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Components Test Installation

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I. INTRODUCTION

A sodium leak and subsequent fire occurred at the Sodium Components Test Installation (SCTI), operated by the Liquid Metal Engineering Center (LMEC), on August 5, 1972 when a thermowell failed in the inlet line to the intermediate heat exchanger (IHX). The failed thermowell, TR-104-62E, was found to be completely severed at the stem-to-support junction at a minimum-thickness region of 0.078 in. Examination disclosed a fatigue-type failure. The analysis of flow conditions at the thermowell, which was 13 in. downstream of a butterfly-type flow control valve, showed that resonance of the stem could have developed from Von Karman vortex shedding when the control valve was in a partly open position. The 1/4-in. -long exposed tip of the 1/16-in. -OD metal-sheathed thermocouple was also found to have broken off.

An investigation of other thermowells in the SCTI disclosed that there were several of the same or similar design as TR-104-62E and that conditions which caused failure to this thermowell were also present at several other locations. Therefore, 32 other thermowells in the sodium system and one in the steam and feedwater system were removed and either replaced with an FFTF-type thermowell or a skin thermocouple or capped without a replacement temperature sensor. One of these other thermowells was found with the thermocouple tip broken off, three tips were bent with prominent cracks at the Nicrobraz alloy attachment fillets, and five others were bent with no fillet cracking.

Chemical analyses conducted on sodium containment metal surfaces that were exposed to Met-L-X (NaCl with additives) fire extinguishant showed chloride levels about the same as operating systems which had not been exposed to Met-L-X. Cleaning of sodium reaction products and extinguishant was completed; damaged wire, tubing, and thermal insulation were replaced; replacement thermowells or skin thermocouples were installed; and the sodium system was placed back into service by September 22, 1972.

II. DESCRIPTION OF INCIDENT

On Saturday, August 5, 1972, at 2:40 A.M., a sodium leak and resultant local fire occurred at the LMEC-operated Sodium Components Test Installation (SCTI). The leak was located just upstream of the primary-side inlet nozzle of the intermediate heat exchanger (IHX). The plant was operating at approximately 32% power level in accordance with the Atomics International Modular Steam Generator (AI-MSG) steady-state test procedure, TP-04-PE-009. The 30% test point had been completed and power conditions were being changed for operation at 40% power.

Sodium operating conditions at the primary inlet to the IHX at the time of the leak were 850°F, ~20 psig, and 1800-gpm flowrate with a sodium plugging temperature of less than 250°F. The primary system expansion tank was pressurized to 10 psig. Operation of the plant had been very stable up to the time of the leak, and there had been no prior operational problems. The initial indication of an abnormal condition was an IHX upper tubesheet high-differential temperature alarm. The alarm was followed immediately by a full-scale indication on the differential temperature recorder. Apparently, the fire had fused the external thermocouple lead wires creating an erroneous signal.

Within 15 to 30 sec of the temperature alarm, the Pyralarm (smoke detection-type fire alarm) system for the SCTI high bay was activated. An operating crew member, who was dispatched to investigate the cause of the fire alarm, immediately confirmed the existence of a sodium fire in the SCTI high-bay area in the vicinity of the IHX primary inlet line.

Since there was no possibility of isolating such a leak and continuing system operation, a manual scram was initiated and draining of both primary and secondary sodium systems, as well as the water system, was begun. Simultaneously, the Protective Services Control Center was notified and a taped message was broadcast in the SCTI area warning personnel that sodium and sodium reaction products had been released. Protective Services personnel

arrived at the site within 7 min of notification and assisted SCTI personnel in extinguishing the fire. The air conditioning system for the SCTI control room was deactivated while sodium combustion aerosols were in the area. The data acquisition system (DAS) was set for maximum scan during the sodium draining operation. Sodium draining was accomplished by opening all drain valves and venting the 20-psig nitrogen gas that had been maintained on the primary and secondary fill and drain tanks. The primary expansion tank pressure was increased to 14 psig to effect more rapid draining.

The leak, estimated at 50 to 200 lb of sodium, occurred at the primary sodium system 10-in. piping near the inlet to the IHX. The inlet is about 25 ft above the floor of the facility (floor at grade level). A photograph of the IHX area of the SCTI is shown in Figure 1. Sodium was initially released under approximately 20-psig pressure, but decreased to 10 to 14 psig when the pump was stopped and the draining commenced. The sodium spray impinged upon adjacent equipment, wiring, and insulation and ultimately collected on thermal insulation, structural steel, and equipment near the floor. The fire did not extend into the area of the steam generator and no damage was sustained by the test unit.

