Greg Kolb

Topics:
Heat recovery steam generators
Once-through heat recovery
Alloys
Availability
Reliability

EPRI AP-5772
Project 2653-9
Final Report
April 1988

# Evaluation of a Once-Through Heat Recovery Steam Generator Concept

Prepared by
ARINC Research Corporation
Annapolis, Maryland

# REPORT SUMMARY

|  |  |
|---|---|
| SUBJECT | Combustion turbines and combined cycles |
| TOPICS | Heat recovery steam generators<br>Once-through heat recovery<br>Alloys<br>Availability<br>Reliability |
| AUDIENCE | Generation managers and engineers |

## Evaluation of a Once-Through Heat Recovery Steam Generator Concept

A once-through heat recovery steam generator made from all-alloy steel offers the potential for high reliability in combined-cycle plants. This study evaluated the reliability, availability, and maintainability of this modular-design steam generator.

**BACKGROUND** Early combined-cycle power plants experienced operating and maintenance problems with drum-type, carbon steel heat recovery steam generators (HRSG) offered by gas turbine vendors and others. The Solar Turbines, Inc., concept of a modular, all-alloy steel, once-through HRSG promised to alleviate erosion and corrosion problems, as well as control and complexity factors, encountered with drum-type HRSGs. Under project RP2653-1, EPRI developed conceptual designs for the piping, instrumentation, and control systems (P&IDs) for both the Solar Turbines HRSG and a generic drum-type unit. These designs were used as the basis for evaluation in this study.

**OBJECTIVE** To perform an independent assessment of the reliability, availability, and maintainability characteristics of the Solar Turbines HRSG.

**APPROACH** Using the instrumentation and control systems and the equipment defined in the P&IDs, investigators compared the reliability and maintainability of the two designs. They used EPRI's UNIRAM computer modeling methodology to compare the reliability and maintainability of the once-through design and the drum-type design. Data for the newer drum-type HRSGs presently in use came from EPRI's ERAS database. Investigators also compiled a bibliography on alloy 800 and its use as a tubing material.

**RESULTS** The drum-type HRSG system has a calculated availability of 98.52% versus a predicted availability of 99.10% for the once-through system, based on a mean time between failure (MTBF) of 40,000 h for the alloy 800 tubing in the once-through unit. Changing this MTBF to 400,000 h increases the resulting availability by only 0.05%, demonstrating that other system components and system configurations—not tubing MTBF—govern availability.

The report also includes a comprehensive bibliography on alloy 800, the material specified for the once-through design, to further help utilities evaluating this new technology.

EPRI PERSPECTIVE

This comparison has shown a 0.58% difference in HRSG system availability between the alloy steel once-through design and the carbon steel drum-type design. As a small difference between two large numbers that were based on a series of assumptions, this 0.58% should not by itself serve as a quantitative basis for a procurement decision. However, this comparison assumed that the drum-type unit did not include a hot gas bypass damper and stack. If a bypass system were included with the drum-type unit, the once-through system—which would allow simple-cycle operation without a bypass—becomes comparatively more attractive. Bypass systems have proven to be troublesome maintenance components and have adversely affected heat rate by leaking hot gas to the atmosphere, thus bypassing the HRSG.

In other industry experience, as of spring 1988, two small (20,000 lb/h) once-through HRSGs have each accumulated more than 40,000 h and 707 starts with an availability of well over 99%. Additionally, EPRI project RP2653-1 is conducting a comprehensive technical evaluation of the once-through HRSG design. This evaluation includes an extensive field test of a partial HRSG module at Houston Lighting and Power Company's T. H. Wharton plant, scheduled for completion in 1989.

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PROJECT

RP2653-9
EPRI Project Manager: Henry Schreiber
Advanced Power Systems Division
Contractor: ARINC Research Corporation

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# Evaluation of a Once-Through Heat Recovery Steam Generator Concept

**AP-5772**
**Research Project 2653-9**

Final Report, April 1988

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## NOTICE

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Annapolis, Maryland

# ABSTRACT

This report presents the results of a reliability, availability, and maintainability (RAM) evaluation of a once-through concept for a combined-cycle heat recovery steam generator (HRSG). The project included a review of differences in reliability and maintainability characteristics of the once-through concept and a typical drum-type HRSG design. A special effort was placed on an investigation of the expected performance of the thin-wall alloy 800 boiler tubing used in the once-through HRSG. An analysis was performed by using the UNIRAM computer modeling methodology to compare the predicted availability of the once-through HRSG design with that of a drum-type system. The results of this project provide a basis for understanding the RAM characteristics of the once-through HRSG concept and identify areas where additional research may be beneficial in evaluating this new design for application within the utility industry.

# CONTENTS

# SUMMARY

ARINC Research Corporation evaluated the reliability, availability, and maintainability (RAM) characteristics of a once-through heat recovery steam generator (HRSG) for the Electric Power Research Institute (EPRI). The project, performed under Research Projects (RPs) 2653-2 and 2653-9 and documented in this report, was an analysis of the conceptual design of the HRSG performed by Solar Turbines Incorporated. Heat recovery steam generators have caused availability and maintenance problems in utility applications; the Solar Turbines design is intended to improve reliability and availability. The once-through HRSG does not require a steam/water drum, and the use of a corrosion-resistant alloy allows passive water treatment without chemical injection or blowdown. The use of corrosion-resistant materials also eliminates the need for protective shutdown procedures such as nitrogen blanketing. Though the conceptual design holds considerable promise for utility applications, it also represents a departure from previous HRSG designs, with some possibility of technical and economic risk to first users. ARINC Research Corporation analyzed the design RAM characteristics to determine the technical viability of the design from an availability standpoint.

The Solar Turbines HRSG represents a new technology for heat recovery applications. The design of the HRSG is new, and although small-scale commercial applications of the technology are successfully operating, a large body of data from these applications are not yet available for assessing RAM characteristics of this design. Technical issues include tube life (relative to erosion and corrosion resistance) and susceptibility to weld cracking. Such issues require a full life cycle of operation to resolve. The design departs sufficiently from fired once-through super-critical boilers and industrial applications of similar alloys to raise questions regarding the applicability of data from those sources. However, because availability is important to future electric utility plants, this emerging technology warrants evaluation. This report documents a RAM analysis of the once-through HRSG design and compares the RAM characteristics to modern drum-type HRSG designs anticipated for new combined-cycle installations.

The analysis was performed by gathering applicable data, developing component reliability and maintainability estimates, and evaluating system level availability and reliability and maintainability characteristics of the two designs. Data on alloy 800, the tube material, was obtained from several sources. Although primarily subjective and qualitative in nature, these data were useful in understanding failure modes and potential problems that could be encountered in utility applications.

Considerable effort was spent evaluating potential failure modes of the once-through HRSG tubing, including erosion, corrosion, gas side acid attack, and fatigue. For a natural gas application, no failure mechanism was identified that would prevent a 30-year lifetime for the HRSG. Alloy 800 is highly corrosion-resistant compared with traditional carbon steel boiler tubes, but if operated below the sulfuric acid dew point, it could suffer some sulfuric acid attack. Use of sulfur-bearing fuels without feedwater heating could have considerable effect on unit life expectancy. Alloy 800, although more resistant to general corrosion, could experience stress corrosion cracking affecting life expectancy if proper water treatment is not maintained. Alloy 800 has been described as difficult to weld, and proper quality control is required at fabrication to prevent weld cracking and subsequent field problems. With proper fuel quality consistent with feedwater temperature, feedwater maintenance, and quality control at manufacture, it is expected that the technology will provide a 30-year life cycle.

It was concluded that the HRSG design is technically feasible for natural gas applications. It also shows promise for high-sulfur fuel applications, although higher feedwater temperatures may be required to maintain gas side tube metal temperatures high enough to prevent corrosion under these conditions.

The UNIRAM availability assessment methodology was used to determine expected availabilities for the once-through and drum type HRSG designs. UNIRAM calculates availability of a system as a function of component reliability and maintainability as well as system configuration. Reliability and maintainability data were obtained from the EPRI Reliability Assessment System (ERAS), a database of outage reports and maintenance work orders representing more than 400,000 h of combined-cycle plant operation.

The RAM analysis indicated an availability advantage for the once-through HRSG design, in comparison with a drum-type design, of approximately 0.6 percentage point. At worst, the once-through design would be expected to be at least as good as the drum-type design with respect to system availability. A base-case mean time between failures (MTBF) value of 40,000 h for the once-through boiler tubes was selected in this analysis, based on operating experience seen by two Solar Turbines industrial once-through HRSG units in natural-gas-fired, combined-cycle systems (each of these two units have experienced approximately 40,000 h of operation to date with no known tube failures). The RAM analysis included a sensitivity study varying this MTBF value from 4000 to 400,000 h. Table S-1 summarizes the results of the UNIRAM analysis. The various once-through HRSG analysis cases represent UNIRAM runs using different once-through boiler tube MTBF and MDT input values, as indicated in the table.

Table S-1

RAM ANALYSIS RESULTS SUMMARY

different tube lifes

| | Drum Type HRSG System | Once-Through HRSG System | | | |
|---|---|---|---|---|---|
| | | Case 1 | Case 2[a] | Case 3 | Case 4[b] |
| Once-Through Boiler Tube MTBF (h) | -- | 4,000 | 40,000 | 400,000 | 999,999 |
| Once-Through Boiler Tube MDT (h) | -- | 24 | 24 | 24 | 1 |
| HRSG System Availability (%) | 98.52 | 98.57 | 99.10 | 99.15 | 99.16 |
| Difference Between HRSG Designs (%) | -- | 0.05 | 0.58 | 0.63 | 0.64 |

Previous Report COMPOSITE HI SERV FACTOR .980

[a] Base case.

[b] Once-through boiler tube "perfectly available" case.

LO SERV FACTOR .95 STAG 100

High uncertainties are associated with some of the derived statistics used in the RAM analysis models for both HRSG designs, thus reducing the significance of the 0.6% availability advantage for the once-through HRSG. It may be more important to

$$= \frac{875}{875 + 12.9}$$

recognize the similarities in availability for once-through concept and modern drum-type HRSG designs. The most significant conclusion that can be drawn from this analysis is that the once-through HRSG concept has the potential of improving the operating and maintenance characteristics of combined-cycle systems, while maintaining the high availability required in the utility applications.

## Section 1

## INTRODUCTION

This report presents the results of a review and analysis of reliability, availability, and maintainability (RAM) characteristics of an alloy steel once-through heat recovery steam generator (HRSG). This work was performed by ARINC Research Corporation for the Advanced Power Systems Division of the Electric Power Research Institute (EPRI) under EPRI Research Projects (RPs) 2653-2 and 2653-9. The once-through HRSG is being developed for utility combined-cycle applications by Solar Turbines Incorporated. Bechtel National, Inc., has also provided engineering services to EPRI and Solar Turbines in support of this review and evaluation effort.

This study was based on design information and assumptions and operational data provided by EPRI, Solar Turbines, and Bechtel and industry information and data from numerous sources.

### TECHNICAL BACKGROUND

#### Combined-Cycle Plants

In combined-cycle systems, electrical power is produced by generators driven by a combination of gas turbines and steam turbines as shown in Figure 1-1. Waste heat from the gas turbine exhaust is recovered by the HRSG to produce steam to drive the steam turbine. The water/steam cycle is a closed system with the steam turbine exhaust being condensed and recycled as feedwater to the HRSG. The gas turbine exhaust temperatures upstream of the HRSG can approach 1100°F (590°C).* The use of the waste heat steam cycle greatly improves the heat rate of the total power system, and in many power-generation applications, the operation of the gas turbine without the waste heat steam cycle is economically unacceptable. Supplemental duct firing may be added to increase the HRSG inlet gas temperatures and steam flow. Steam cycle optimization may result in the use of multiple-stage (multiple-pressure) HRSGs.

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*Conversions to SI are provided in parentheses for original measurements expressed in this report.

