NOx CONTROL
for the
CHENG CYCLE COGENERATION SYSTEM

Prepared by:

Brian T. Kelleher
INTERNATIONAL POWER TECHNOLOGY
333 Twin Dolphin Drive, Suite 725
Redwood City, California 94065
Telephone: 415-592-9020
Telefax: 415-592-9028

and

Manfred Haselgrübler
VOEST-ALPINE MASCHINENBAU
P.O. Box 5, A-4031
Linz, Austria
Telephone: 732-585-2609
Telefax: 732-585-0479

November 22, 1988

DISCLAIMER

This paper includes emission estimates derived from test data collected at existing Cheng Cycle gas turbine installations. The projections reflect nominal emissions rates only, and in no way represent manufacturer guarantee levels. Guarantee levels must always be conservatively adjusted for site and equipment variability.

Table of Contents

List of Figures

Introduction

In many countries, small gas turbines (less than 10 MW) have previously been exempt from the NOx emissions standards applied to large power stations. Over the last few years however, some countries have tightened NOx control requirements so that they now apply even to small gas turbines. Water injection, a conventional and proven NOx control technique, is normally used to satisfy these control requirements. Unfortunately, water injection adds cost and complexity to the gas turbine system.

The Cheng Cycle Series 7 Cogeneration system meets typical Western European NOx emission limits without the need for water injection. The Series 7 incorporates the Allison 501-KH gas turbine, a steam injected version of Allison's popular 501 turbine. Low NOx emission levels are an intrinsic characteristic of the Cheng Cycle system due to the steam injection.

The Cheng Cycle is not simply a method for NOx control. It was developed to increase the power output and efficiency of the conventional gas turbine. In Cheng Cycle cogeneration plants, steam not needed for heating or manufacturing, up to the full unfired waste heat boiler capacity, can be injected into the turbine to dramatically increase electric power output. Low NOx emissions are a secondary benefit of the high rates of steam injection.

Where stringent NOx regulations apply, Cheng Cycle plants can be equipped with water injection systems like those used on conventional, non-steam injected turbines. Cheng Cycle plants with combined steam and water injection systems have demonstrated significantly lower NOx emission levels than are typically attainable through the use of water injection alone. Emissions from Cheng Cycle plants equipped with combined steam and water injection approach the low emission levels achieved by very expensive post combustion NOx removal systems. Future wet NOx control system enhancements for the entire 501 gas turbine product line will allow the Cheng Cycle system to continue to set the standard for cost effective NOx reduction in gas turbines.

Section 1
NOx Emission Regulations for Gas Turbines

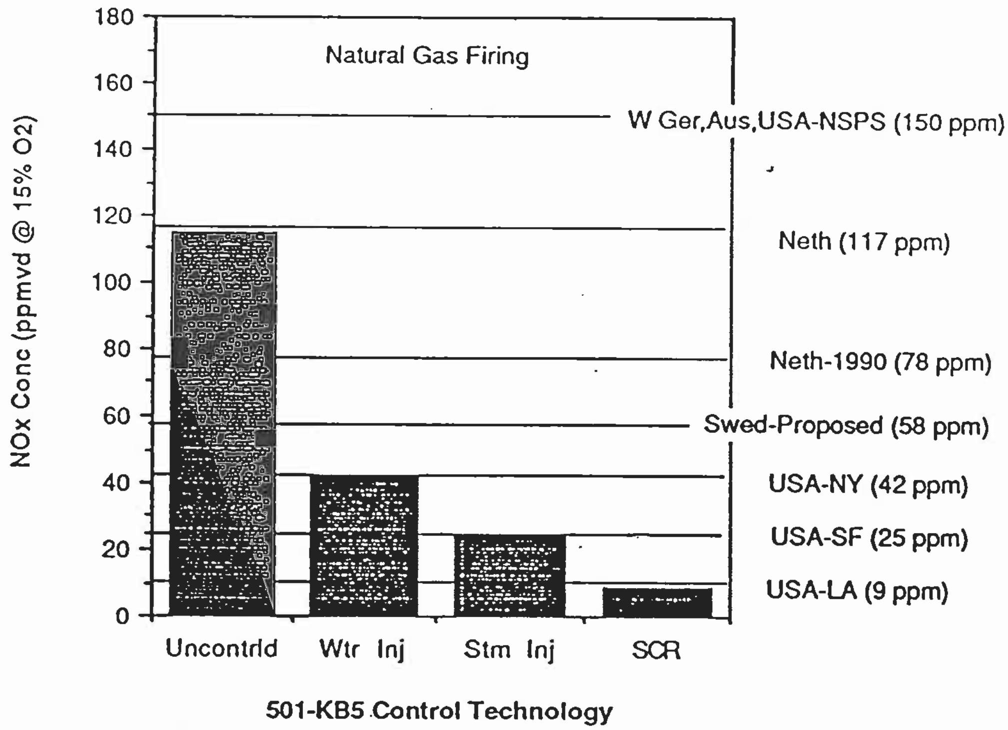
Nitrogen oxides (NOx) are the primary air pollutants of concern for industrial gas turbines. The high firing temperatures characteristic of the gas turbine engine create higher exhaust gas NOx levels than conventional boiler burner technology. Uncontrolled gas turbine NOx emissions are in the order of 100-130 ppmvd (15% O_2) for natural gas firing and 150-200 ppmvd (15% O_2) for distillate fuel firing. A conventional boiler emits about 50 ppmvd (15% O_2) on natural gas fuel.