The size of the fire decreased noticeably about 15 min after initiation of draining operations, presumably as a consequence of reduction of the sodium level below the point of leakage. Fire suppression activities could safely be undertaken at that time. SCTI emergency procedures require the use of hand-dispersed calcium carbonate as the primary fire extinguishant material except in cases where effective control cannot be achieved. In the latter circumstances, Met-L-X (85 to 95% NaCl with the remainder additives) can be utilized with the concurrence of the SCTI shift leader. In the present instance, the decision was made to use Met-L-X because of the extensive and spatially widespread nature of the fire in congested areas and because of the presence of sodium on vertical surfaces where Met-L-X exhibits better adherence than calcium carbonate. One 150-lb and two 30-lb containers of Met-L-X were distributed on the burning sodium. Limited amounts of shoveled calcium carbonate were also used where

Figure 1. SCTI System in Area of Intermediate Heat Exchanger (IHX)
(insulation covering removed from pipe and IHX at center of photograph)

conditions allowed. Containment of the fire, except for a few small pools, was accomplished in about 18 min. During the fire, sodium-oxide smoke in the high bay was quite heavy; however, very little smoke was evident outside the open side of the SCTI building. A few minutes after the fire was contained, there was essentially no residual smoke in the high bay area.

A visual inspection conducted immediately after the fire was contained disclosed the source of the leak as thermowell TR-104-62E, which monitored sodium temperature at the IHX primary inlet. A heavy deposition of reaction products was in evidence around thermowells in the immediate vicinity of the leak and extensive damage occurred to the local insulation. Numerous thermocouple and electrical lead wires in the proximity of the leak had been badly burned. Wiring located several feet above the leak was also damaged, and insulation on the secondary sodium outlet line located 5 ft above the fire was discolored from smoke, but apparently was not damaged. Piping lines adjacent to and below the leak showed the effects of sodium impingement; but the outer insulation layer, whether aluminum-jacketed or covered with cloth and Arabol (resin sealer), remained generally intact. The thermal insulation was generally undamaged, except in the area immediately adjacent to the leak. A heavy deposition collected on the concrete pad at the base of the IHX directly below the leak resulting in significant spalling of the concrete. The concrete pad all around the IHX was covered with a heavy layer of Met-L-X. Some discoloration and deposits of sodium were observed on horizontal structural beams between the leak point and the floor, but no distortion of these members could be detected. Several nonmetallic air supply lines to valve actuators were destroyed. Several small gas and air valves were seriously damaged, partly from heat and partly from adherence of reaction products. Five circuit breakers were found in the tripped position.

The sodium fire damaged two metal instrumentation wire trays located near the failed thermowell and destroyed or damaged about 80 instrumentation wire pairs located in the trays. These wires, along with about 50 other assorted heater, instrumentation, and control system electrical wires also

damaged by the fire, or removed during subsequent repair activities, were replaced. Six sets of composition pneumatic supply hoses used for valve actuation and many copper instrumentation lines were damaged and required replacement. Two hundred feet of flexible electrical conduit and 25 condulets or junction boxes connected to the conduits were replaced as a result of fire damage and repair activities. The extent of damaged insulation that required replacement was estimated to be 15 ft of 10-in. and 20 ft of 2-in. formed pipe insulation and 200 ft² of block insulation on the IHX. Figures 2, 3, 4, and 5 show damage incurred by the SCTI systems and structure below the leak as a result of the sodium fire and fire extinguishing actions.

Three air-actuated valve operators that were in the proximity of the fire and susceptible to heat damage were removed and returned to the supplier for checkout and refurbishment. No structural damage of the operators was found. All nonmetallic gaskets, seals, and O-rings were replaced as a normal practice in valve operator refurbishment.

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Figure 2. Damage to Lines and Structure Below Sodium Leak
(sections of cloth and Arabol or aluminum sheet insulation
covering removed from IHX at left and from
sodium pipe in center)

Figure 3. Damage Incurred by Sodium Lines,
Conduit, and Structure Below Leak

Figure 4. Fire Damage and Reaction Products or Fire Extinguishant Collection on Support Systems Below Sodium Leak (some cloth insulation covering removed from IHX)

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Figure 5. Deposits on Sodium Secondary Inlet Line and Flow Control Valve at Base of IHX Immediately Below Leak

III. FAILED THERMOWELL DISCUSSION

A. THERMOWELL CONFIGURATION AND LOCATION

The failed thermowell configuration (No. 7593-0407 design) is shown schematically in Figure 6. The annulus at the tip between the thermocouple and thermowell is sealed with a Nicrobrazed alloy fillet. The 1.04-in.-diameter ring on the thermowell stem is designed to provide radial support while allowing for longitudinal thermal expansion. The minimum cross-sectional thickness in the thermowell was approximately 5/64 (0.078) in. between the threaded hole in the thermowell support and the upper end of the 1/2-in.-diameter thermowell stem. The thermowell failure and sodium leakage occurred at this minimum thickness area.