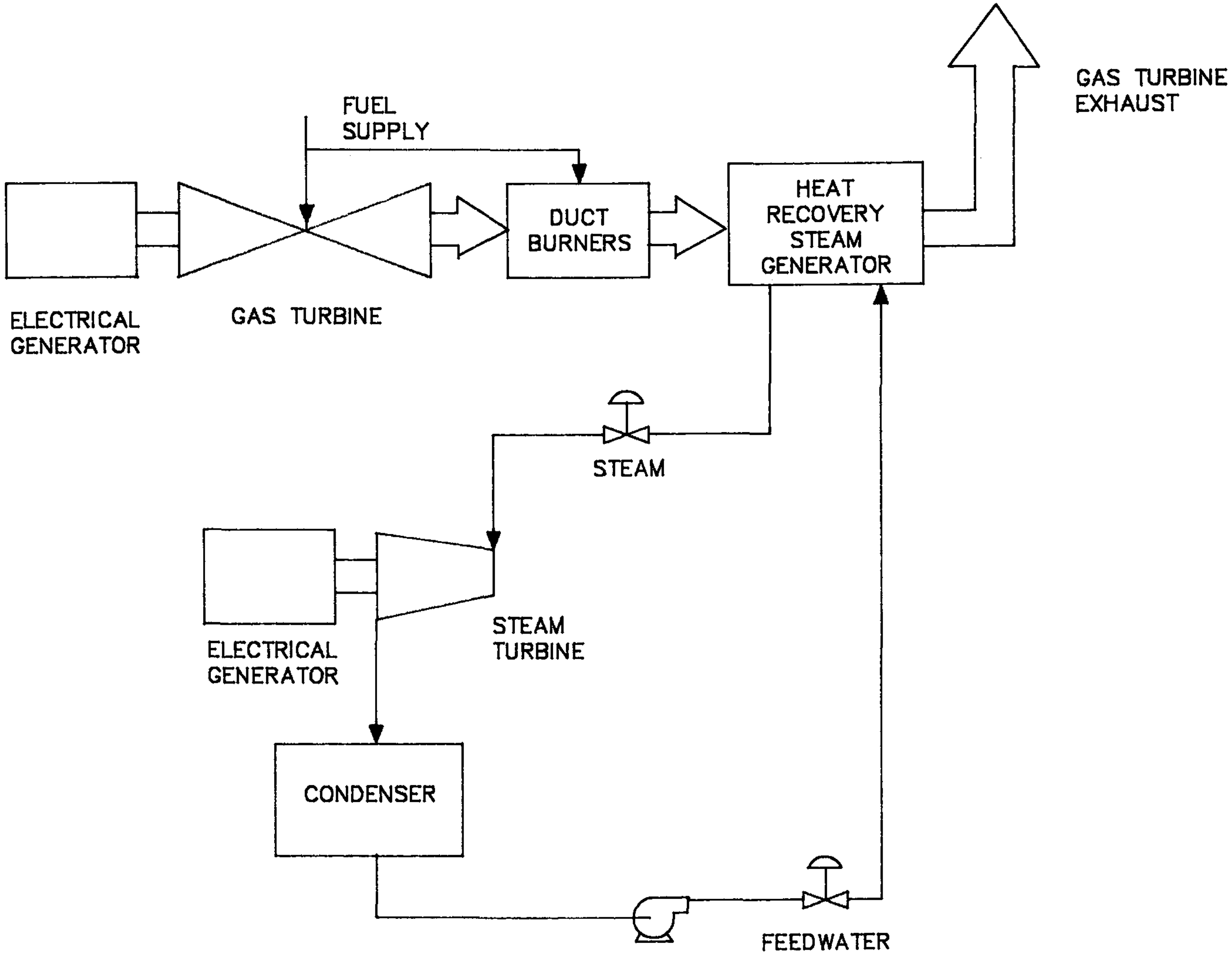

Figure 1-1. Combined-Cycle System

## Natural Circulation Drum-Type HRSG Design

HRSG designs typically seen in current utility applications are natural circulation or forced circulation drum-type boiler systems. A simplified schematic of a natural circulation system is shown in Figure 1-2. The drum-type HRSG has three distinct sections: the economizer, evaporator, and superheater. The economizer preheats the feedwater before it enters the evaporator. The evaporator section includes the steam drum, the convection tubes, and the downcomers. The steam from the evaporator section is further heated in the superheater section. Boiling occurs in the convection tubes, and differences in densities between the liquid in the downcomers and the two-phase mixture (liquid and vapor) in the convection tubes result in the natural circulation used in natural circulation boilers.* The steam drum allows the separation of vapor and liquid. A continuous blowdown is required to remove the dissolved and suspended solids that become concentrated in the steam drum as the liquid water is evaporated in the boiler system.

Drum-type HRSGs are typically arranged in the gas turbine exhaust duct in a counter-current flow configuration with the economizer section in the coolest part of the gas stream and the superheater section in the hottest part of the gas stream. In typical HRSG designs, the economizer and evaporator tubing are carbon steel materials and cannot be exposed to hot, dry operation because of temperature limitations of the material. If it is necessary to operate the gas turbine when the drum-type HRSG is out of service, a gas bypass system must be provided. Also, the use of carbon steel materials in the economizer forces the system to be designed to operate with exit gas temperatures greater than the acid dew point when using high-sulfur fuels. The drum-type HRSG designs typically include feedwater deaerators and oxygen-scavenging chemical treatment to minimize corrosion throughout the system. Feedwater flow into the HRSG is regulated on the basis of the liquid level in the steam drum and steam/feedwater flow comparisons.

## Solar Turbines HRSG Design

The Solar Turbines Incorporated's once-through HRSG concept is represented schematically in Figure 1-3. The HRSG consists of many parallel serpentine circuits fabricated from corrosion-resistant alloy 800 tubing. Only one circuit is shown in the figure.

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*In forced circulation drum-type boilers, a circulating pump forces drum water through the evaporator tubes.

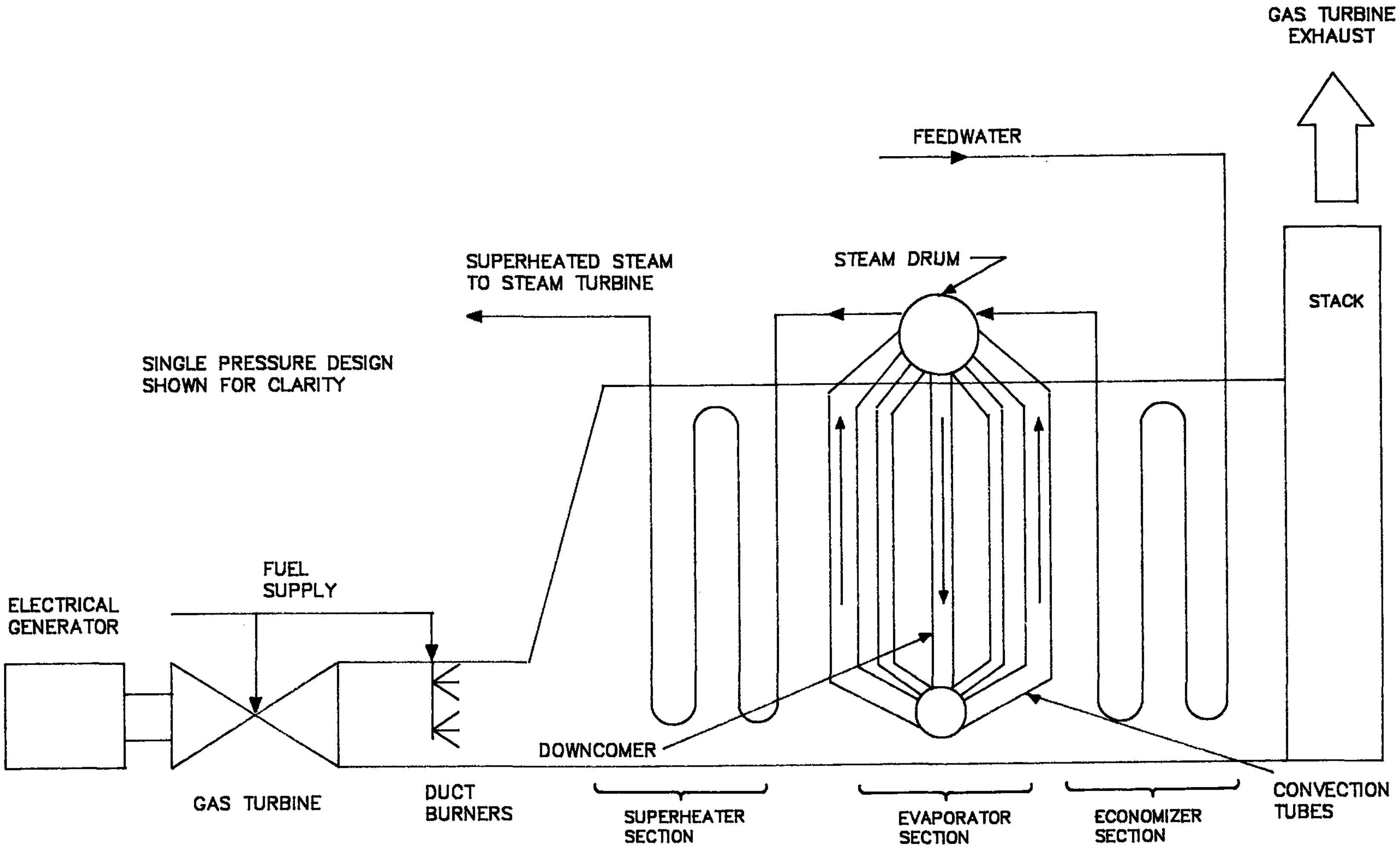

Figure 1-2. Natural Circulation Drum-Type HRSG

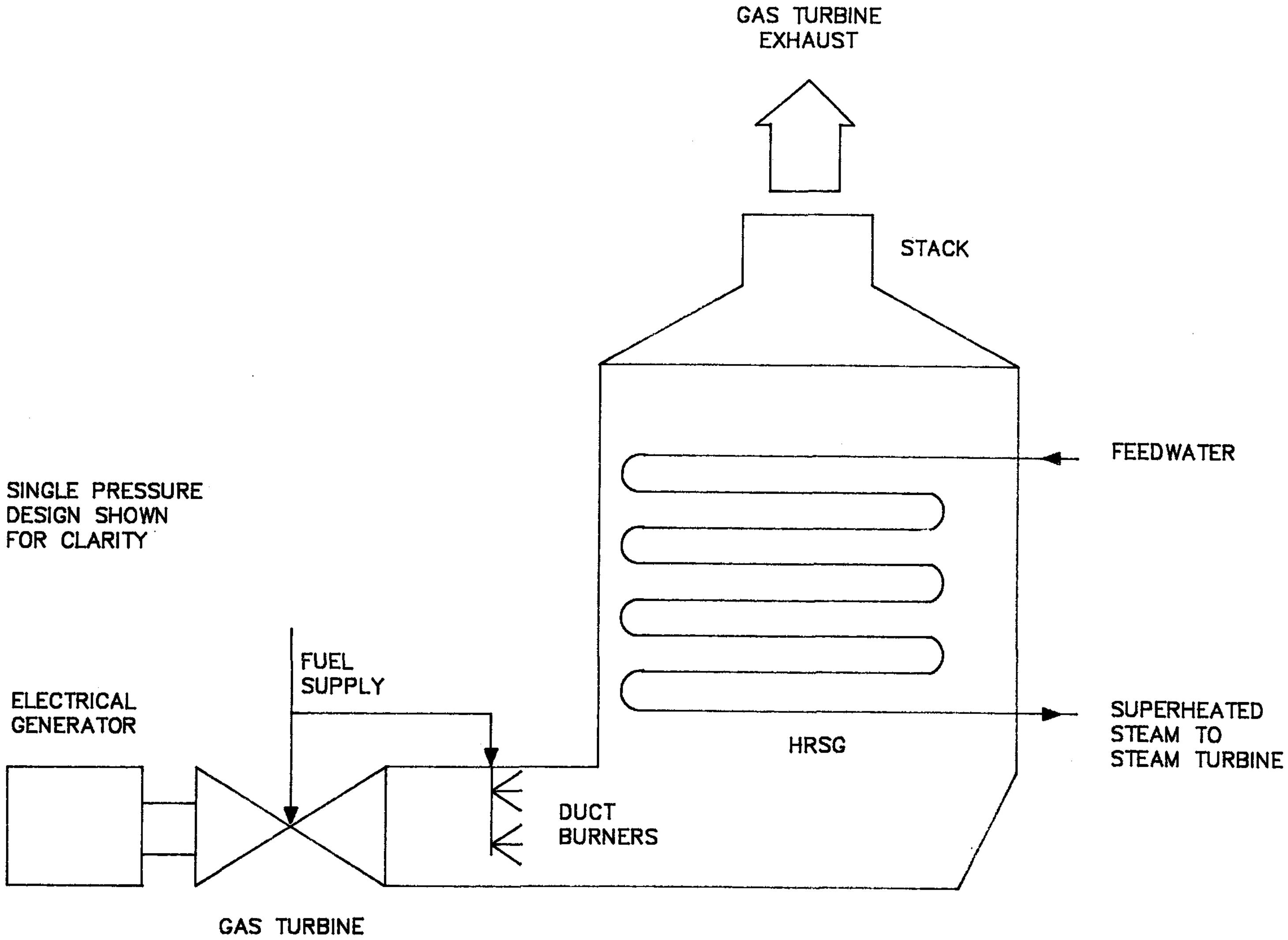

Figure 1-3. Solar Turbines Once-Through HRSG

The HRSG tube wall thickness in the Solar Turbines' design is significantly less than that typically seen in the drum-type HRSG designs with carbon steel tubes. This thinner wall results from the combined effects of smaller diameter tubes, the higher strength of alloy 800, and much lower corrosion and erosion allowance requirements.

The Solar Turbines HRSG is a countercurrent flow heat exchanger that converts feedwater into superheated steam. There are no physical distinctions between the economizer, evaporator, and superheater zones. These three zones can "float," depending on the heat transfer and thermodynamic balance of the system. Because of the float, any section of tubing can theoretically be a part of the economizer, evaporator, or superheater zones, depending on the operating conditions at any particular time.

The once-through design does not need a steam drum for separation of vapor from liquid, and accordingly, there is no requirement for blowdown. Everything that enters the once-through boiler with the feedwater (including all dissolved and suspended solids) either accumulates in the boiler or leaves the boiler in the superheated steam supplied to the steam turbine. The solids content in the feedwater must be kept extremely low to prevent problems in the boiler and steam turbine; consequently, a feedwater polishing demineralizer is required. It is stated by Solar Turbines that feedwater deaerators and oxygen scavenging chemical injection are not required if stainless steel piping and corrosion-resistant pump internals are used in the feedwater system between the demineralizer and the HRSG.

