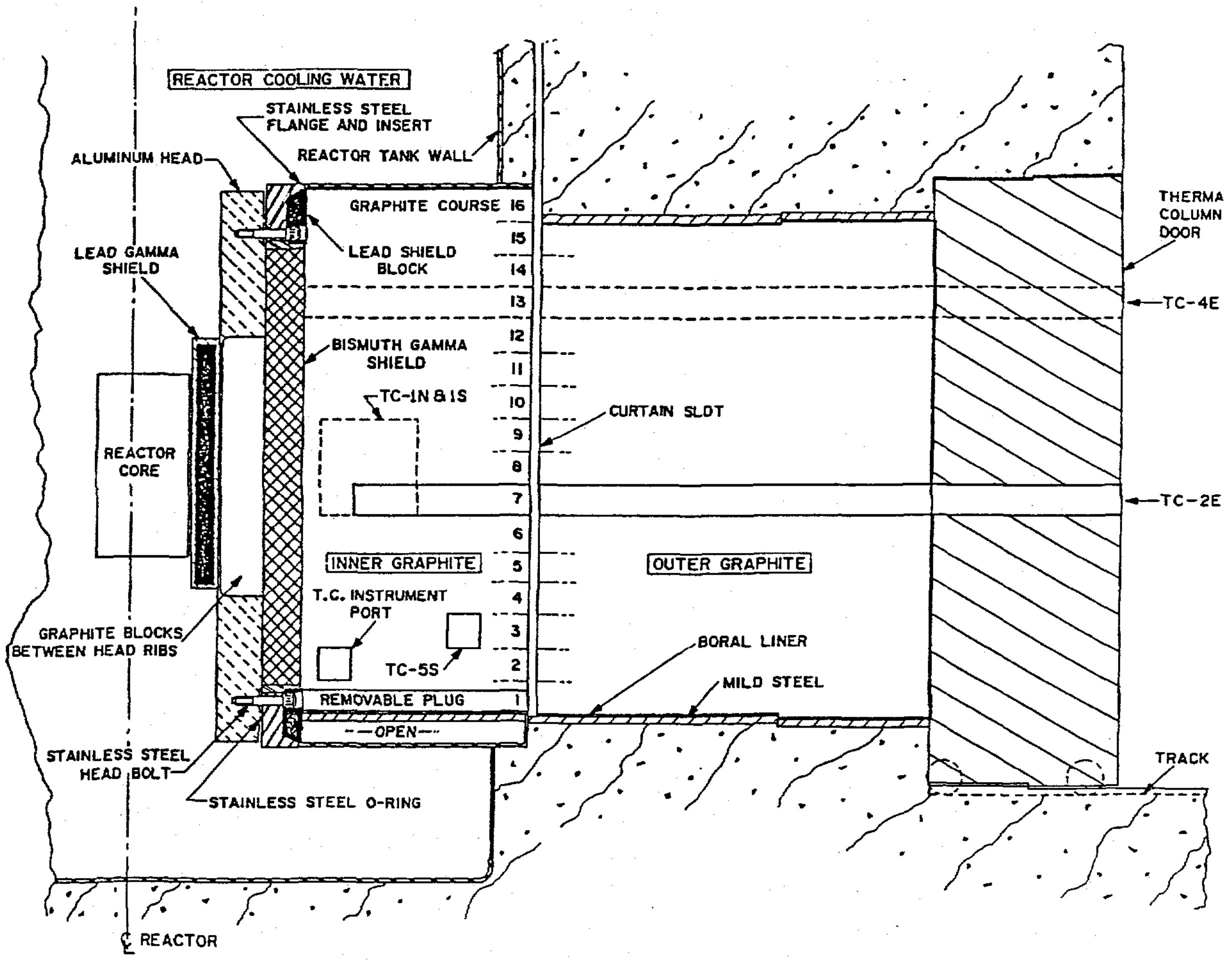

Fig. 6. OWR thermal column.