The failed thermowell was one of two probes mounted in the same circumferential plane, each 15 degrees off the vertical on the upper surface of the transition section of a horizontally mounted 8-by 10-in. concentric reducer. One additional thermowell was mounted at the upper surface of the 10-in. pipe section about 5 in. downstream of the two thermowells. The failed thermowell was approximately 13 in. downstream of the centerline of an 8-in. butterfly flow control valve (see schematic in Figure 7 and photographs of the actual installation in Figures 8 and 9).

B. HYDRODYNAMIC CONDITIONS

The fatigue-type crack on the thermowell and proximity of the butterfly control valve suggested that the thermowell failed from flow-induced vibration. The hydrodynamic analysis conducted to substantiate this theory considered the natural frequency of each design, the Von Karman forcing frequency, and the resulting stresses from Von Karman vortex shedding. To simplify the analysis, only the maximum temperature and flow conditions were considered. The influence of velocity variations due to thermowell location and various opening positions of the control valve provided the basis for the vibration analysis.

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Figure 6. Failed Thermowell TR-104-62E Configuration

LMEC-31196

Figure 7. Plan View of Primary Sodium Inlet Line to IHX

Figure 8. Side View of IHX Primary Sodium Inlet Line with Failed Thermowell TR-104-62E and Butterfly Control Valve

Figure 9. Side View of IHX Primary Sodium Inlet Line and Failed Thermowell after Removal of Sodium Reaction Products

Following a quantitative review of thermal analyses conducted for many other similar instrumentation installations, the conclusion was reached that thermal transient stresses would be insufficient to cause a fatigue failure.

The analysis for the maximum operating flow velocity, 16.5 ft/sec (calculated for a sodium flowrate of 3940 gpm in a 10-in. pipe), results in a Von Karman forcing frequency of 79 cps (cycles per second) for the failed thermowell. The computed natural frequency is 306 cps. The stress at the failed area, assuming 0.1 damping factor, is nominally 3150 psi, far below the endurance limit. Therefore, failure would not be predicted for hydrodynamic loading based on uniform flow in a 10-in. pipe. (These calculations are shown in Appendix A.) However, considering area reduction (approximately 50% for an 8- by 10-in. reducer) with possible eddy flow currents, velocities to 40 ft/sec would be feasible with resulting Von Karman forcing frequency of 276 cps resulting in a stress of 81,900 psi. Fatigue failure would be expected to occur under these conditions.

Examination of butterfly valve flow characteristics indicates that at maximum flow conditions, the jet velocities immediately downstream of the control valve could be as much as 4.2 times the upstream flow velocity (see calculations in Appendix B). Therefore, velocities in excess of that required to provide a forcing frequency equal to the thermowell natural frequency could be expected to cause subsequent fatigue failure.

C. METALLOGRAPHIC EXAMINATION OF FAILURE^{(1)*}

The stem of the failed thermowell was broken away from the support, as indicated in the radiograph shown in Figure 10, and could be rotated freely within the assembly. The stem was retained in the assembly by the thermocouple wires which were still attached. The 1/16-in. thermocouple tip which protruded 1/4 in. beyond the thermowell was also found to have been broken off.

*Superscripts refer to the References listed at the end of this report.

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Figure 10. Radiograph of Failed Thermowell TR-104-62E Prior to Removal (Note abnormal position of stem inside of pipe stub, apparently retained in position by the thermocouple wire. Insert at left is photograph of removed assembly.)

The fracture face, shown in Figures 11 and 12, was relatively bright in appearance with the fracture origin indicating a brittle fracture characteristic of fatigue. The absence of localized deformation (necking) at the fracture origin would also indicate a fatigue fracture. A small amount of deformation was present in the shear lip area. No material flaw (stress concentration) was detected at the fracture origin. The fracture initiated in the machined fillet at intersections of the thermowell stem and support and propagated in fatigue across the wall at an angle of approximately 20 degrees to the base of the thermowell support. The final failure was in tension and resulted in a shear lip which occurred in a plane approximately 45 degrees to the base of the support. Shear lips and fatigue origin are shown in Figure 12 as they relate to the direction of sodium flow.

Dimensional measurements of the disassembled thermowell showed a diametral clearance of 0.035 in. between the thermowell collar and pipe stub (Figure 6). A cross-sectional slice taken through the thermowell at the point of fracture indicated a wall thickness of approximately 5/64 (0.078) in. compared with the stem wall thickness of 5/32 (0.156) in. The fillet radius between the thermowell stem and the support was determined to be approximately 1/16 in.

Chemical analyses of the removed specimens by X-ray fluorescence showed the thermowell to be Type 347 SS and the pipe stub to be Type 304 SS. Metallurgical analyses of specimens in the area where the failure occurred indicated little variation in the microstructures from the material in other areas.