In the Solar Turbines HRSG, the feedwater flow is regulated to maintain the required outlet steam superheat condition. Accordingly, outlet steam temperature is the primary parameter measurement for feedwater control. System dynamics require a feed-forward control logic with feedwater flow and gas temperature as additional control input.

## PROJECT OBJECTIVES AND TECHNICAL APPROACH

The purpose of this project was to identify and evaluate the RAM characteristics of the Solar Turbines once-through HRSG design and to provide a comparison with drum-type boilers used in utility combined-cycle applications. This work was sponsored by EPRI as a part of the continuing efforts of EPRI to evaluate the Solar Turbines development of this concept for utility applications. Special emphasis was to be placed on information gathering and data development associated with those aspects of the design concept expected to be significant to system reliability and availability.

Information and assumptions relative to the design, operation, and maintenance of both the once-through HRSG concept and typical drum-type HRSG systems were obtained from EPRI, Solar Turbines, and Bechtel, as well as other industry sources. The data development efforts included a detailed investigation of the alloy 800 as it relates to this application. This investigation included a comprehensive review of literature dealing with the alloy and discussions with numerous material and industry experts.

Comparative availability analyses were completed for the once-through and drum-type HRSG designs using the UNIRAM* computer modeling methodology. UNIRAM uses component reliability and maintainability data as well as component and system fault tree logic to compute system availability. Availability models for both HRSG designs were developed based on specific design and operation assumptions specified by EPRI and Solar Turbines. Component reliability and maintainability statistics were developed using data from the EPRI Reliability Assessment System (ERAS).** Baseline and component criticality ranking analyses were completed. These analyses included an evaluation of the sensitivity of the once-through HRSG system availability to the reliability of the once-through boiler tubing.

## REPORT ORGANIZATION

Section 2 documents the investigation of the characteristics of alloy 800 when it is used as the tube material in the Solar Turbines once-through HRSG. This study included the review of numerous documents dealing with alloy 800. These documents are listed in a bibliography, included as Appendix A.

The results of the comparative RAM analyses of the Solar Turbines once-through HRSG and a representative drum-type HRSG design are presented in Section 3. That section also includes a review of the system designs and assumptions used as the bases for

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*UNIRAM is a computer modeling and analysis system developed by ARINC Research for EPRI for RAM evaluation of power generation systems.

**ERAS is a computer-based RAM data and analysis system based on outage and maintenance data provided by 11 utilities operating combustion turbines and combined-cycle power generation equipment.

the analysis and a description of the UNIRAM models developed for the two HRSG designs. The computer data input files for the UNIRAM models are included in Appendix B. Section 4 presents conclusions and recommendations resulting from this study.

## Section 2

## REVIEW OF ALLOY 800 TUBE MATERIAL CHARACTERISTICS IN THE ONCE-THROUGH HRSG APPLICATION

This section presents the results of an investigation of the characteristics of alloy 800 relative to its use as tube material for the Solar Turbines once-through HRSG. Alloy 800 is used with Solar Turbines' industrial cogeneration MARS and Navy ship heat recovery RACER versions of the once-through HRSG design. It was also selected for the utility version HRSG tube material to provide a corrosion-resistant system that eliminates or reduces corrosion problems typically seen with carbon steel tube systems. This material should also simplify over-all system design and operating requirements by eliminating the need for corrosion protection features and procedures, such as chemical injection, feedwater deaeration, and special shutdown and layup procedures. The use of this alloy instead of carbon steel also allows greater flexibility in operation, such as the capability of hot, dry operation.

The Solar Turbines HRSG design employs smaller diameter tubes than typically used in utility HRSGs, thus reducing the wall thickness requirements to meet the system pressure criteria. Alloy 800 also has much higher strength ratings than does carbon steel (according to the American Society of Mechanical Engineers [ASME]) and considerably greater resistance to corrosion and erosion (thus leading to smaller required thickness allowances). For these reasons, the Solar Turbines HRSG tube walls are significantly thinner than typical carbon steel HRSG tube walls.

The use of the thinner wall alloy 800 tubes, as well as unique HRSG design features and expanded operating capabilities, represents a significant departure from the carbon steel tube, drum-type systems currently used in utility applications. Alloy 800 is far superior to carbon steel in many areas, including resistance to general corrosion and erosion, and is apparently a good choice for this application. Even so, it is important to identify those characteristics of alloy 800 that may affect the ultimate service life of the once-through HRSG or lead to unavailability due to maintenance and repair requirements. It is also important to identify those areas where special attention may be required during the continuing design development and evaluation efforts to reduce the occurrence of in-service failures.

Accordingly, a significant portion of this contract effort was dedicated to the investigation of alloy 800 and its application in the Solar Turbines once-through HRSG design.

The information presented in this section includes an overview of the approach used in researching the characteristics of alloy 800 for this application; a description of the HRSG tubes and the anticipated operating conditions to which the tubing will be subjected; and a summary of the findings on alloy 800 performance characteristics, including both general characteristics and those specifically related to this application. Cited references are included at the end of this section. A comprehensive bibliography of literature collected and reviewed is included as Appendix A.

## OVERVIEW OF RESEARCH CONDUCTED

This review of alloy 800 was directed toward the following:

- The Solar Turbines HRSG design and operating conditions
- Testing and operating experience for the Solar Turbines HRSG
- Properties and performance characteristics of alloy 800
- Industry applications of alloy 800 and its performance in these applications
- Anticipated tube failure modes in the once-through HRSG

Emphasis was placed on corrosion, erosion, fatigue, and weld failures (the expected tube failure modes). Information collection efforts included interviewing known experts, technical societies, suppliers, users, and research and development (R&D) groups and reviewing appropriate reference literature. Meetings were held with representatives of Solar Turbines and the David Taylor Naval Ship Research and Development Center in Annapolis, Maryland, and numerous telephone conversations were held with industry and technical specialists. The literature search effort included a review of numerous technical papers and abstracts, conference proceedings, standard technical references, and alloy 800 supplier literature. Technical groups such as the American Society of Metals (ASM) and the National Association of Corrosion Engineers (NACE) were relied on as information sources.

The literature search resulted in the collection of approximately 80 technical papers as well as the complete proceedings of several technical conferences. Professional literature services were used to obtain abstracts for more than 500 additional related papers. A comprehensive bibliography of the published material reviewed in this investigation is included as Appendix A.

There are currently five full-scale commercial Solar Turbines once-through HRSGs in industrial service: two at the Phillips Gas Compression Station near Okarche, Oklahoma, and three at the Los Angeles Sanitation Cogeneration site. The Los Angeles units have been in operation a short time; however, the two Okarche units, downstream of natural gas-fired combustion turbines, have each achieved approximately 40,000 h of operation without any known tube failures. The information reviewed in this study included metallurgical reports on tube specimens removed from the Okarche units after approximately 9,000 h of operation (1). An attempt was also made to obtain data from Navy R&D efforts. The only such data available were the results of very limited stress corrosion cracking testing of alloy 800 at DTNSRDC. Although full-scale developmental Navy RACER tests have been initiated, no data were available for this study because of limited operation time.

These investigative efforts resulted in an understanding of the characteristics of alloy 800 and some insight into its expected performance in the Solar Turbines once-through HRSG. Another important result was the development of a comprehensive base of information and the identification of data sources that could support additional research in the development of the once-through HRSG concept or other EPRI projects concerned with the application of alloy 800.

There is an apparent lack of quantitative data on alloy 800 that was noted by almost all of the technical specialists interviewed and also in several of the references reviewed (2-5). In many cases, where quantitative data were presented, the information was either not conclusive or was not applicable to the once-through HRSG. As a result, some of the more significant findings from these investigations are qualitative in nature.

## HRSG TUBE DESIGN AND OPERATING CONDITIONS

The following paragraphs describe the design characteristics of the once-through boiler tubing and its expected operating conditions.

### Description of HRSG Tubes

The Solar Turbines once-through HRSG consists of many parallel serpentine tube circuits. Each circuit contains numerous 180° bends. The bend sections are attached to straight tube sections by butt welds, requiring two butt welds for each bend. Carbon steel, stainless steel, or alloy 800 fins are brazed onto the outside of the straight tube sections with a high-temperature nickel chromium braze alloy by a proprietary manufacturing process. Commercially standard dimensioned tubing is used, with typical nominal wall thicknesses of 0.049 in. (1.2 mm), 0.058 in. (1.5 mm), and 0.065 in. (1.7 mm), depending on the specific design requirements of the HRSG unit. Even when pressure rating calculations allow a thinner wall, 0.049 in. (1.2 mm) is the minimum wall thickness used because of fabrication and handling requirements. A corrosion allowance of 0.004 in. (0.10 mm) has been determined by Solar Turbines to be adequate for expected HRSG life; however, the actual thickness margin (over that required for the design pressure rating) is typically greater than the 0.004-in. (0.10-mm) corrosion allowance requirement because of the practice of using the next higher standard wall thickness. For example, in one typical design, an actual thickness margin of 0.011 in. (0.28 mm) exists (6). For comparison, the carbon steel tube wall thickness in the economizer and evaporation sections of a typical natural circulation drum-type HRSG in similar applications may range from 0.100 to 0.165 in. (2.54 to 4.19 mm), with 0.120 in. (3.05 mm) being a common thickness (7).

### Water/Steam Side Conditions and Operating Characteristics

The once-through HRSG design can be described as a continuous heat exchanger that converts entering feedwater to superheated steam. As with typical once-through boiler designs, there are no blowdown streams, and consequently, everything that enters the boiler either accumulates in the boiler or passes through to the steam turbine. The HRSG can be divided into three zones: (1) the all-liquid economizer zone, (2) the mixed-phase evaporating or boiling zone, and (3) the all-steam superheating zone. The location of the boiling zone is not fixed and may float between the inlet and outlet as determined by the heat balance at any specific time. The entering feedwater temperature will be on the order of 100°F (40°C) or slightly higher (based on the condenser hotwell temperature plus a small temperature rise due to the feed pumps), and the superheated steam temperature at the outlet will be on the order of 1000°F (540°C). System pressures may range from 50 to 1500 psig (340 to 10,300 kPa), resulting in boiling temperatures of 300° to 600°F (150° to 320°C) in the evaporating zone. Because all of the entering water is boiled dry, the feedwater must be demineralized. The demineralized feedwater will have a total dissolved solid content on the order of 10 to 20 parts per billion (ppb). In the boiling zone, local dissolved solids concentration may be considerably higher than this at some locations as the water is evaporated. The solids remaining after evaporation, which may contain chlorides, will either pass through the steam generator with the superheated steam to the steam turbine or will be deposited as scale in the HRSG tubing. The anticipated typical Solar Turbines once-through HRSG system design will not include a feedwater deaerator or chemical injection in the feedwater or boiler systems. Demineralization is the only expected water treatment. Liquid velocities will be on the order of 2 to 3 ft/s (0.6 to 0.9 m/s), and steam velocities will be on the order of 100 ft/s (30 m/s) in the HRSG tubing.

### Gas-Side Conditions

The gas turbine fuel typically will be low-sulfur natural gas, although higher sulfur fuels may be used in some applications. The hot gas temperature will be on the order of 1100°F (590°C). Soot may accumulate on the cold end of the HRSG during operation in liquid fuel applications. The HRSG is capable of hot, dry operation; it is recommended to occasionally operate in this mode to "cook-off" soot, if it accumulates, rather than using soot blowers. In certain operating conditions with high-sulfur fuels, the tubing temperatures may be lower than the sulfuric acid dew point, thereby allowing sulfuric acid to collect on the outside of the economizer (preheater) section of the HRSG tubing. During shutdown periods, the tubing may be exposed to moisture and, possibly, sulfuric acid for extended periods of time.*

## ALLOY 800 CHARACTERISTICS AND EXPECTED PERFORMANCE

The following subsections summarize the results of the review of alloy 800 in general and the specific characteristics of this alloy relative to the tube failure modes in the once-through HRSG application.

### Description of Alloy 800

Alloy 800 is a nickel alloy widely used in industry applications requiring high-temperature strength and resistance to corrosion. Its composition, as specified by

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*Even with the use of the corrosion-resistant alloy 800 tubes in the once-through HRSG design, it may be advisable to employ simple procedures to minimize the exposure of the once-through HRSG to condensed sulfuric acid during shutdown periods when using high sulfur fuels. Two possible approaches would be to water-wash the unit to remove soot and condensed sulfuric acid from the HRSG at the beginning of the shutdown period or to run the unit dry for a short period before shutdown to cook off accumulated soot. (Soot tends to absorb condensing sulfuric acid, thus increasing the corrosive effects.) In any case, it is important to keep the unit as dry as possible during the shutdown period. The concerns of acid corrosion during shutdown periods are obviously much greater with carbon steel drum-type units.

ASME for use under Section I of the ASME Boiler and Pressure Vessel Code (8), is shown in Table 2-1.

