8205170397 XA

CONTENTS

FOREWORD

This Technical Evaluation Report was prepared by Franklin Research Center under a contract with the U.S. Nuclear Regulatory Commission (Office of Nuclear Reactor Regulation, Division of Operating Reactors) for technical assistance in support of NRC operating reactor licensing actions. The technical evaluation was conducted in accordance with criteria established by the NRC.

1. INTRODUCTION

1.1 PURPOSE OF REVIEW

This Technical Evaluation Report (TER) documents the Franklin Research Center's (FRC) evaluation of work performed to determine the cause of a tube rupture in the Rochester Gas and Electric (RG&E) Corporation's Ginna B steam generator on January 25, 1982. An independent assessment was conducted of (1) the data generated for RG&E by Westinghouse Research and Development Center and by Battelle Columbus Laboratories and (2) the analysis carried out for the U.S. Nuclear Regulatory Commission (NRC) by Brookhaven National Laboratory.

In determining the actual cause of the tube failure, the primary concern was to ascertain whether other tubes in the generator were subject to similar failure on restarting the generator or whether the failure was due to circumstances specific to this particular tube in this particular generator.

2. TECHNICAL EVALUATION

The scope of the work included the following:

1. Attend meetings concerning the cause of the tube rupture.
2. Review documentation relevant to the tube rupture.
3. Visit Brookhaven National Laboratory to discuss work in progress and to view samples.
4. Prepare a technical evaluation report (TER) based on Tasks 1 through 3 above.

2.1 MEETINGS AND SITE VISITS

The following meetings were attended:

1. Rochester Gas and Electric Corporation, April 6, 1982
2. Brookhaven National Laboratory, April 14, 1982
3. Westinghouse Research and Development Center, April 27, 1982
4. Nuclear Regulatory Commission, Bethesda, MD, April 30, 1982

2.2 DOCUMENTS

The following documents were reviewed:

1. Examinations Performed on Tube R45C52 from the B Nuclear Steam Generator of the Rochester Gas and Electric Ginna Plant, August 10, 1978
2. Notes: RG&E/NRC Meeting, February 10, 1982
3. Steam Generator Tube Experience, NUREG-0886, February 1982
4. Summary and Notes on March 1, 1982 Meeting, RG&E/NRC, March 3, 1982
5. NRC Report on the January 25, 1982 Steam Generator Tube Rupture and R. E. Ginna Nuclear Power Plant, NUREG-0909, April 1982
6. Metallurgical Examination of Ginna Steam Generator Tubes, April 23, 1982 (also included in 8)

7. Documentation, Diagrams, Photographs, and Micrographs from Battelle Columbus Laboratories, Presented at a Meeting at Westinghouse R&D Center, April 27, 1982

8. Steam Generator Evaluation, Ginna Steam Generator Tube Failure Incident, April 26, 1982

9. Ginna Station Steam Generator Evaluation, NRC Meeting, April 30, 1982

2.3 TECHNICAL EFFORTS

2.3.1 Metallurgical

The documentation prepared by Westinghouse for RG&E, in particular Document 6, was definitive in representing the damage which had been incurred by the burst tube (R42C55) and by other tubes adjacent to it in Wedge Area 4. Tube rubbing and foreign object damage were clearly evident, and it is now certain that tube [illegible]C55 had burst as a result of severe wall thinning along an approximately 4-inch length. This thinning could only have occurred as a result of rubbing against an adjacent tube; in turn, rubbing along such a long length would only have occurred if the adjacent tube had been severed at the tube sheet.

A sequence of tube rubbing and severing had initiated at the peripheral tubes. Based on all the evidence, including early documentation, it is most probable that the initial damage which led to plugging of the peripheral tubes had been foreign-object-induced. This damage consisted of nicks and/or wear. Once plugged, a tube would not be subject to further deterioration unless a foreign object were striking or rubbing it. As demonstrated by Westinghouse tests, repeated impacts can lead to the collapse of a plugged, non-leaking tube. A collapsed tube is then susceptible to fatigue failure (severing) owing to both vibration and further interaction with the foreign object. A severed tube would then rub against adjacent tubes until leaking or eddy current indications called for plugging or until a burst occurred.