The examination of the exposed edge at the thermocouple tip which had broken off (Figure 13) and one other similar thermowell subsequently removed, which showed a bent and cracked thermocouple tip, indicated a tensile-bending load type of failure. Some necking of the thermocouple tubewall was observed along with some grain deformation, secondary cracking, and tearing. The two failure modes appeared to be very similar. No sodium leakage path was found across the Nicrobrazed alloy fillet at the thermocouple sheath attachment with the thermowell stem.

Figure 11. View of Thermowell Support and Fracture Face of Thermowell (Note relationship of fatigue origin to direction of sodium flow.)

Figure 12. Higher Magnification of Fracture Face (Figure 11) Showing Fatigue Origin and Shear Lips (Mag 4X)

Figure 13. Broken Thermocouple Tip in TR-104-62E Showing Cracks in Nicrobrazo Alloy Fillet (Note thermocouple wires inside tip) (Mag 10X)

D. HISTORY OF SCTI THERMOWELL FAILURES

This failure was the second thermowell failure incident observed at the SCTI. The first failure was detected December 9, 1965 and involved two thermowells installed at the secondary sodium inlet to the IHX immediately downstream of the flow control valve. These failures were discovered during the checkout of a discrepant thermocouple output for one of these two adjacent thermowells. No external sodium leakage or fire occurred as a result of those failures. The failed thermowells were replaced with a like design.

All the thermocouples which mechanically failed at the SCTI were of the same design (7593-0407, Figure 6) and all were installed near the discharge of a sodium butterfly control valve. In the present instance, the thermowells were existing installations and a new control valve had been installed immediately upstream in the only available pipe location.

The original design of thermowell TR-104-62E included a socketweld mounting connection into the 1-in. nominal pipe size nozzle. However, this connection was changed prior to the original installation to impose a stagnant pool of sodium in the thermowell attachment to minimize thermal transient stresses. This modification consisted of machining a space in the thermowell support (see Figure 6) which resulted in forming the 5/64 (0.078)-in. minimum dimension where the failure occurred. The modified design incorporated a butt weld joint in place of a socketweld for the support-to-pipe stub attachment.

IV. OTHER THERMOWELL INVESTIGATIONS AND CHANGES

A. SODIUM SYSTEM THERMOWELL STUDY⁽²⁾

Stress and vibration analyses were conducted using methods similar to the failed thermowell analysis (Section III-B of this report) for other SCTI sodium system thermowell designs (see Figures 14, 15, and 16) and installation locations. The results of the analyses for a uniform sodium flow velocity of 16.5 ft/sec are shown in Table 1. The natural frequency is based on the thermowell acting as a fixed beam; but since the thermowell extension is not rigidly attached at the upper end, and the mounting section contains some flexibility, the natural frequency will actually be closer to the vortex shedding frequency (Von Karman forcing frequency). In addition, fluid line perturbations, such as reducers, valves, adjacent thermowells, elbows, etc., would cause a higher fluid velocity with a corresponding increase in the Von Karman forcing frequency.

A ratio of natural frequency-to-forcing frequency of 1.5 is the absolute minimum recommended where all details of the system are known. Because of the many unknowns described above, it was determined that thermowells in the sodium lines which had a ratio of natural frequency-to-forcing frequency less than 4 or 5 should be removed to preclude possible failure. This would indicate that thermowell types 7593-0407 and 7593-52001 (shown in Figures 6 and 15) should be removed. In reaching a decision on the thermowells, consideration was also given to the fact that many thermowells may not have been fabricated or installed in accordance with their specification. Thermowells downstream of butterfly control valves, regardless of the calculated frequency ratio, were considered to be a poor risk because of the ill defined turbulence associated with the valve. All thermowells in the sodium system which included an exposed metal sheath thermocouple tip would be eliminated by this reasoning.

A summary of all the sodium system thermowell changes made, including replacement actions taken, is shown in Table 2. The decision on whether the removed thermowells were to be replaced with a new thermowell design (type 7593-CE132306, Figure 16) or by a skin thermocouple or simply removed and the opening capped was based on an evaluation of the instrumentation needs of the SCTI sodium systems.