Table 2-1

ALLOY 800 CHEMICAL REQUIREMENTS

| Constituent | Percentage |
|---|---|
| Nickel | 30.0-35.0 |
| Chromium | 19.0-23.0 |
| Iron | 39.5 minimum |
| Carbon | 0.10 maximum |
| Manganese | 1.50 maximum |
| Sulfur | 0.015 maximum |
| Silicon | 1.00 maximum |
| Copper | 0.75 maximum |
| Aluminum | 0.15-0.60 |
| Titanium | 0.15-0.60 |

As listed in Table 2-1, iron, nickel, and chromium are the major constituents of this alloy. Aluminum and titanium are also required in very small quantities. In vendor literature, alloy 800 is briefly described as being "strong and resistant to oxidation and carburization at elevated temperatures" and resisting "sulfur attack, internal oxidation, scaling, and corrosion in a wide variety of atmospheres" (9).

Alloy 800 was developed in 1949 by the International Nickel Company, Inc., for use as sheathing for electric heating elements. The trade name for this alloy as marketed by Inco Alloys, Inc., a subsidiary of the International Nickel Company, is Incoloy 800. This alloy is currently offered by several suppliers under the generic designation of alloy 800, and it is covered by various ASTM specifications and Sections I, III, and VIII of the ASME Boiler and Pressure Vessel Code.

Currently, alloy 800 is used extensively in a variety of high-temperature applications that require a high degree of corrosion resistance. Major applications include:

- Heat-treating material support hardware
- Pyrolysis tubes in ethylene furnaces
- Headers and pigtails in steam/hydrocarbon reforming processes
- Superheater and reheater tubes in fossil-fuel power plants
- Various components in developmental coal gasification processes
- Superheater and reheater tubes in high-temperature gas reactor (HTGR) nuclear power plants
- Steam generator tubes in pressurized water reactor (PWR) and sodium-cooled reactor nuclear power plants

The general characteristics of alloy 800, as cited by the literature, include:

- Good high-temperature strength properties
- Resistance to general corrosion in various environments
- Susceptibility to attack by certain acids, including sulfuric acid
- Resistance to stress corrosion cracking from chlorides and caustics
- Susceptibility to crevice corrosion and pitting in chloride environments
- Tendency to become sensitized (susceptible) to intergranular corrosion when exposed to temperature of 1000°F (540°C) and higher
- Susceptibility to cracking at welds if common industry welding practices are followed; good success with welding can be achieved if appropriate procedures are followed and precautions are taken

Most of the current R&D related to the properties of alloy 800 appear to be associated with the nuclear industry and the developmental coal-conversion technologies. Much of the nuclear-related R&D effort is directed toward minimizing or preventing tube failures due to stress corrosion cracking and other corrosion mechanisms in PWR steam generators. Limited data exist to help understand the various corrosion processes and other potential failure mechanisms of alloy 800 used in boiler tube applications. Some of the likely failure modes under expected HRSG operating conditions are discussed below.

Performance Characteristics of Alloy 800 Relative to Tube Failure Modes

The following categories of tube failure modes for the Solar Turbines HRSG are anticipated:

- Corrosion
- Erosion
- Fatigue
- Weld failures

Each failure mode of alloy 800 is described in the following subsections.

Corrosion. There are five types of corrosion to be considered:

- General corrosion
- Stress corrosion cracking
- Intergranular corrosion
- Crevice corrosion
- Pitting

The primary cause of general corrosion in any HRSG is the exposure to sulfur products on the gas side of the tubing, which is a function of the sulfur content of the gas turbine fuel.* With low-sulfur fuels, this corrosion is minimal. The gas side of the once-through HRSG tubing may be exposed to sulfur in two forms: as gaseous $SO_2$ and as condensed sulfuric acid when tube surface temperatures fall below the acid dew point. The presence of soot on the cooler portions of the HRSG may increase the exposure to sulfuric acid by absorbing the acid. The condensed acid can stay on the tubing for long periods of time during shutdown periods.** Various industry applications with exposures to $SO_2$ and $H_2S$ at elevated temperatures indicate corrosion rates for alloy 800 of 0.0001 to 0.003 in. (0.0025 to 0.076 mm) per year (3, 10, 11). Vendor literature notes that alloy 800 can be affected by sulfuric acid (11), but no corrosion rates were provided. The inference can be drawn that general corrosion may have some effect on the alloy 800 HRSG service life in high-sulfur applications with conditions conducive to the formation of sulfuric acid. However, alloy 800 is far superior to carbon steel with respect

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*Water-side general corrosion is also a concern in carbon steel tube HRSG systems when feedwater treatment problems are experienced (such as ineffective deaeration).
**See footnote on page 2-5.

to resistance to sulfuric acid attack, and accordingly, the expected in-service life of the alloy 800 HRSG should be significantly better than carbon steel tube HRSGs under these conditions. Most applications for the once-through HRSG are expected to be with low-sulfur fuels; therefore, it is doubtful that sulfuric acid corrosion will be a concern in commercialization of this design.

In the Solar Turbines HRSG application it was assumed that stress corrosion cracking (SCC) concerns are limited primarily to corrosion caused by exposure to chlorides. Chlorides can be present in the relatively concentrated solids at certain locations in the evaporating zone of the steam generator. Chlorides can also be present on the gas side, especially if the atmosphere surrounding the plant has high levels of salt concentration, as could be the case in a coastal area. Chlorides also can be introduced through water injection and evaporative cooler systems on the combustion turbine. Alloy 800 generally is considered to be resistant to SCC in chloride environments (11, 12), although SCC failures have been noted in nuclear applications (13, 14). SCC test data in the literature showed mixed results on the susceptibility of alloy 800 to chloride SCC (15, 16). In some cases, tests were conducted for up to 10,000 h without SCC occurring (15). Other tests showed SCC occurring within one week (16). Limited SCC tests were conducted at the David Taylor Naval Ship Research and Development Center during which SCC could not be induced in alloy 800 specimens in chloride solutions in tests lasting up to 7500 h (17).

Alloy 800 may become sensitized to intergranular corrosion upon exposure to temperatures of approximately 1000°F (540°C) and higher (11, 18). The HRSG tubing will exceed this temperature during hot, dry operating modes. Also, sensitization can occur in localized regions during welding. When sensitized, the material is susceptible to intergranular corrosion in aggressive environments. The degree of sensitization is both temperature- and time-dependent; the relationship is fairly complex and continued exposure to high temperatures may eventually permanently desensitize the material.* It should be noted, however, that even when sensitized,

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*The degree of sensitization of alloy 800 increases with high-temperature exposure time up to a limiting state (depending on the temperatures) beyond which continued exposure to elevated temperatures causes the material to return to a desensitized state, thus regaining the corrosion-resistant qualities lost when becoming sensitized. For example, alloy 800, which has been annealed at 2000°F (1090°C) during manufacture, will become sensitized after about 400 h of service at 1000°F (540°C) and will become desensitized after 200,000 h of service at the same temperature [1000°F (540°C)]. These respective times change significantly when exposed to temperatures of 1100°F (590°C); the time required to become sensitized is approximately 10 h, and the time required to become desensitized is on the order of 20,000 h. At 1400°F (760°C), these times become 15 min and 3 h, respectively. At 1500°F (820°C) the alloy never experiences the sensitized state (18).

the resistance of alloy 800 to intergranular corrosion exceeds that of 300 series stainless steels.

The literature indicates that alloy 800 is susceptible to crevice corrosion in the presence of chlorides (11, 19). The Solar Turbines HRSG has been designed to minimize built-in crevices on the inside of the tubing. Crevice conditions can exist, however, under scale deposits, in weld cracks (discussed later in this section), and at various locations on the outside of the tubing (e.g., where the fins are attached).

Alloy 800 is indicated to be susceptible to pitting corrosion in chloride environments (4, 16, 19). The literature identifies this as a concern in PWR steam generator applications; and it is noted that there is a significant lack of data on the pitting resistance of alloys such as alloy 800, especially in low chloride applications (4). The results of a pitting corrosion test for alloy 800 show pit growth rates ranging from 2 to 10 mils (0.05 to 0.25 mm) per year in "steam blanket" locations on simulated PWR steam generator tube sections and that the pitting was more prevalent at crevice locations (20).

During the study, it was noted by one material specialist that whether or not chloride contamination is present, alloy 800 can be susceptible to cracking when stressed under oxidizing conditions with crevices and grain boundary chromium depletions (21). Therefore, it should not be inferred that the presence of chlorides is necessary for the initiation of the various corrosion mechanisms previously discussed.

As a final point related to corrosion and the once-through HRSG design, several technical specialists indicated that demineralizer breakdown products may be corrosive to the HRSG tubing. This should be investigated further when specifying demineralizer system equipment and resins. If demineralizer options are available, design decisions should be made that minimize this possible source of corrosion in the HRSG.

Erosion. The types of tubing erosion damage to be considered in the Solar Turbines HRSG application include the following:

- Water and steam flow erosion in the "all liquid" and "all steam" flow zones

- Liquid (or particulate) impingement and liquid cavitation
- Gas side erosion

The examination of tube specimens removed from the Okarche steam generator after 9000 h of operation showed no evidence of water or steam flow erosion on the inside of the tubes or erosion on the outside (gas side) of tubes. The inside surface of one circuit at the inlet location showed distress that could have resulted from impingement erosion (1); however, it is also possible that this indication could have been an original manufacturing defect occurring during the drawing of the tube. During normal operation, this part of the steam generator sees "all liquid" flow at relatively low velocities. During certain startup modes, it is possible for steam flashing to occur at this location, which may result in liquid entrainment in the higher velocity steam flow. The Okarche report also suggests the possibility of solid particulates (from an unexplained source) causing impingement damage. Another possible explanation could be liquid cavitation during certain operating modes. Liquid cavitation damage can be described as a form of liquid impingement damage (22).

Several sources dealing with the topic of erosion and erosion/corrosion (a corrosion phenomenon enhanced by erosion activities) of alloy 800 were reviewed. All of the investigations documented by these sources, however, were for severe applications, such as coal conversion processes, which are very different from the Solar Turbines HRSG application. No source was found with erosion data for alloy 800 (or similar materials) applicable to the Solar Turbines HRSG. Limited information was obtained from telephone conversations with various technical specialists (19, 23). These conversations confirmed that applicable data probably do not exist, because the erosion of alloy 800 or other similar materials in similar industry applications (with relatively low water, steam, and particulate-free gas flow velocities) has never been a concern and, therefore, has never been an area of study. The erosion rate of all chrome-bearing alloys with "normal" water and steam flow velocities has always been considered by industry to be negligible. The flow velocities in the Solar Turbines HRSG application are well within the "normal" acceptable velocity limitations.

Specific data were obtained during one conversation on the results of high-velocity seawater tests recently conducted by the Navy for alloy 800 in hydrofoil applications (19). The results of these tests showed that there was no detectable erosion with seawater velocities up to 120 ft/s (37 m/s). Erosion was noted for velocities greater than 150 ft/s (46 m/s). From those findings, it could be inferred that water flow erosion is unlikely in the Solar Turbines HRSG if velocities never reach 120 ft/s (37 m/s). This would apply even to water slugs entrained in steam flow if steam flow rates are kept at less than 120 ft/s (37 m/s). Available design information indicates that water and steam flow velocities in the Solar Turbines HRSG are on the order of 3 ft/s (0.9 m/s) and 100 ft/s (30 m/s), respectively.

It was the general opinion of the various specialists contacted that tube failures caused by water or steam flow erosion will not occur in the Solar Turbines HRSG despite the thinner wall tubing and the large number of 180° bends in the serpentine configuration. Several of the specialists interviewed said that liquid impingement and cavitation, however, may have some effect over the life of the unit, especially due to the thinner wall tubing design. Damage rates, however, would be unpredictable, because neither applicable data nor analytical models exist. Gas-side erosion may be a concern with the tubing if high gas velocities with particulate loading exist in local areas (<u>19</u>). No further information was obtained on gas-side erosion, because erosion data for alloy 800 in clean gas-flow environments (without abrasive particulates) were not available.

As noted with general corrosion, alloy 800 has considerably greater resistance to erosion effects than does carbon steel, and accordingly, it would be expected that the alloy 800 HRSGs would perform better than carbon steel tube HRSGs, where the same erosive conditions exist.

Fatigue. The Solar Turbines HRSG tubing will experience cyclic loading due to thermal stresses and system pressurization during startup and shutdown events. Cyclic thermal stresses can also be caused by load fluctuations and floating of the boiling zone during steady-state operation. Fatigue or rupture failures would be a possible failure mode for the HRSG tubing if the mechanical limitations of alloy 800 are exceeded. However, the mechanical properties of alloy 800 seem adequate for the circumstances according to well-substantiated data. As can be seen from the following information, a tube failure due to fatigue or creep rupture appears to be unlikely if the HRSG is designed in accordance with ASME code limitations.

The maximum operating temperature of the Solar Turbines HRSG tubing is expected to be about 1000°F (540°C). A fatigue strength of 38,000 psi (262,000 kPa) is indicated for alloy 800 at 1000°F (540°C) with a life of 100 million cycles (11). The number of stress load cycles during a 30-year life for the Solar Turbines HRSG would be expected to be much less than 100 million. The rupture strength of alloy 800 at 1000°F (540°C) over 300,000 h (34 years) is shown as 24,000 psi (165,000 kPa) (24). The maximum allowed design stress for alloy 800 at 1000°F (540°C), according to the ASME Boiler and Pressure Vessel Code (8), is 14,700 psi (101,400 kPa). Assuming that the Solar Turbines HRSG is designed in accordance with the ASME code requirements and that the maximum allowed stresses are not exceeded during any operating mode, it appears that a tube failure due to mechanical fatigue would not be expected during a 30-year operating life.