There was no evidence that the chemical environment or metallurgical deficiencies in the Inconel 600 tubing played any role in the bursting of the tube. Furthermore, there was no indication of chemical attack on any of the mechanically deteriorated tubes. In fact, fresh fracture details were evident on tubes that clearly had failed early in the sequence of events leading to the tube rupture.

It is important to note that (1) a critical event in the sequence of events leading to the tube failure was the continuing degradation and ultimate severing of plugged tubes and (2) a plugged tube was no longer subject to inspection in the routine maintenance program. Accordingly, there was no way of anticipating either the type of failure that occurred or the degree of plugged tube degradation in Wedge Area 4.

The failure analysis performed at Battelle and Brookhaven corroborated the Westinghouse results. None of the examined tubes exhibited deterioration due to any mechanism other than wear and fatigue in conjunction with foreign object damage.

The flow model and simulated wear tests conducted by Westinghouse (Document 9) indicate that nothing in the postulated sequence of events leading to the failure is inconsistent with experimental data.

Television viewing of in-place peripheral tubes revealed some tubes with minor dings or nicks on the outer diameter (OD). On samples removed from the steam generator, it was evident that such damage was minimal and should not detract from the tube's service capability. Accordingly, as long as excessive eddy current indications are not noted, it does not appear necessary to remove or plug other tubes with similar indications.

2.3.2 Foreign Objects

The foreign objects recovered from the generator are tabulated on pages 3.5-1 and 3.5-2 of Document 8. The largest items were three pieces of 0.5-in thick carbon steel plate, one about 4 x 6.3 in, one 1.5 x 3.5 in, and one eliptical with axes 2 and 2.4 in. The Westinghouse calculations and tests demonstrated that the largest object would readily induce the type and extent of damage noted on the peripheral tubes.

Since the presence of such foreign objects had never been suspected, no inspections had been carried out to assure that this type of debris was not present. If a video inspection system or an acoustic monitoring system had been in place, it now appears certain that not only would the foreign object have been found, but the severe deterioration of the peripheral tubes would also have been detected.

2.3.3 Impact Model

2.3.3.1 Theory

In the theory given in Document 8, an impacting mass (foreign object) is accelerated by cross flow in the space between the wrapper and the outermost (peripheral) tubes in a wedge area. Upon impact with a tube, the impacting mass moves together with the tube. The tube moves in its lowest resonant mode. The tube is regarded as "fixed-fixed" at the tube sheet and the first support plate. The maximum force between the impacting mass and the tube must be sufficient to cause local plastic deformation in order to contribute to the eventual collapse of the tube. Collapse of a plugged tube will occur as a result of a sufficient number of impacts, especially if there is excess pressure outside the tube. This excess pressure, about 1,000 psi, will occur if the plugged tube has no leak.

This model of the interaction between impacting object and tube is open to question. There is a local deformation near the location of the impact. This local deformation is entirely elastic unless the peak stress exceeds the elastic limit, whereupon some plastic deformation will occur. We now assume that the impact is borderline, that is, not quite strong enough to cause plastic deformation. The elastic deformation may be modeled as a spring with a large spring constant, k. The impacting mass, m_i, strikes this spring, which is mounted on the effective mass, m_t, of the tube. m_t is, in turn, attached to ground via another spring, with spring constant k_1.

The resonant frequency of m_i joined to m_t by k is very high compared to the resonant frequency of m_t joined to ground by k_1. Consequently, the duration of contact between the impacting mass and the tube is short compared to the period of the tube oscillation. Spring k_1 is negligibly deflected during the impact. The theoretical calculation of the peak force should not be based on the model used in Document 8.