NOTE: DIMENSIONS IN INCHES

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Figure 14. Type 7593-44867F Thermowell

LMEC-31199

Figure 16. Type 7593-CE132306 Replacement Thermowell
(Similar to FFTF Design)

TABLE 1
SCTI SODIUM THERMOWELL HYDRODYNAMIC CONDITIONS
(at 16.5 ft/sec flow velocity)

Thermowell Design Type	D (in.)	C/I (in. ⁻³)	A (in. ²)	L (in.)	f_n (cps)	f_{VK} (cps)	F (lb)	M (in.-lb)	Amplifi- cation Factor	S (psi)
7593-0407 (Figure 6)	0.50	87.0	1.99	6.75	306	79	5.2	35.08	1.033	3150
7593-44867F (Figure 14)	0.75	10.23	3.0	4.0	1641	52	7.85	31.40	~ 1.0	321
7593-52001 (Figure 15)	0.63	9.8	2.0	7.5	241	63	5.5	41.25	~ 1.0	404
7593-CE132306 (Figure 16)	0.25	81.9	0.607	3.25	1515	158	1.59	5.16	~ 1.0	422

D = outside diameter of thermowell at section under investigation

C/I = inverse of section modulus, nominal value

A = projected area of thermowell in flow stream

L = length of thermowell immersed in sodium

f_n = natural frequency

f_{VK} = Von Karman shedding frequency

F = drag force

M = moment at base of thermowell, F times L

S = stress at base of thermowell from hydrodynamic loading

TABLE 2

SCTI SODIUM SYSTEM THERMOWELL DISPOSITION SUMMARY

Item	Tag Number	Disposition			
		Remove and Cap	Install Skin Thermocouple	Replace with New Thermowell	Leave in Place
	<u>7593-0407 (Figure 6)</u>				
1	TSc-1-1E	X	X		
2	TSc-1-2E	X	X		
3	TSc-1-3E	X	X		
4	TR-104-62E	X	X		
5	TdR-101-2E	X	X		
6	TSc-1-4E	X	X		
7	TSc-1-9E	X	X		
8	TR-104-63E			X	
9	TdR-101-3E	X	X		
10	TSc-1-10E	X	X		
11	TRC-100E			X	
12	TRC-101E			X	
13	TRC-103E	X		X	
14	TR-100E			X	
15	TR-102-1E	X	X	X	
16	TR-500E			X	
17	TSc-1-5E	X	X		
18	TR-104-64E	X	X		
19	TdR-101-4E	X	X		
20	TSc-1-6E			X	
21	TR-104-61E	X	X		
22	TdR-101-1E	X	X		
23	TR-501-E			X	
24	TR-102-2E			X	
	<u>7593-44867F (Figure 14)</u>				
25	TW 501	X			X
26	TW 551G				X
27	TW 552G				
	<u>7593-52001 (Figure 15)</u>				
28	TR-101E			X	
29	TR-108-1E	X	X		
30	TSc-1-7E			X	
31	TR-107E			X	
32	TdR-101-7E			X	
33	TR-103-62E	X	X		
34	TR-103-61E	X	X		
35	TdR-101-6E			X	
		<u>20</u>	<u>18</u>	<u>13</u>	<u>2</u>

B. EXAMINATION OF REMOVED SODIUM SYSTEM THERMOWELLS

Twenty-four of the 33 thermowells removed were submitted for macro-examination of their exterior surfaces. Of the 24 thermowells examined, 20 had the same thermocouple tip design.

No other thermowell indicated a pending failure at the stem-to-support junction where sodium leakage occurred at thermowell TR-104-62E. The thermocouple in the thermowell on the same diametral circle as the failed thermowell was also found to have had its tip broken off. Three other thermowells exhibited bent thermocouple tips with prominent cracks in the Nicrobrazed alloy fillet; five others had sensor tips which were slightly bent but with no evidence of fillet cracking. The remaining ten thermowell tips showed no signs of bending or fillet cracking.

C. STEAM AND FEEDWATER SYSTEM THERMOWELL STUDY⁽³⁾

An evaluation of the 22 thermowells in the steam and feedwater system was also conducted to determine if a hydrodynamic-induced vibration problem similar to that in the sodium system existed. The thermowell types installed in the steam and feedwater system at the time of the sodium thermowell failure were as follows:

<u>Type</u>	<u>Figure No.</u>	<u>Quantity Installed</u>
1) 7593-0407	6	7
2) 7593-CE13230-1	17	6
3) 7593-44867F	14	2
4) TI-101-2	18	7

The steam and feedwater system thermowell analysis is an extension of that described earlier for the sodium systems. The analysis is complicated by the method of installation and the variety of configurations and thermowell lengths. A heavier weld boss attachment is used in the steam and feedwater system with a shorter thermowell length and lesser immersion depth than similar thermowells in the sodium system.

NOTE: DIMENSIONS IN INCHES

LMEC-31200

Figure 17. Type 7593-CE13230-1 Thermowell

NOTE: DIMENSIONS IN INCHES

LMEC-31201

Figure 18. Type TI-101-2 Thermowell

The analysis disclosed that only one thermowell, Tag No. TS-1-30E (Figure 6), had a forcing frequency greater than the natural frequency at full power conditions; therefore, resonance could be expected to occur at intermediate power levels. All other thermowells had ratios of natural frequency-to-shedding frequency that would preclude a resonant condition and very low stagnation pressure stresses. Only the one steam and feedwater system thermowell, TS-1-30E, was removed, the opening capped, and an existing skin thermocouple used for temperature indication at that location. Visual examination disclosed that no damage had occurred to this single steam and feedwater system thermowell.