Cracking failures have occurred in alloy 800 applications as a result of cold-work residual stresses (25). This problem can be prevented by appropriate heat-treating procedures. Solar Turbines manufacturing procedures currently include the annealing of tube bend sections to relieve stresses developed during the bending process.

Weld Failures. The literature indicates that welding is an area of concern with all nickel alloys and especially with alloy 800. This concern is substantiated by evidence that cracks were found in approximately half of the welds examined in the tube specimens removed from the Okarche steam generator (1). It was determined that these cracks were associated with incorrect current tail-off rates at the end of the circumferential welds. Solar Turbines claims to have corrected these procedures. Solar Turbines also claims that the discovered cracks would not have propagated or resulted in tube failure. At this writing, more than 40,000 h of operating time has been accumulated by this steam generator without such a tube failure.

Cracking at welds is not uncommon with alloy 800, and there may, in fact, be a definite tendency toward this problem (2, 26-28). The welding of alloy 800 requires weld procedures very different from and more sophisticated than the welding of steel. Improper weld procedures will result in cracks at the weld and heat-affected zone (26, 28). The allowable variations in alloy composition also can be a significant cause of faulty welds with alloy 800 (5). A general lack of information on the welding characteristics of alloy 800 is noted in the literature (2, 5, 26).

In reviewing the tube welding concerns, it is appropriate to look at the comparison between the Solar Turbines design (with alloy 800 tubes) and a typical carbon steel drum-type system. The number of tube welds in the drum-type HRSG is comparable with that of the Solar Turbines HRSG. Solar Turbines uses a single-pass, automated welding process that inherently provides consistency in the type of weld produced;

multiple-pass manual welding techniques are used with the thicker wall carbon steel tubes in the drum-type boiler, which can lead to variations in weld quality.

The presence of weld cracks in either design type (alloy 800 tubes or carbon steel tubes) conceivably could lead to tube failure problems, including fatigue (due to stress concentrations at the cracks), crevice corrosion, and erosion caused by steam leaking from cracks that fully penetrate the tube wall. The significance of the potential problems associated with welds is compounded by the large number of welds in a steam generator unit. These potential failure problems can be prevented by the use of appropriate welding and nondestructive testing procedures. The extent of nondestructive testing applied would probably be governed by the trade-off between increased manufacturing costs and cost benefits realized.

### Information and Data Source Summary

Table 2-2 lists the references cited for each of the failure modes reviewed in the preceding discussions.

Table 2-2

DATA SOURCES FOR FAILURE MODES

| Failure Mode | References |
|---|---|
| General Corrosion | 3, 10, 11 |
| Stress Corrosion Cracking | 11, 12, 13, 14, 15, 16, 17 |
| Intergranular Corrosion | 11, 18 |
| Crevice Corrosion | 11, 19 |
| Pitting Corrosion | 4, 16, 19, 20 |
| Erosion | 1, 19, 22, 23 |
| Fatigue | 11, 24, 25 |
| Weld Failures | 1, 2, 5, 26, 27, 28 |

Additional Comments

In conjunction with the ARINC Research investigation of alloy 800 characteristics, Bechtel provided the following relevant comments (paraphrased by ARINC Research in this report):

1. Weld Cracking. The most effective way to prevent weld cracking is to use proven and qualified welding and nondestructive examination techniques. Most users of alloy 800 have established qualified procedures to mitigate weld cracking.

2. Attack by Sulfuric Acid. Alloy 800 is resistant to only low concentrations of sulfuric acid. However, there is little need to be concerned about attack by high concentrations of sulfuric acid, because commercial grades of natural gas contain low statutory limits of sulfur. Furthermore, there have been no reported incidents of sulfuric acid attack on alloy 800 during downtime in flue gas generated by burning natural gas. If fuel oils, such as No. 2 and No. 6, and coal gasification products are used, the quantity of sulfur can be limited. If higher sulfur fuels are used, it is suggested that shutdown procedures be used to prevent sulfuric acid attack by avoiding buildup of corrodents. For example, the procedures stated in National Association of Corrosion Engineers (NACE) procedure RP-01-70, "Protection of Austenitic Stainless Steel in Refineries Against Stress Corrosion Cracking by Use of Neutralizing Solutions During Shutdown," may be modified for use during extended shutdowns. Laboratory testing to quantify corrosion rates of alloy 800 may not be necessary.

3. Chloride Pitting, Crevice Corrosion, and Stress Corrosion Cracking. Alloy 800 is more resistant to chloride corrosion than the more common 18-8 stainless steels. The probability of such corrosion problems is low if the water chemistry is controlled. However, the probability would increase with crevices and scale buildup.

4. Sensitization. Control of the welding process (heat input) is required to minimize sensitization effects. However, the solution heat treatment, which is the only way to reverse sensitization, may not be possible with field-erected equipment. Weld sensitization problems can be mitigated by both fabrication and HRSG operation controls. During fabrication, low-heat input welding procedures should be required, and HRSG startup and shutdown procedures (as discussed above) to prevent corrodents from accumulating may be necessary.

## SUMMARY

The current industry uses of alloy 800 in high-temperature corrosive applications indicate that this alloy is a good choice for the once-through HRSG design. Full-scale operation of this HRSG concept with the alloy 800 tubes has been demonstrated only to a limited degree; however, it is noteworthy that two industrial full-scale, once-through HRSGs (with alloy 800 tubes) have, as of December 1987, each seen approximately 40,000 hours of operation with no known tube failures.

During this research effort, it was found that a considerable number of technical sources on alloy 800 exists; however, quantitative data relevant to the reliability of this tubing material in the once-through HRSG application is lacking. The information obtained indicates that in low-sulfur fuel applications, the alloy 800 tubing should be expected to perform well with respect to general corrosion, erosion, and fatigue. Alloy 800 may be susceptible to pitting and crevice corrosion effects if certain conditions exist, and high-sulfur applications may require special attention to ensure that sulfuric acid attack is not a problem. The literature and once-through HRSG manufacturing experience both indicate that weld cracking can frequently occur if improper welding techniques are used. The examination of tube specimens from an operating HRSG has resulted in the discovery of inside surface indications that suggest the possibility of impingement or cavitationeffects; however, no other evidence or data have been discovered to verify this interpretation.

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## Section 3

## HRSG SYSTEM ANALYSIS

This section presents the results of an analysis that compared the predicted availability of the Solar Turbines once-through HRSG, based on component reliability and maintainability characteristics, with that of a natural circulation drum-type HRSG. The UNIRAM computer modeling methodology was used in performing this analysis. The outage and maintenance data from 28 HRSG units operated by utilities cooperating with the ERAS project were used in developing failure rate and mean downtime statistics for the UNIRAM models.

The design characteristics of the most current Solar Turbines HRSG concept and modern drum-type HRSG configurations were reviewed. While working closely with EPRI and Solar Turbines, appropriate design bases and assumptions were developed for this analysis. The design review identified RAM characteristics and considerations of the once-through HRSG concept relevant to its comparison with drum-type HRGSs. UNIRAM models were developed for both once-through and drum-type HRSG designs. The UNIRAM analysis quantified expected HRSG availabilities and identified the relative effect of each component on HRSG availability. The UNIRAM analysis also quantified the sensitivity of the Solar Turbines HRSG system availability to the reliability of the once-through boiler tubing.

This section includes a description of the once-through and drum-type HRSG configurations reviewed in this analysis, design review discussions of the two designs relevant to RAM considerations (a detailed review of reliability considerations of the once-through HRSG tubing is presented in Section 2), a review of the UNIRAM models and input data developed for both HRSGs, and the UNIRAM analysis results. The UNIRAM computer input data files are presented in Appendix B.

### ANALYSIS SCOPE

Diagrams of the drum-type and once-through HRSG systems included in this analysis are presented in Figures 3-1 and 3-2. The UNIRAM analysis was limited to the feedwater system and components within the HRSG system and excluded plant operational variables, such as scheduled maintenance and reserve shutdown hours.