2.3.3.2 Consequences of Alternative Model

If m_i impacts with velocity v_i, its momentum and kinetic energy are, respectively, $m_i v_i$ and $m_i v_i^2/2$. The peak force occurs when the distance between the ends of the spring reaches its minimum. This occurs when m_i and m_t have the same velocity. Conservation of momentum requires that this volocity be $m_i v_i/(m_i + m_t)$. The combined kinetic energy is $(m_i + m_t)\ (m_i v_i/(m_i + m_t))^2/2$. Subtracting this from $m_i v_i^2/2$ we obtain the energy (elastic plus plastic, if any) stored in the spring. From this, we find the fraction of the initial kinetic energy that is delivered to the spring. This fraction is $m_t/(m_i + m_t)$. If m_i is small compared to m_t, almost all the incoming kinetic energy is delivered to the spring.

2.3.3.3 Effect of Particle Size

We consider a reference impacting particle of mass m_o and cross section area (perpendicular to the flow) A_o. We also consider a geometrically similar particle with linear dimension s times that of the reference particle. The mass of the particle is $m_o s^3$ and its cross section area is $A_o s^2$. The acceleration produced by the drag force is $-du/dt$, given by

$$m_o s^3\ du/dt = cA_o s^2 \rho_w u^2/2$$

where:

$u = v_w - v$

v_w = velocity of water = constant

v = velocity of particle

ρ_w = density of water

c = drag coefficient = 1

$B = c\rho_w A_o/2m_o$

This equation may be integrated, leading to

$$v = v_w - \frac{1}{\frac{B}{s}t + \frac{1}{v_w}}$$

where v is assumed to be = 0 for t = 0. The distance traveled in time t is found by another integration to be

$$x = v_w t - \frac{s}{B} \ln\left(\frac{B}{s} v_w t + 1\right)$$

Eliminating t between these two equations,

$$\frac{Bx}{s} = y - \ln(y+1)$$

where

$$y = \frac{v}{v_w - v}$$

A plot of Bx/s versus v/v_w is shown in Figure 2-1. For v small compared to v_w, y is small and Bx/s is approximately $y^2/2$, so that, for large s compared to Bx,

$$\frac{v}{v_w} = \frac{1}{1 + \frac{1}{y}}$$

$$= \frac{1}{1+\sqrt{\frac{s}{2Bx}}} \quad (v << v_w)$$

If s is small compared to Bx, y is large and v is nearly equal to v_w.

For large s, v is roughly proportional to $1/\sqrt{s}$. The kinetic energy of the impacting particle (assuming that the travel distance, x, before impact is the same for all particles) is proportional to $m_o s^3 \, (1/\sqrt{s})^2$. That is, the kinetic energy is proportional to s^2.

For small s, the kinetic energy is proportional to s^3. Applying the fraction $m_t/(m_i + m_t)$ found in Section 2.3.3.2, the energy delivered to the spring is proportional to