V. RECOVERY

A. SURFACE CLEANING AND EXAMINATION

Extensive cleanup was required at the SCTI to remove sodium reaction products and the Met-L-X fire extinguishant that had been sprayed over the area around the IHX. All damaged or contaminated thermal insulation and wires were removed from the metal surfaces, and the exposed surfaces were wiped with a demineralized water-dampened, lint-free cloth. This was followed by wiping with technical-grade acetone on a lint-free cloth, or spraying as necessary to flush crevices and other difficult-to-reach areas. Absence of contaminants or discoloration on the final wiping cloth was used as verification of surface cleanliness. Cleanliness of the cleaned metal surfaces was maintained by wrapping the exposed surfaces with polyethylene sheeting. In addition, a desiccant bag was affixed to the surface of the IHX inlet nozzle to maintain a dry atmosphere at that surface.

Following the cleanup, exposed metal surfaces were visually (unaided-eye), macroscopically (2X to 10X), and liquid penetrant examined (selected areas). The examinations did not reveal any damage or degradation of the metal surfaces.

In addition, selected exposed cleaned metal surfaces were sampled by means of a surface swab technique and analyzed for the presence of residual chlorides and fluorides. A minimum surface area of 1 ft² was swabbed with paper towels moistened with deionized water and wiped dry with a dry side of the same towel. The results of the chloride analyses from 15 surface smear samples, after correcting for background chlorides in the paper, averaged 11.8 $\mu\text{gm/in.}^2$ with a maximum concentration of 24 $\mu\text{gm/in.}^2$. For comparative purposes, surface smear samples were collected using the same procedure from representative sections of piping on another test facility, which had not been exposed to Met-L-X extinguishant, and from new pipe in storage. Average chloride residue from these two areas were 29 and 8.2 $\mu\text{gm/in.}^2$, respectively. Therefore, final chloride concentrations on surfaces exposed to the fire and subsequent fire extinguishant cleanup operations were found comparable to

concentrations on piping not exposed to those conditions. Fluoride concentrations in the samples were too low to be measurable.

B. THERMOWELL REPLACEMENTS

From the analysis, it was concluded that in reduced diameter pipe sections of the system, the thermowells shown in Figures 6 and 15 would resonate at the calculated maximum flow velocities from Von Karman forcing frequencies which approached the natural frequency of the thermowell. The Von Karman frequencies and natural frequencies are sufficiently far apart to preclude damage under any predicted flow conditions for the Figure 14 design and the new replacement design shown in Figure 16. For these reasons, the following thermowell changes were made (detailed tabulation for sodium system changes is given in Table 2):

- 1) All 24 type 7593-0407 (Figure 6) design thermowells were removed. Eight of these were replaced with the new design shown in Figure 16 (7593-CE132306). The remainder were capped.
- 2) All eight of the type 7593-52001 (Figure 15) design thermowells were removed. Five of these were replaced with the new design type 7593-CE132306 (Figure 16). The remainder were capped.
- 3) Two of the type 7593-44867F (Figure 14) design were retained in their present location; one was removed and capped.
- 4) Nineteen skin-type thermocouples (18 sodium system, 1 steam and feedwater system) were installed where existing thermowells had been removed and capped.

C. CHECKOUT OF REPAIRED SYSTEMS

All systems were installed or repaired and checked per Engineering and Operations standard procedures. The SCTI sodium system was placed back into service on September 22, 1972.

VI. SUMMATION AND RECOMMENDATIONS

A. REPLACEMENT THERMOWELL DESIGN

The replacement thermowell design (7593-CE132306), shown in Figure 16, is very similar to the design being employed in FFTF. The sensor tip end is identical to the FFTF design; the pipe mounting attachment differs, however. A dry thermowell design with a spring-loaded removable thermocouple was used to avoid breakage of the tip as noted in this report. Thermocouple response time is sacrificed, however, when a drywell design is used in place of an exposed tip design.

Hydrodynamic analysis of this FFTF thermowell design under SCTI operating conditions established the following characteristics:

For the 10-in. section at 16.5-ft/sec flow velocity, the Von Karman forcing frequency was 158 cps and stress was 422 psi. The natural frequency was 1515 cps. Even in an 8-in. section of an 8-by 10-in. reducer, a forcing frequency of only 540 cps was calculated. This gives a ratio of f_n/f_{VK} of about 3, which is well above the recommended minimum of 1.5. This information is shown in tabular form in Table 1. This design appears satisfactory for installation in any portion of the system, excluding the location immediately downstream of the butterfly control valves.