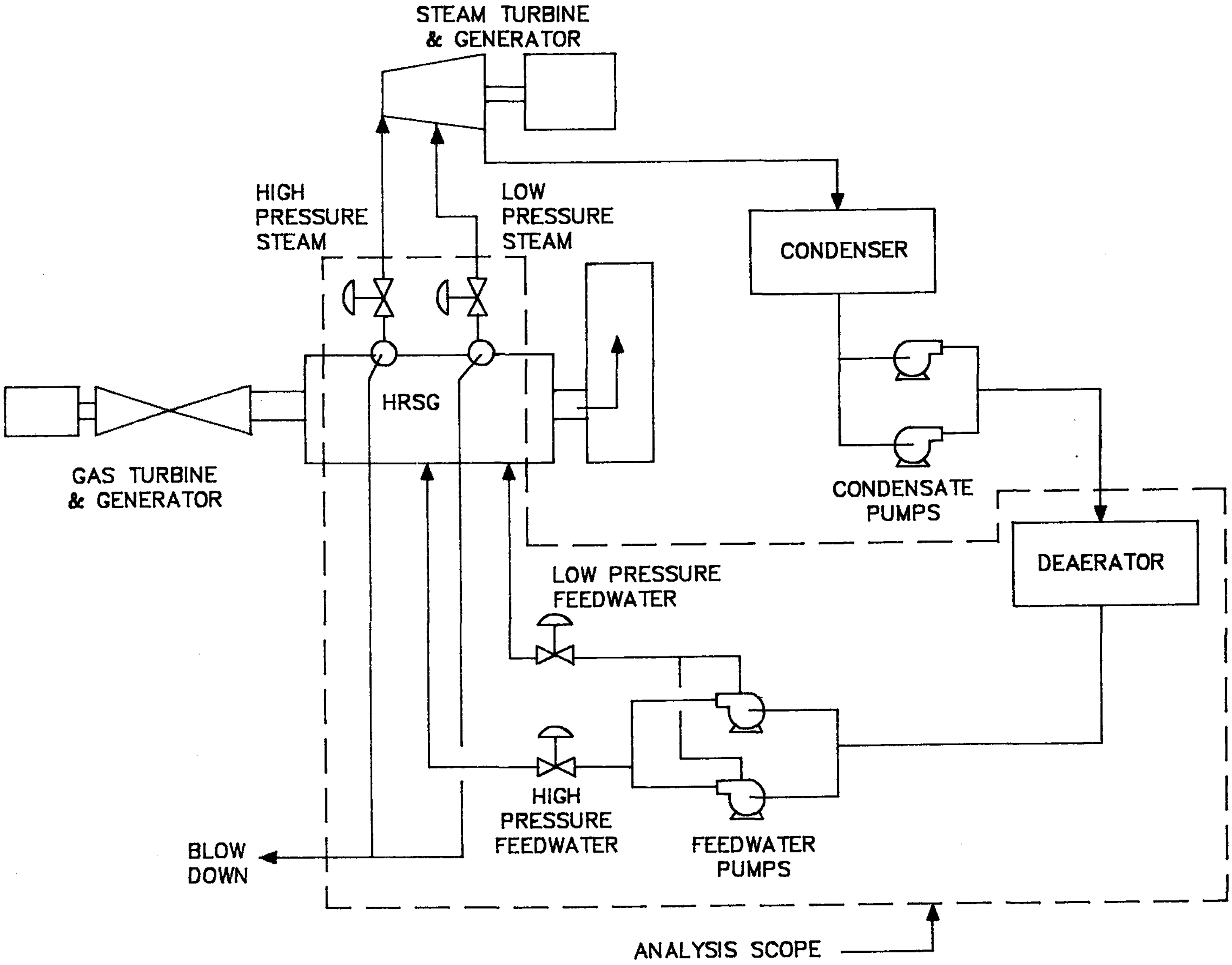

Figure 3-1. Dual Pressure Drum-Type HRSG System Diagram

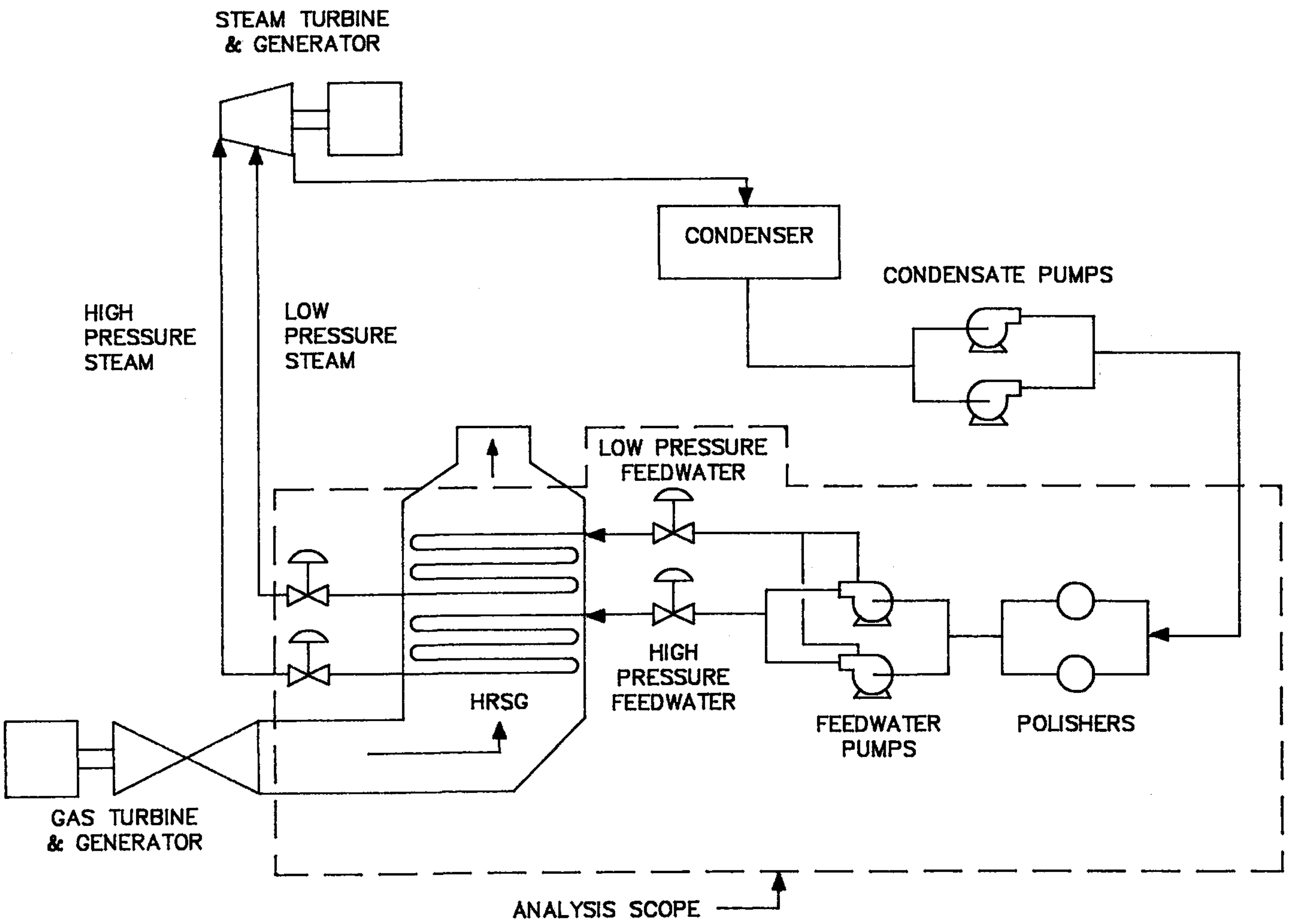

Figure 3-2. Dual Pressure Once-Through HRSG System Diagram

Dual-pressure systems were assumed for both HRSG designs to be consistent with modern HRSG installations. In addition to major differences between the boiler design for the two HRSGs, the analysis models also included different feedwater system components. As seen in the figures, a feedwater deaerator was included in the drum-type system but not in the once-through system. Similarly, the once-through system includes feedwater polishers that are not required in the drum-type design. These differences are discussed later in this section.

## DESIGN REVIEW DISCUSSIONS

The following subsections review RAM considerations of the once-through HRSG design and its comparison with drum-type systems. This information is presented under four topic areas: feedwater system; boiler; HRSG instrumentation and controls; and HRSG piping, valves, and ductwork. As evidenced in the description of the UNIRAM model (presented later in this section), these categories are consistent with the UNIRAM model structure used in this analysis.

### Feedwater System

There are major differences in the feedwater treatment requirements of the typical drum-type HRSG installations and the once-through HRSG design.

Drum-type systems typically have carbon steel feedwater piping as well as carbon steel economizer and evaporator tubing and steam drums. Corrosion of these components is minimized by deaeration of the feedwater and the addition of chemicals. Some deaeration occurs in the condenser, but most drum-type systems intended for cyclic operation also require a separate deaerating feedwater heater. The deaerators are frequently a source of maintenance problems. Some modern drum-type HRSG designs intended only for base-load operation eliminate this separate deaerator, relying on the deaeration that occurs in the condenser. The deaeration limitation of the condenser inhibits the operation of these HRSGs at reduced loads typical of cyclic operating modes. Because of the expected operation flexibility of the once-through HRSG, it is appropriate to compare the once-through HRSG with drum-type systems that include feedwater deaerators and are thus capable of both cyclic and base-load operation.

The feedwater purity requirements (with respect to dissolved solids) are very stringent in the once-through HRSG. The once-through design requires the addition of full-flow feedwater polishers upstream of the boiler feed pumps to maintain the solid content low enough (50 ppb or less) to protect the boiler and steam turbine.

This water quality requirement is typical of requirements for super-critical, once-through boiler systems that are fired by fossil fuels. Polishers are not required in drum-type HRSG systems. The polishers included in the current Solar Turbines HRSG concept are mixed-bed, nonregenerative demineralizers. Two 100% capacity demineralizers are included to allow replacement of the spent resin in one demineralizer while the HRSG system is operating. The use of nonregenerative demineralizers improves system reliability by eliminating the need for on-line chemical regeneration systems.

The Solar Turbines HRSG concept also includes the use of stainless steel piping and 12% chrome pump internals in the feedwater system between the polishers and the HRSG. By using the corrosion-resistant materials in the feedwater system and the HRSG, Solar Turbines states that deaeration provided by the conventional condenser is adequate for all operating conditions. Accordingly, the Solar Turbines HRSG design does not include a separate feedwater deaerator. Also, the use of corrosion-resistant materials results in the statement by Solar Turbines that the addition of chemicals for corrosion control is not required.

The following comments need to be made regarding the full-flow demineralizers and the possibility that addition of chemicals may actually be required. The use of chemicals for corrosion and pH control may have a detrimental effect on the demineralizer resins that may lead to further complications. For example, hydrazine, a chemical commonly used for this application, leads to the formation of ammonia in the system, which in turn may cause a rapid depletion of the demineralizer resin. As the resin becomes depleted, it tends to break down into small particles that may be carried past filters into the feedwater system. It is suspected that the deposition of these spent resin particles in piping systems may contribute to corrosion in some cases. These potential concerns should be taken into consideration when specifying and sizing the polishing demineralizers in the once-through system, especially if oxygen scavenging or pH control is included in the design.

### Boiler

The configuration differences between the once-through and drum-type boilers were described in Section 1. Reliability considerations of the once-through boiler tubing were discussed in detail in Section 2. The following is a review of maintainability characteristics of the once-through design.

The principal difference in boiler tube maintainability between the once-through and drum-type designs is the accessibility to individual tubes for repair. The Solar Turbines HRSG consists of several parallel modules, with each module containing many parallel serpentine tube circuits. With the current Solar Turbines design, the primary approach to tube repair is to plug (by welding) both ends of the leaking tube circuit. It is assumed that the once-through boilers will be sufficiently oversized to allow tube plugging without causing a derating over the life of the boiler. The inlet end of each tube circuit is readily accessible through a flanged connection at the feedwater inlet to each module. Because of an all-welded construction concept on the steam side of the HRSG, access to the outlet end of each tube circuit requires entering the boiler casing by cutting and rewelding the casing or by using man-ways, if provided. Once inside the casing, the outlet end of each tube is accessible without having to remove adjacent tubes. Solar Turbines design enhancements currently being considered include redesigning the boiler casing to provide access via man-ways to all of the weld joints on each serpentine tube circuit. This design change will allow repair and restoration of leaking tube circuits, thus minimizing reductions of the boiler capacity over its life.

Drum-type boiler tube repairs require entry into the boiler casing. In many cases the repair of a tube in a drum-type system may require the removal and replacement (by cutting and welding) of several rows of tubes to gain access to the tube being repaired. Because of the nature of this effort, it is common for utilities to continue to operate boilers with leaking tubes, providing that sufficient condensate makeup is available.

### HRSG Instrumentation and Controls

In a drum-type HRSG system, feedwater flow is typically controlled by referencing drum level as the primary input and inlet feedwater and outlet steam flow rates as secondary input. The reliability of drum-level sensing instrumentation is a common problem in boiler operation, and it is anticipated that newer drum-type systems will provide instrument redundancy at each drum-level sensing location.

The system control specifications for commercial utility once-through HRSGs have not yet been fully developed. In a once-through HRSG, the feedwater flow is regulated to maintain the required amount of superheat in the outlet steam. Expected system dynamics will require a sophisticated feed-forward control logic, including accurate measurements for this control, such as outlet steam temperature, feedwater flow rate, and gas temperature. Due to the need for high reliability in the control input, the control sensing instrumentation for the once-through HRSG will probably have redundancy at each sensing location. In this analysis it is assumed that triplication with a two-out-of-three voting system will apply for this instrumentation.

### HRSG Piping, Valves, and Ductwork

A major difference between the once-through and drum-type HRSG designs is the number of valves and the extent of connecting piping. Most of the valves associated with the drum-type boiler (such as blowdown, vent, and drain valves) are not required with the once-through boiler configuration. Failures and maintenance associated with these valves do not apply to the once-through design.

There are also major differences in the gas ductwork if simple-cycle operation (combustion turbine operation when the HRSG is shut down) is required. Drum-type HRSGs are not capable of hot, dry operation because of the temperature limits of the materials used in the economizer and evaporator section tubing. If it is intended to operate the combustion turbine when the drum-type HRSG is shut down, a gas bypass damper and stack must be included in the system installation. Gas bypass dampers have historically been a maintenance problem and a source of power loss due to leakage.

The once-through HRSG is capable of hot, dry operation because of the high-temperature characteristics of the tube material. In fact, this operating mode is recommended as a means for periodically removing soot when using dirty fuel in the combustion turbine. Therefore, a gas bypass system is not required to operate the combustion turbine when the once-through HRSG is down. The exclusion of the gas bypass system in once-through HRSG designs eliminates the reliability and maintenance concerns associated with this equipment. This advantage is meaningful only when considering the possibility of simple-cycle operation. Newer drum-type systems, which are intended only for combined-cycle operation, may also omit the bypass damper.

## UNIRAM MODEL

### Overview

The two HRSG UNIRAM models were broken down into subsystems consistent with the preceding design review discussion categories. The availability block diagram (ABD) that applies to both the once-through and drum-type models is presented in

Figure 3-3. As can be seen, the ABD includes four serially connected subsystems: feedwater system; boiler; HRSG instrumentation and controls; and HRSG piping, valves, and ductwork. The ABD indicates that the unavailability of any of the four subsystems causes the HRSG to be unavailable. This ABD represents a binary model with no reduced operating states.

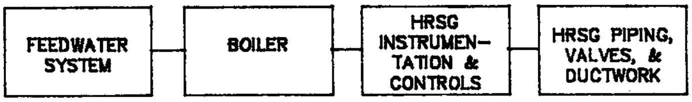

Figure 3-3. Availability Block Diagram for Once-Through and Drum-Type HRSG UNIRAM Models

The UNIRAM analysis includes the computation of system-level availability that is based on component reliability and maintainability characteristics and the component-to-system fault tree logic. The subsystem fault trees for the once-through and drum-type HRSGs are shown in Figures 3-4 and 3-5, respectively. Each of these fault trees are discussed in greater detail later in this section.

UNIRAM fault trees typically include various combinations of "and" gates and "or" gates; however, in this analysis only "or" gates exist in the fault trees. A general "or" gate indicates that the failure of any element under the gate causes the failure of the element above the gate. For example, in Figure 3-4 the "or" gate symbol under the feedwater system box indicates that the failure of any of the four components below the "or" gate results in the failure of the feedwater system subsystem. This analysis also includes qualified "or" gates that require the simultaneous failure of a specified number of elements below the gate to fail before the element above the gate fails. For example, in Figure 3-4 the simultaneous failure of any two of the three inlet gas temperature measurement components results in the failure of the HRSG instrumentation and controls subsystem.

The lowest level elements in the fault trees shown in Figures 3-4 and 3-5 are the components for the UNIRAM analysis HRSG models. The subsystem fault trees in Figures 3-4 and 3-5, along with the ABD in Figure 3-3, define the component-to-system fault tree logic for the two HRSG models.