$$\frac{s^n}{1 + \frac{m_o}{m_t} s^3}$$

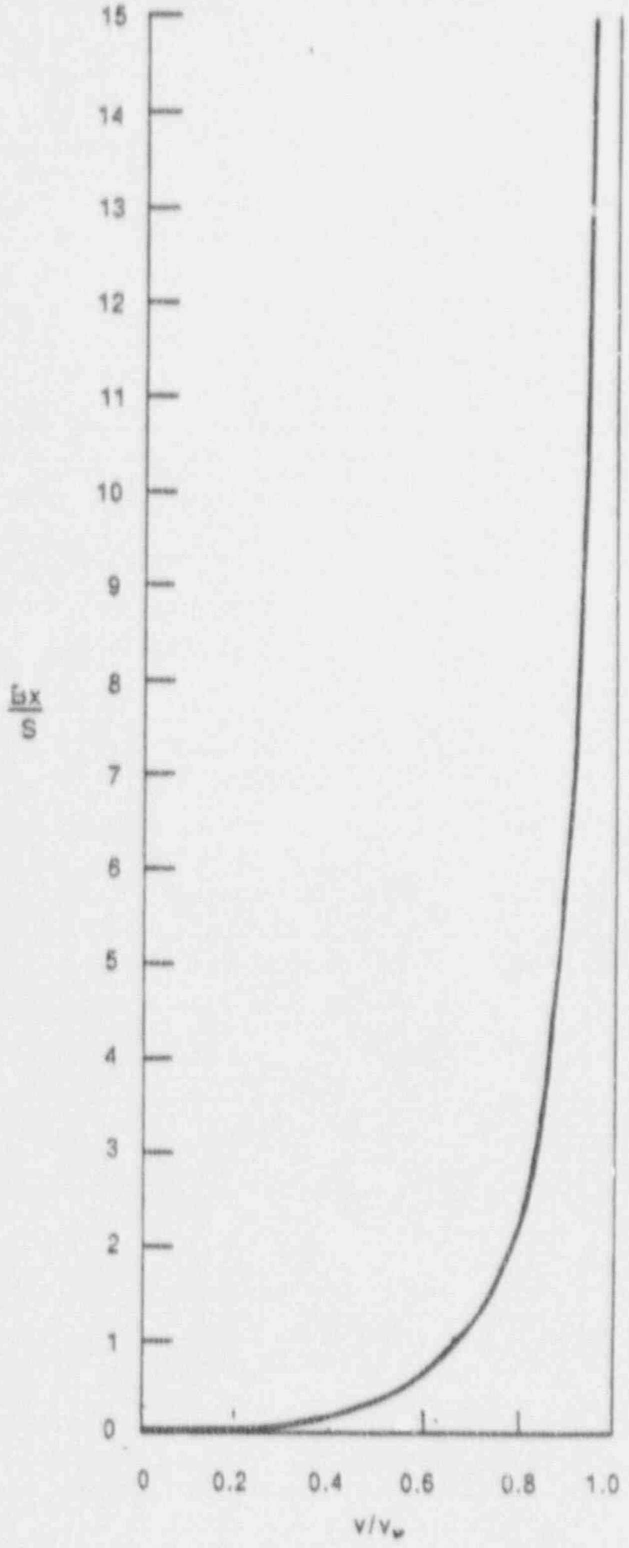

Figure 2-1. Ex/s versus v/v_w

objects were also measured and compared with the minimum static concentrated load capable of causing local plastic deformation. In addition, the mobility of small foreign objects may have been observed. The large foreign object remained trapped in the modeled wedge area for the duration of the test run that was shown on videotape at the April 30, 1982 meeting. It could be seen to strike the target tube several times in approximately the same spot. This supports the scenario for damage, in which a peripheral tube is ultimately flattened and torn so that it becomes separated from the tube sheet and then wears its neighboring tubes. If observations have also been made with sufficiently small foreign objects, with $s = 0.1$, say, there may be experimental support for the expection that such small objects are so highly mobile that they never strike a tube in the same place twice. But even if such experiments have not been performed, it is reasonable to conclude that if objects larger than, say, 0.25 inches in typical dimension are removed, the above scenario will not be repeated.

2.3.3.5 Laboratory Test Models

Two laboratory test setups were shown after the meeting on April 27, 1982, the first of which is shown in Document 9. In this test, a model impacting mass is propelled upward against the side of a horizontally mounted tube specimen. The mounting fixture enables an external pressure to be applied to the tube. The impacting peak force is measured, the tube is moved axially or rotated about its axis between successive impacts, and the tube is backed so that it does not bend.

This experiment appears to be well designed to yield valid data relating (1) the peak force to the occurrence of permanent deformation and (2) the effect of external pressure in collapsing the tube once substantial ovality is produced.