B. SODIUM FIRE FIGHTING METHODS AND MATERIALS

Chloride-free extinguishants are recommended because of the impossibility of guaranteeing that all traces of chloride can be removed from a facility if the extinguishant contains principally sodium chloride (Met-L-X). For this reason, the continued use of Met-L-X at LMEC is not acceptable and actions have been taken to replace it with chloride-free sodium carbonate.

At the present time, however, no anhydrous sodium carbonate base, halogen-free, dry powder extinguishant for fighting sodium fires has been developed and approved by the Underwriters' Laboratories, Inc. (UL). The appropriate UL approval and listings must be obtained before an extinguishant is placed

into service for compliance with the Occupational Health and Safety Administration standards, the California Health and Safety Code, and the National Fire Protection Association standards.

Negotiations have been initiated with a manufacturer to develop an anhydrous sodium carbonate extinguishant and obtain a UL listing for the agent and hardware combination to be used as a Class D extinguishant for sodium fires. When available, three trailer-mounted extinguishers, each capable of dispensing approximately 3000 lb of powder extinguishant, will be placed into service at LMEC. These units will be readily recharged and will represent a significant upgrading in the capability of controlling large sodium fires at the LMEC.

Until this equipment is available, however, the following practices will be observed at LMEC:

- 1) First, use manually applied desiccated CaCO_3 .
- 2) If the above step 1 is impractical or inadequate, use Met-L-X portable extinguishers next.
- 3) If the preceding two steps cannot control the fire, use Met-L-X wheeled extinguishers only, and only on the direction of the shift leader.
- 4) The site Protective Services Department will not use Met-L-X on stainless steel materials unless the sodium fire cannot be controlled with CaCO_3 .

Procedures have been implemented at SCTI to drain sodium by gravity only in case of an external leak and not pressurize the system to drain more quickly. The advantage of reducing the time to drain is more than offset by the additional damage caused from sodium spray when the system is pressurized.

C. SODIUM LEAK PROTECTION

The following methods have been suggested to avoid damage to parts exposed to a sodium leak, both from jet impingement and subsequent fire considerations:⁽⁴⁾

- 1) Secondary containment (most efficient but also highest cost).

- 2) Protective impingement shields and drip pans (limited accessibility for installation exists and line and cable penetrations must be provided and sealed).
- 3) Specific equipment protection (providing shrouds around expensive, critical, or long-lead replacement items — most economical approach).

Only a combination of methods 2 and 3, above, would be considered for existing LMEC facilities such as the SCTI for the following reasons:

- 1) Sodium leaks experienced in the past have been relatively evenly distributed throughout the major components of the system, and the majority of these were small in size (1 to 10 lb of sodium).
- 2) Retrofit of facilities not designed for secondary containment would be expensive and must be evaluated in the light of low probability of failure.
- 3) Absence of radioactive sodium biases the evaluation towards less expensive protection.

No major fire protection shields or other changes had been incorporated into the SCTI facility at the time of this report. However, LMEC has submitted recommendations to the AEC to provide additional drip pans and protective shields around components which are critical to the safe shutdown of all LMEC facilities.

REFERENCES

1. G. A. King, "Metallurgical Analysis of Failed SCTI Thermowell No. TR-104-62E," LMEC-TDR-73-2 (January 15, 1973)
2. "Replacement of Thermowells in the SCTI Facility," LMEC letter 72LMEC-DRF-6550 (August 19, 1972)
3. "Replacement of Thermowells in the SCTI Facility," LMEC letter 72LMEC-DRF-6710 (August 25, 1972)
4. "LMEC Sodium Facility Sodium Leak/Fire Damage Protection Proposal," LMEC letter 73LMEC-DRF-0425 (January 26, 1973)

APPENDIX A ANALYSIS

1. Natural Frequencies

Natural frequencies of the thermowells were derived by IBM computer program. They were analyzed as fixed free and did not include the pipe stiffness. If this were included, the frequencies would be approximately 10 to 15% lower.

2. Von Karman Forcing Frequencies

These are based on the relationship:

$$f_{VK} = (V/D) \times (\text{Strouhal's number}) , \quad \dots(1)$$

where

V = flow velocity (ft/sec)

D = diameter of projected thermowell (ft)

f_{VK} = Von Karman forcing frequency (cps),

Strouhal's number = 0.2 if Re is less than 1×10^5 .

Strouhal's number = 0.47 if Re is 3×10^5 or more.

$$Re = \frac{3600 D_o V \rho}{\mu} , \quad \dots(2)$$

where

Re = Reynold's number

D_o = thermowell OD (ft)

ρ = fluid density (lb/ft³)

μ = viscosity (lb/ft-hr).