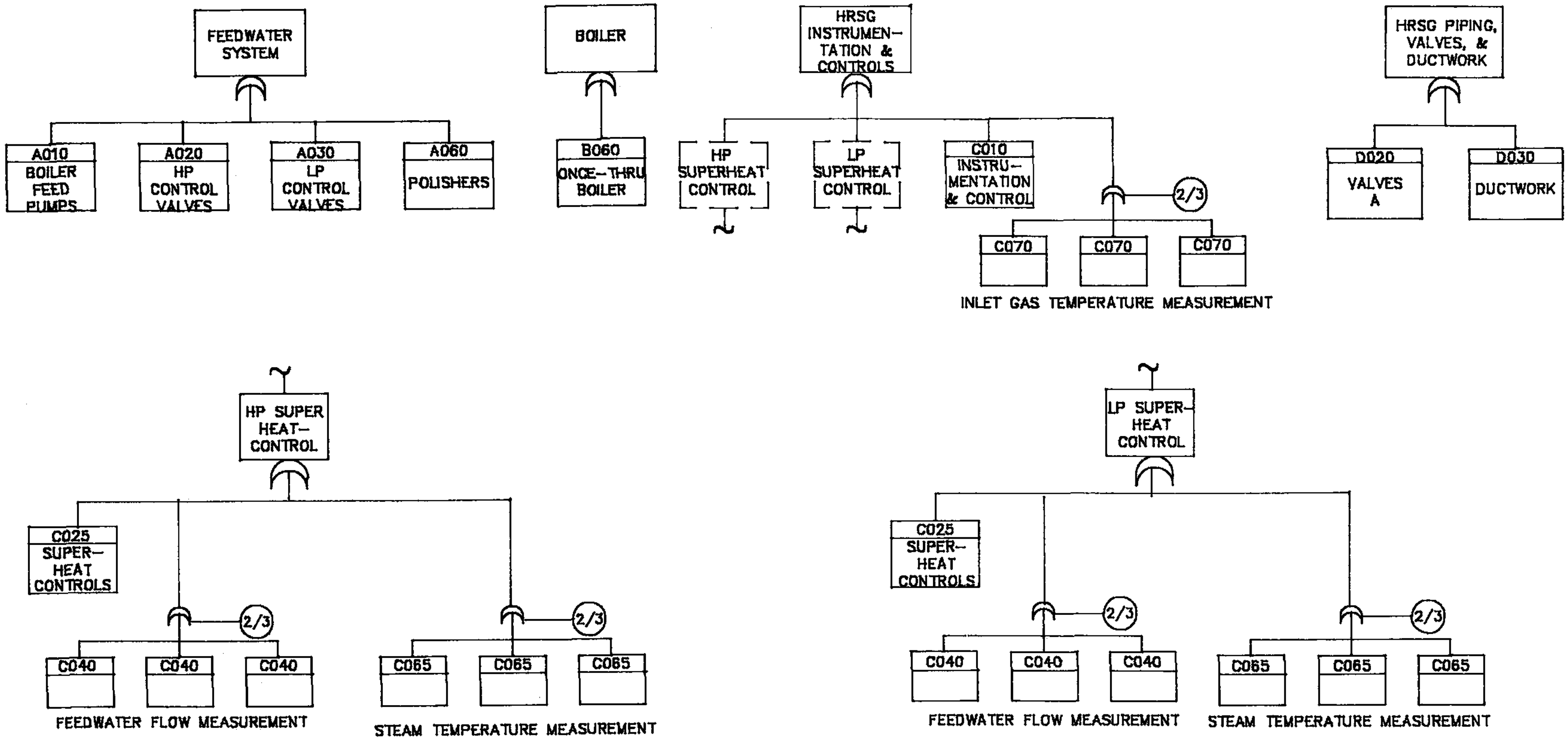

Figure 3-4. Once-Through HRSG Fault Trees

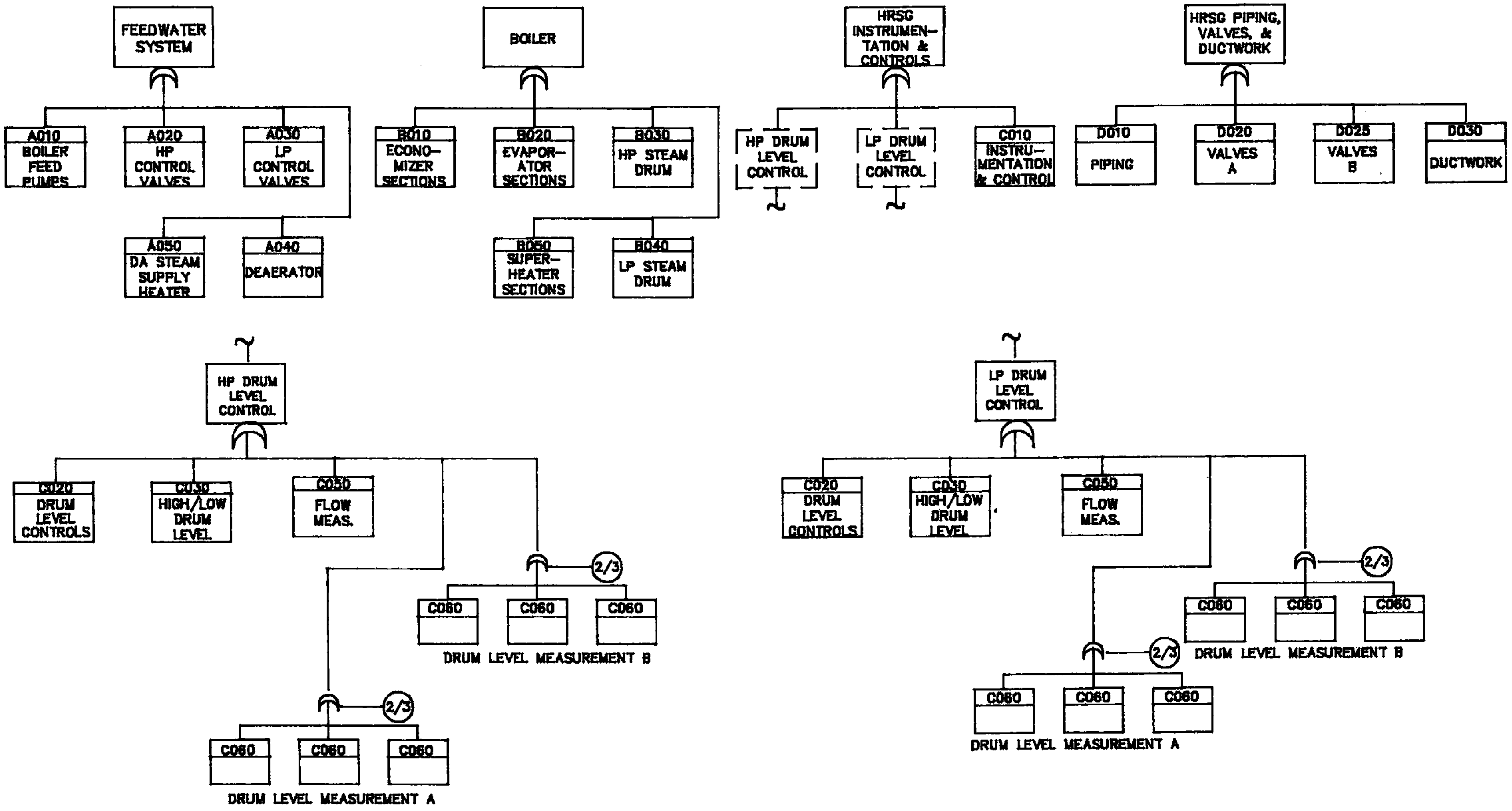

Figure 3-5. Drum-Type HRSG Fault Trees

Table 3-1 lists the component input data for both models. The input data consist of reliability parameters, in terms of mean time between failures (MTBF), and maintainability parameters, in terms of mean downtime (MDT). The MTBF and MDT values for components for both models were derived using the ERAS database, except where noted otherwise. This database includes maintenance and outage data for 11 utilities operating combustion turbines in combined and simple-cycle operation. Most plants have been cooperating with the project since 1982. Twenty-eight HRSG units are represented in the data with 416,617 combined operating hours at the time of this study. The HRSGs in the ERAS database are all single-pressure, forced circulation, drum-type systems, and the analysis models were constructed so that they utilized the ERAS data in a manner that represents the more modern, dual-pressure, natural circulation HRSG designs. (A single-pressure HRSG has a single steam drum. A dual-pressure HRSG includes two steam drums. Therefore, the number of many of the components directly associated with the steam drum in a single-pressure system is doubled in a dual-pressure system. Also, a natural circulation design is represented by excluding the circulating pumps and associated components.)

Table 3-1 also lists the number of ERAS failure events that were used to compute the MTBF and MDT values for each UNIRAM model component. In some cases, the number of failure events is as low as 1 (for example, component no. B050 repre- senting superheater tube failures). Obviously, the statistical uncertainty associated with the MTBF and MDT statistics for this component is high. Conversely, those components represented by numerous failure events have lower uncertainties associated with their statistics.

The following subsections describe each of the fault trees and the associated component data for the two UNIRAM models.

### Feedwater System

The boiler feed pumps and high-pressure and low-pressure feedwater control valves in a once-through HRSG would be essentially the same as those in a drum-type system, and accordingly, these components are treated the same in both models. The drum-type model includes a deaerator and a deaerator steam supply heater (DASSH). In this analysis it was assumed that the DASSH would be of a type found only in three HRSGs represented in the ERAS database; therefore, the input data for this

Table 3-1

DRUM-TYPE AND ONCE-THROUGH HRSG UNIRAM MODELS SUBSYSTEM/COMPONENT LISTING

| Subsystem and Component | No. of ERAS Events | MTBF (h) | MDT (h) | Notes | |
|---|---|---|---|---|---|
| Feedwater System | | | | | |
| A010-Boiler Feed Pumps[a] | 93 | 4,480 ✓ | 17.1 | 1 | |
| A020-H.P. Control Valves[a] | 25 | 16,665 ✓ | 16.8 | 1 | |
| A030-L.P. Control Valves[a] | 25 | 16,665 ✓ | 16.8 | 1 | |
| A040-Deaerator[a] | 30 | 13,887 | 4.0 | 2 | |
| A050-D.A. Steam Supply Heater[b] | 1 | 36,215 | 6.5 | 2 | |
| ~~A060-Polishers[c]~~ | ~~3~~ | ~~138,872~~ | ~~4.0~~ | ~~3~~ | OTSG |
| Boiler | | | | | |
| B010-Economizer Sections[a] | 60 | 6,944 | 22.8 | 2 | |
| B020-Evaporator Sections[a] | 16 | 26,039 | 35.4 | 2 | |
| B030-H.P. Steam Drum[a] | 7 | 59,517 | 9.6 | 2 | |
| B040-L.P. Steam Drum[a] | 7 | 59,517 | 9.6 | 2 | |
| B050-Superheater Sections[a] | 1 | 416,617 | 6.3 | 2 | |
| ~~B060-Once-Through Boiler Tubing~~ | | -- | -- | 3 & 4 | OTSG |
| HRSG Instrumentation and Controls | | | | | |
| C010-Inst. and Control -- General[a] | 21 | 9,920 | 5.0 | 1 & 5 | |
| ~~C020-Drum Level Controls -- General[a]~~ | ~~5~~ | ~~83,323~~ | ~~5.8~~ | 2 | Redundant |
| ~~C025-Superheat Controls -- General~~ | | 83,323 | 5.8 | 3 & 6 | OTSG |
| C030-High/Low Drum Level[a] | 55 | 7,575 | 1.2 | 2 | |
| ~~C040-Feedwater Flow Measurement~~ | | 104,154 | ~~11.6~~ | ~~3 & 7~~ | OTSG |
| C050-Flow Measurement[a] | 4 | 104,154 | 11.6 | 2 | |
| C060-Drum Level Measurement[a] | 25 | 33,329 | 4.6 | 2 & 8 | |
| ~~C065-Steam Temp. Measurement[c]~~ | ~~4~~ | ~~104,154~~ | ~~4.0~~ | ~~3~~ | OTSG |
| ~~C070-Inlet Gas Temp. Measurement~~ | | ~~104,154~~ | ~~4.0~~ | ~~3 & 9~~ | OTSG |
| HRSG Piping, Valves, and Ductwork | | | | | |
| D010-Piping[a] | 4 | 52,077 | 6.3 | 2, 5, & 10 | |
| D020-Valves A[a] | 22 | 9,469 | 8.6 | 1, 5, & 11 | |
| D025-Valves B[a] | 15 | 13,887 | 5.9 | 2, 5, & 12 | |
| D030-Ductwork[a] | 5 | 83,323 | 87.6 | 1 | |

---

[a] Derived from curtailing events in ERAS database (28 operating HRSG units with 416,617 combined operating hours).

[b] From curtailing ERAS data for only three HRSG units (36,215-h database).

[c] MTBF values from curtailing and noncurtailing ERAS data (416,617-h database)--MDT values estimated based on limited ERAS data.

Notes:

1. Applicable to both drum-type and once-through models.
2. Applicable to drum-type models only.
3. Applicable to once-through models only.
4. See Table ~~X~~3-2 and related discussion.
5. ERAS MTBF values adjusted for dual-pressure design (divided by two).
6. Assumed to be the same as C020-Drum Level Controls -- General.
7. No ERAS data -- assumed to be the same as C050-Flow Measurement.
8. ERAS MTBF value doubled -- assumed two drum level measurement locations for each ERAS boiler.
9. Assumed to be the same as C065-Steam Temperature Measurement.
10. Piping events seen in ERAS data applicable to drum-type HRSG only.
11. System valves applicable to both drum-type and once-through HRSGs.
12. System valves applicable to drum-type HRSG only.