Since a statically applied force produces the same local stresses and strains as the same peak force applied dynamically, it would appear to be sufficient to apply the force statically. This might have led to a simpler experiment. Furthermore, backing the tube to prevent it from bending should make no difference in the final result, provided the peak applied force pressure, although Document 8 shows that external pressure can be a significant contribution. For some of the collapsed tubes, it may have played an essential role. Collapse (or flattening by impact alone) could have occurred because there was no internal pressure opposing or preventing it. However, even if internal pressure had somehow been provided, thus preventing tube collapse, severe tearing after many impacts by large foreign objects still might not have been prevented. Therefore, removal of foreign objects is necessary, as well as sufficient, to prevent a repetition of the tube burst incident.

3. CONCLUSIONS

3.1 METALLURGICAL

1. The tube burst failure resulted from rubbing-induced wall thinning.
2. Damage to the burst tube and to other tubes was caused by mechanical means, with initial major tube deterioration having been initiated by foreign objects.
3. There was no evidence that embrittlement or corrosion of the tube material contributed to the failure.
4. The sequence of events leading to the failure required foreign object induced deterioration of plugged tubes. Accordingly, an adequate inspection system to monitor the presence of foreign objects should be implemented to preclude another tube burst failure.

3.2 FLOW DYNAMICS

3.2.1 Theoretical Impact Model

The use of "fixed-pinned" tube end conditions may be more appropriate for the models used than the "fixed-fixed" conditions that were used. An alternative model is suggested in which the tube effective spring constant does not enter. Instead, the spring constant representing local tube deformation is included.

For impacting objects of a given shape, the peak energy stored in the spring varies roughly as s^n, where s is the linear size scale factor and n is between 2 and 3. Because of the fairly sensitive dependence on s, the impacting mass that causes incipient plastic deformation does not have to be determined very precisely.

3.2.2 Tampa Flow Model

This flow model is suitable for its intended purposes. It was used to show that the largest foreign object found can remain trapped in a wedge area long enough to strike a peripheral plugged tube many times with enough force to cause it eventually to be flattened. It is also capable of being used with smaller foreign objects, say 0.1 times the size (linear dimension) of the largest one studied, thereby providing experimental verification that peak impacting force is much less than that needed to cause plastic deformation, and confirming that such objects are so highly mobile that they do not impact twice near the same location on a tube.

3.2.3 Flow-Induced Vibration

The stability limit for round tubes with fixed-pinned ends is high enough that it is very unlikely that round tubes will experience excessive flow-induced vibration even if local flow velocities are higher near the region from which tubes have been removed. In the unlikely event that excessive flow-induced vibration were to occur, collisions between tubes would be detected by the acoustic monitoring system to be employed in the future.

3.2.4 Test Models

The two test models shown at Westinghouse Research and Development Center on April 27, 1982 are valid for their intended purposes, although simpler experimental setups may also have served.

3.2.5 Scenario Leading to Tube Rupture

The scenario is reasonable and accounts for the tube rupture. In view of the results obtained, it is reasonable to expect that removal of large foreign objects will prevent the recurrence of the tube burst scenario.

TECHNICAL EVALUATION REPORT

RUPTURED TUBE ANALYSIS FOR GINNA

ROCHESTER GAS AND ELECTRIC CORP.
R. E. GINNA NUCLEAR POWER PLANT

NRC DOCKET NO. 50-244	FRC PROJECT C5506
	FRC ASSIGNMENT 8
NRC CONTRACT NO. NRC-03-81-130	FRC TASKS 306, 307

Prepared by

Franklin Research Center
20th and Race Street
Philadelphia, PA 19103

Author: L. Leonard
G. P. Wachtell
FRC Group Leader: L. Leonard

Prepared for

Nuclear Regulatory Commission
Washington, D.C. 20555

Lead NRC Engineer: K. Wichman

May 12, 1982

Franklin Research Center
A Division of The Franklin Institute
The Benjamin Franklin Parkway, Phila., Pa. 19103 (215) 448-1000