3. Hydrodynamic Drag

The hydrodynamic drag is calculated from the following relationship:

$$F = \frac{C_d \rho V^2 A}{2g} , \quad \dots(3)$$

where

F = drag force (lb)

C_d = drag coefficient

A = area of projectile (ft²)

g = acceleration due to gravity (ft/sec²).

4. Stress Resulting from Drag

$$S = \frac{MC}{I} \quad \dots(4)$$

$$I = \frac{\pi}{64}(D_o^4 - D_i^4) \quad \dots(5)$$

$$M = FL , \quad \dots(6)$$

where

S = stress (psi)

C = distance from neutral surface (in.)

I = moment of inertia (in.⁴)

M = moment (in.-lb)

D_o = outside diameter (in.)

D_i = internal diameter (in.)

L = length (in.).

5. Amplification Factor

$$= \frac{1}{\sqrt{\left[1 - \left(\frac{f_{VK}}{f_n}\right)^2\right]^2 + \left(2\zeta \frac{f_{VK}}{f_n}\right)^2}}, \quad \dots (7)$$

where

f_n = natural frequency (cps)

ζ = dampening = 0.1 for welded metal.

6. Maximum Flow Velocity

$$V = \frac{Q}{A\rho}, \quad \dots (8)$$

where

Q = flowrate (lb/hr)

A = flow area (ft²).

Given:

$Q = 1.71 \times 10^6$ lb/hr at 870°F

$\rho = 52.5$ lb/ft³ at 870°F,

$$A_{10\text{-in. sch 40S}} = 0.5475 \text{ ft}^2.$$

From Equation 8:

$$V = \frac{1.71 \times 10^6}{(3.6 \times 10^3)(52.5)(0.5475)} = 16.5 \text{ ft/sec}.$$

7. Sample Calculation

Given:

$$V = 16.5 \text{ ft/sec}$$

$$D_o = 0.5 \text{ in.}$$

$$\mu = 0.623 \text{ lb/ft-hr}$$

$$C_D = 1.7$$

$$A = 1.985 \text{ in.}^2$$

$$L = 6.75 \text{ in.}$$

$$C = 0.25 \text{ in.}$$

$$f_n = \underline{306} \text{ cps (from computer program)}$$

The Reynold's number from Equation 2 is:

$$Re = \frac{(0.5)(16.5)(52.5)(3600)}{(12)(0.623)} = 2.08 \times 10^5$$

Strouhal's number, therefore = 0.2.

Applying Equation 1:

$$f_{VK} = \frac{(16.5)(12)(0.2)}{(0.5)} = 79 \text{ cps}$$

From Equation 7:

$$\text{Amplification factor} = \frac{1}{\sqrt{\left[1 - \left(\frac{79}{306}\right)^2\right] + \left(0.2 \times \frac{79}{306}\right)^2}} = 1.033$$

The hydrodynamic drag from Equation 3 is:

$$F = \frac{(1.7)(52.5)(16.5)^2(1.985)}{(64.4)(144)} = 5.2 \text{ lb}$$

and moment (Equation 6) is:

$$M = (5.2)(6.75) = \underline{35.08} \text{ in.-lb} \quad .$$

Moment of inertia calculated from Equation 5 is:

$$I = \frac{\pi (0.5^4 - 0.25^4)}{64} = 0.00287 \text{ in.}^4$$

Therefore, multiplying Equation 4 by the amplification factor, the stress would be:

$$S = \frac{(1.033)(35.08)(0.25)}{0.00287} = 3150 \text{ psi} \quad .$$

APPENDIX B

IHX PRIMARY INLET BUTTERFLY CONTROL VALVE ANALYSIS

(Ref: Paper No. 60-10A-105, "Torque and Cavitation Characteristics of Butterfly Valves," Turgut Sarpkaya, Journal of Applied Mechanics, Volume 28, December 1961)

$$\frac{V_o}{V_j} = \frac{C_{C1} + C_{C2}}{2} \left(1 - \frac{\sin a}{\sin \beta} \right)$$

where

V_o = velocity upstream

V_j = velocity of jet

C_{C1} = contraction coefficient

C_{C2} = contraction coefficient

a = angle of opening

β = angle of complete closure .

For the two flow extremes where a is 20 deg and 40 deg and β is 90 deg:

a (deg)	C_{C1}	C_{C2}	$\sin a$	$\sin \beta$
20	0.851	1.571	0.342	1
40	0.768	0.570	0.642	1

At 20 deg:

$$\frac{V_o}{V_j} = \frac{(0.851 + 1.571)}{2} \left(1 - \frac{0.342}{1} \right) = 0.483$$

$$V_j = 2.14 V_o$$

At 40 deg:

$$\frac{V_o}{V_j} = \frac{(0.768 + 0.570)}{2} \left(1 - \frac{0.642}{1} \right) = 2.39$$

$$V_j = 4.17 V_o$$