# DRUM HRSG

$\lambda_{TOT} = \sum \lambda_i$ for series

$$\frac{1}{4480} + \frac{2}{16665} + \frac{1}{13887} + \frac{1}{36215} + \frac{1}{6944} + \frac{1}{26039} +$$

$$\frac{2}{59517} + \frac{1}{416617} + \frac{1}{9920} + \frac{1}{7575} + \frac{1}{104154} + \frac{1}{33329}$$

$$+ \frac{1}{52077} + \frac{1}{9469} + \frac{1}{13887} + \frac{1}{83323} = 1.1425 \times 10^{-3} = \sum \lambda_c$$

MTBF = 875 hrs

$$\text{MDT} = \frac{\sum \lambda_c \, \text{MDT}_c}{\sum \lambda_c}$$

$$\frac{\left.\begin{array}{l} \frac{17.1}{4480} + \frac{16.8+16.8}{16665} + \frac{4}{13887} + \frac{6.5}{36215} + \frac{22.8}{6944} + \frac{35.4}{26039} \\ + \frac{9.6+9.6}{59517} + \frac{6.3}{416617} + \frac{5}{9920} + \frac{1.2}{7575} + \frac{11.6}{104154} + \\ \frac{4.6}{33329} + \frac{6.3}{52077} + \frac{8.6}{9469} + \frac{5.9}{13887} + \frac{87.6}{83323} \end{array}\right\} .0147}{1.1425 \times 10^{-3}}$$

MDT = 12.9 hrs

$$A = \frac{875}{875 + 12.9} = .985$$

Agrees with Table S-1

component was derived from ERAS data for only those three units. It should be noted that the ERAS data included only a single event for this component. Full-flow feedwater polishers were represented in the once-through model by a single component. Because the ERAS HRSGs do not have full-flow polishers, the component input data were derived from noncurtailing events associated with makeup water demineralizers. Those ERAS demineralizer events associated with the chemical regeneration systems were excluded, because the once-through polisher demineralizers are assumed to be of the nonregenerative type.

### Boiler

The drum-type model includes components representing the economizer, evaporator, and superheater tubes, as well as the high-pressure and low-pressure steam drums. The input data for these components were derived using ERAS outage data. Only one HRSG outage event caused by a superheater tube failure was found in the ERAS data.

The single boiler component in the once-through model represents failures of the once-through HRSG tubing. As discussed throughout this report, full-scale operating data are very limited for these boilers. For this analysis, 40,000 h was selected as the base case MTBF value for the tubes in a once-through HRSG unit on the basis of the operating experience achieved so far for the two Okarche, Oklahoma, units discussed in Section 2. These two units have each experienced approximately 40,000 h of operation without boiler tube failures. An MDT value of 24 h was assumed for once-through HRSG tube failures on the basis of estimated times required to cool down and enter the boiler casing for tube repair, to complete the tube repair, and to restore the boiler casing.

This analysis included a sensitivity evaluation varying the once-through boiler tube MTBF from 4000 h to 400,000 h. A case with the once-through boiler tubing being "perfectly available" (no failures) was also included in the analysis. The MTBF and MDT values for the once-through boiler tubing used in this analysis are listed in Table 3-2.

### HRSG Instrumentation and Controls

In the drum-type fault tree, component C010, Instrumentation and Control -- General, represents HRSG instrumentation and control ERAS events not directly related to level control. Level control components are shown for both the high-pressure and

## Table 3-2

## ONCE-THROUGH BOILER MTBF AND MDT VALUES

| CASE | MTBF (h) | MDT (h) |
|---|---|---|
| 1 | 4,000 | 24 |
| 2[a] | 40,000 | 24 |
| 3 | 400,000 | 24 |
| 4[b] | 999,999 | 1 |

---

[a] Base case.
[b] Perfectly available case.

low-pressure steam drums. Component C020, Drum Level Controls -- General, represents HRSG level control events not directly related to level sensing instrumentation. Component C030, High/Low Drum Level, represents ERAS HRSG outage events caused by high or low drum level being experienced. Component C050, Flow Measurement, represents level control events associated with outlet steam flow measurement.

It was assumed that the ERAS HRSG steam drums have level sensing instrumentation at at least two locations on each drum with no instrument redundancy at the individual sensing locations. Component C060, Drum Level Measurement, represents the ERAS drum level sensing events that would apply to each of two sensing locations on each steam drum. It was decided that in this analysis the comparison drum-type model would include redundancy at each drum level sensing location (to be consistent with expected newer drum-type system designs). It was also decided that the model would be based on the assumption that the failure of two out of three level sensing instruments at a single location would shut the HRSG down. The drum-type model fault tree includes this two-out-of-three failure logic.

The once-through model fault tree was constructed in a similar manner with triplication and a two-out-of-three failure logic for critical instrumentation. The critical control input signals include the gas temperature measurement, high- and low-pressure feedwater flow measurements, and high- and low-pressure outlet steam temperature measurement. Component C010, Instrumentation and Control -- General, was assumed to apply also to the once-through HRSG. Component C025, Superheat Controls -- General, was included in the model as an assumed counterpart to the drum-type component C020, Drum Level Controls -- General. The feedwater flow measurement component values were assumed to be the same as those of the drum-type model flow measurement component. The steam temperature measurement and inlet gas temperature measurement component values were derived from ERAS noncurtailing event data for steam temperature measurement instrumentation.

### HRSG Piping, Valves, and Ductwork

Two categories of HRSG valves were identified in the ERAS data: those that apply to both drum-type and once-through HRSGs, such as outlet steam safety valves; and those that apply only to drum-type designs, such as blow down valves. The first category of valves was represented by the component named Valves A, the latter category by the component named Valves B. The HRSG piping events seen in the ERAS data were primarily associated with piping that applies only to the drum-type boiler. The ductwork events seen in the ERAS data were assumed to apply to both HRSG designs. Gas bypass damper events were not included in this analysis.

## UNIRAM ANALYSIS RESULTS

The results of the UNIRAM baseline runs completed for this analysis are summarized in Table 3-3. This table lists computed subsystem availabilities as well as total system availabilities for the five runs completed (the single drum-type model run and the four cases for the once-through model). The availability of the once-through HRSG with a 4000-h boiler tube MTBF is essentially the same as that of the drum-type HRSG (a difference of only 0.05% was calculated). The computed availability of the once-through HRSG with a boiler tube MTBF of 40,000 h or greater shows an availability advantage over the drum-type model of about 0.6%. The table indicates that improvements in the once-through boiler tube MTBF beyond 40,000 h have very little effect on the total system availability.

If it can be assumed that the worst-case, once-through boiler tube MTBF will not be less than 4000 h and that the MDT of 24 h is a realistic value for repair of the once-through boiler tubes, then these results indicate that at worst, the two HRSG designs have similar availabilities, and at best, the once-through HRSG design has an availability advantage of about 0.6%. This 0.6% availability advantage applies to all boiler tube MTBF values equal to or greater than 40,000 h.

Table 3-3

HRSG SYSTEM AND SUBSYSTEM AVAILABILITIES (Percentage)
(UNIRAM Baseline Results)

| | Drum-Type HRSG Model | Once-Through HRSG Model* | | | |
|---|---|---|---|---|---|
| | | Case 1 | Case 2 | Case 3 | Case 4 |
| SUBSYSTEM AVAILABILITIES | | | | | |
| Feedwater System | 99.37 | 99.42 | 99.42 | 99.42 | 99.42 |
| Boiler | 99.50 | 99.40 | 99.94 | 99.99 | 100.00 |
| HRSG Instrumentation and Controls | 99.88 | 99.94 | 99.94 | 99.94 | 99.94 |
| HRSG Piping, Valves, and Ductwork | 99.75 | 99.80 | 99.80 | 99.80 | 99.80 |
| HRSG SYSTEM DESIGN COMPARISON | | | | | |
| Total HRSG System Availability | 98.52 | 98.57 | 99.10 | 99.15 | 99.16 |
| Difference Between Drum Type and Once-Through Designs | -- | 0.05 | 0.58 | 0.63 | 0.64 |

---

*Once-through boiler tubing:

| | MTBF | MDT |
|---|---|---|
| Case 1: | 4,000 h; | 24 h |
| Case 2: | 40,000 h (base case); | 24 h |
| Case 3: | 400,000 h; | 24 h |
| Case 4: | 999,999 h (perfectly available case); | 1 h |

Table 3-3 also lists the availability differences between the two HRSG models for the various subsystems. The availability of each of the three nonboiler subsystems is slightly higher for the once-through HRSG than for the drum-type design. This is consistent with the apparent relative simplicity of the once-through design when compared with the drum-type system.

Tables 3-4 and 3-5 list the component criticality rankings for the drum-type model and the base case once-through model. The ranking factors are the respective contributions to the total system unavailability for each component. These rankings indicate which components have the greatest influence on total system availability. As can be seen with the drum-type design, represented in Table 3-4, the economizer and evaporator tubing are near the top of the list, indicating that significant

Table 3-4

DRUM-TYPE HRSG CRITICALITY RANKING

| Ranking Factor[a] | Component |
|---|---|
| 0.3759 | A010 - Boiler Feed Pumps |
| 0.3234 | B010 - Economizer Sections |
| 0.1338 | B020 - Evaporator Sections |
| 0.1035 | D030 - Ductwork |
| 0.0992 | A020 - H. P. Control Valves |
| 0.0992 | A030 - L. P. Control Valves |
| 0.0894 | D020 - Valves A |
| 0.0496 | D010 - Instrumentation and Control -- General |
| 0.0418 | D025 - Valves B |
| 0.0283 | A040 - Deaerator |
| 0.0176 | A050 - D. A. Steam Supply Heater |
| 0.0158 | B030 - H. P. Steam Drum |
| 0.0158 | B040 - L P. Steam Drum |
| 0.0155 | C030 - High/Low Drum Level |
| 0.0118 | D010 - Piping |
| 0.0109 | C050 - Flow Measurement |
| 0.0068 | C020 - Drum Level Controls -- General |
| 0.0014 | B050 - Superheater Sections |
| b | C060 - Drum Level Measurement |

---

[a] Ranking Factor = component contribution to system unavailability, in percent.
[b] Ranking Factor less than 0.0001.

improvements could be made in total system availability by improving the reliability of these components. For example, if economizer tube failures were totally eliminated, the drum-type HRSG availability would improve by 0.32%. In the base case once-through system, represented in Table 3-5, the boiler tube failures have lower rankings, thus indicating that similar improvements in this component reliability (beyond the MTBF value of 40,000 h) will have less effect on the total system availability. For the once-through HRSG base case, the elimination of all boiler tube failures would result in an HRSG availability improvement of only 0.06%.

It is important to use caution when reviewing and interpreting these analysis results. In some cases the component MTBF and MDT input values used in both models were based on very few outage or maintenance events in the ERAS database, thus indicating significant levels of uncertainties for these values. This analysis,

## Table 3-5

## ONCE-THROUGH BASE CASE HRSG CRITICALITY RANKING

| Ranking Factor[a] | Component |
|---|---|
| 0.3782 | A010 - Boiler Feed Pumps |
| 0.1041 | D030 - Ductwork |
| 0.0998 | A020 - H. P. Control Valves |
| 0.0998 | D020 - L. P. Control Valves |
| 0.0899 | D020 - Valves A |
| 0.0594 | B060 - Once-Through Boiler |
| 0.0499 | C010 - Instrumentation and Control -- General |
| 0.0068 | C025 - Superheat Controls -- General |
| 0.0028 | A060 - Polishers |
| b | C040 - Feedwater Flow Measurement |
| b | C065 - Steam Temperature Measurement |
| b | C070 - Inlet Gas Temperature Measurement |

---

[a] Ranking Factor = Component contribution to system unavailability, in percent.
[b] Ranking factor less than 0.0001.

however, was performed using the best available data, and it is believed that these results provide a good baseline understanding of the differences in availability characteristics between the two designs.

## Section 4

## CONCLUSIONS AND RECOMMENDATIONS

The availability of a Solar Turbines once-through HRSG can be expected to be equal to and or better than that of a comparable natural circulation drum-type system. An availability advantage of approximately 0.6% has been calculated for the once-through design; however, this value is based in part on analysis data with significant statistical uncertainties.

The anticipated improved availability of the once-through design is based on the performance expectations of the corrosion-resistant, high-temperature alloy (alloy 800) used as the tubing material, as well as on the inherent simplicity of the once-through HRSG design in comparison with drum-type HRSG systems.

The Solar Turbines HRSG concept also provides advantages in the area of boiler tube maintenance.

The reliability of the once-through HRSG control system and instrumentation has been identified as a critical aspect of the development of this design, but control and instrumentation reliability has also historically been a problem area with drum-type systems.

The success of this design in utility combined-cycle applications is, to a great extent, based on the reliability of the alloy 800 tubing. The available utility industry data are insufficient to predict the tubing reliability in this application. However, because this alloy is commonly used in industrial applications requiring high temperatures and corrosion-resistant qualities, it appears to be a good choice for this design. It is expected that this HRSG design will demonstrate good reliability in the clean fuel (low sulfur) applications typical of combined-cycle facilities. Feedwater heating may be required in the once-through HRSG design to maintain the tube metal temperatures above the acid dew point so that corrosion is minimized when using high-sulfur fuels.

This report identifies specific areas where additional review may be beneficial. The following efforts are recommended for consideration in the continuing evaluation of this concept:

- Conduct detailed investigations into various areas related to HRSG tubing reliability, including:
  - Quantify predicted weld reliability characteristics based on statistical weld completion data for alloy 800 in similar weld configurations
  - Conduct laboratory tests to quantify corrosion and erosion characteristics of alloy 800 under conditions representative of this application
  - Follow up the findings of inside surface damage indications in the Okarche tube samples to determine if erosion, impingement, or cavitation phenomena are occurring
  - Collect tube performance data during in-progress and future field testing activities
- Develop detailed control system design requirements and evaluate their effect on system availability based on the predicted reliability of the control system.

# Appendix A

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## UNIRAM Data Input File -- Drum-Type HRSG

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## UNIRAM Data Input File -- Once-Through HRSG Base Case

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