Nitrogen oxide emissions, principally formed from the combustion of fossil fuels, are responsible for a number of air quality problems in heavily industrialized areas: They form nitrogen dioxide, a toxic gas; they are involved in photochemical reactions that produce ozone; they form toxic aerosols, fine particulates that also create visibility problems; and they ultimately precipitate from the atmosphere as acid rain constituents.

Due to these air pollution problems, environmental regulatory agencies in most industrialized areas of the world have developed standards for controlling NOx emissions from industrial sources. Figure 1-1 shows various gas turbine standards for different parts of Europe and the USA. The standards vary considerably for different areas, generally reflecting the associated severity of local ambient air pollution.

Regulatory standards are normally established relative to the degree of control achievable with a specific control technology. This is illustrated in Figure 1-1. The US EPA New Source Performance Standards (NSPS) which basically apply to non-industrial areas of the country, require no controls other than a properly designed and maintained engine. The 42 ppm standard prevailing in New York is based on levels of control achievable with water injection. In the San Francisco Bay Area, the 25 ppm standard implies steam injection or massive water injection as the standard control technology. In the Los Angeles area of Southern California, where air pollution is a serious health problem, the standard is based on the level of control achievable with Selective Catalytic Reduction.

FIGURE 1-1
EUROPE-USA GAS TURBINE NOx STANDARDS



Section 2
Cheng Cycle Technology Overview

The Cheng Cycle is a state-of-the-art power generation technology which uses a thermodynamically optimized, steam injected gas turbine as prime mover. As in conventional simple or combined cycle gas turbine cogeneration systems, waste heat in the turbine exhaust is directed through a heat recovery steam generator. In a simple cycle system, this steam is used for process or heating purposes. In the Cheng Cycle, a variable portion of the steam is superheated and injected into the gas turbine to increase efficiency and power output. At maximum Cheng Cycle steam injection rates, efficiency is increased by 40% and power output by 65%. Figure 2-1 schematically compares the Cheng Cycle to simple and combined cycle technologies.

The Cheng Cycle Series 7 is a complete, pre-designed cogeneration plant based on the 501-KH gas turbine. The 501-KH is manufactured by the Allison Gas Turbine Division of General Motors Corporation. It is a specially modified version of Allison's 3.6 MW 501-KB5 turbine. In the 501-KH, steam injection can be used to increase output from the 3.6 MW base rating to up to 5.6 MW at full injection levels.

Figure 2-2 shows the wide range of process steam and electric load conditions which the Series 7 can satisfy The system produces approximately 9100 kg/hr of steam without duct firing. The 501-KH is unique in its size range in that virtually all of this unfired boiler steam can be injected into the turbine for power augmentation. Process steam loads up to 19,500 kg/hr can be produced through supplementary fuel firing in a duct burner.

The Series 7 system is comprised of the 501-KH turbine-generator set, matching heat recovery boiler, duct burner, balance of plant systems, and fully integrated digital controls. An exploded view of the modular components of the Cheng Cycle plant is shown in Figure 2-3. The pre-packaged modular design allows for low cost installation and improved plant reliability.

The operating flexibility of the Cheng Cycle system makes it well suited to cogeneration applications where the requirements for

FIGURE 2-1
GAS TURBINE COGENERATION CYCLES

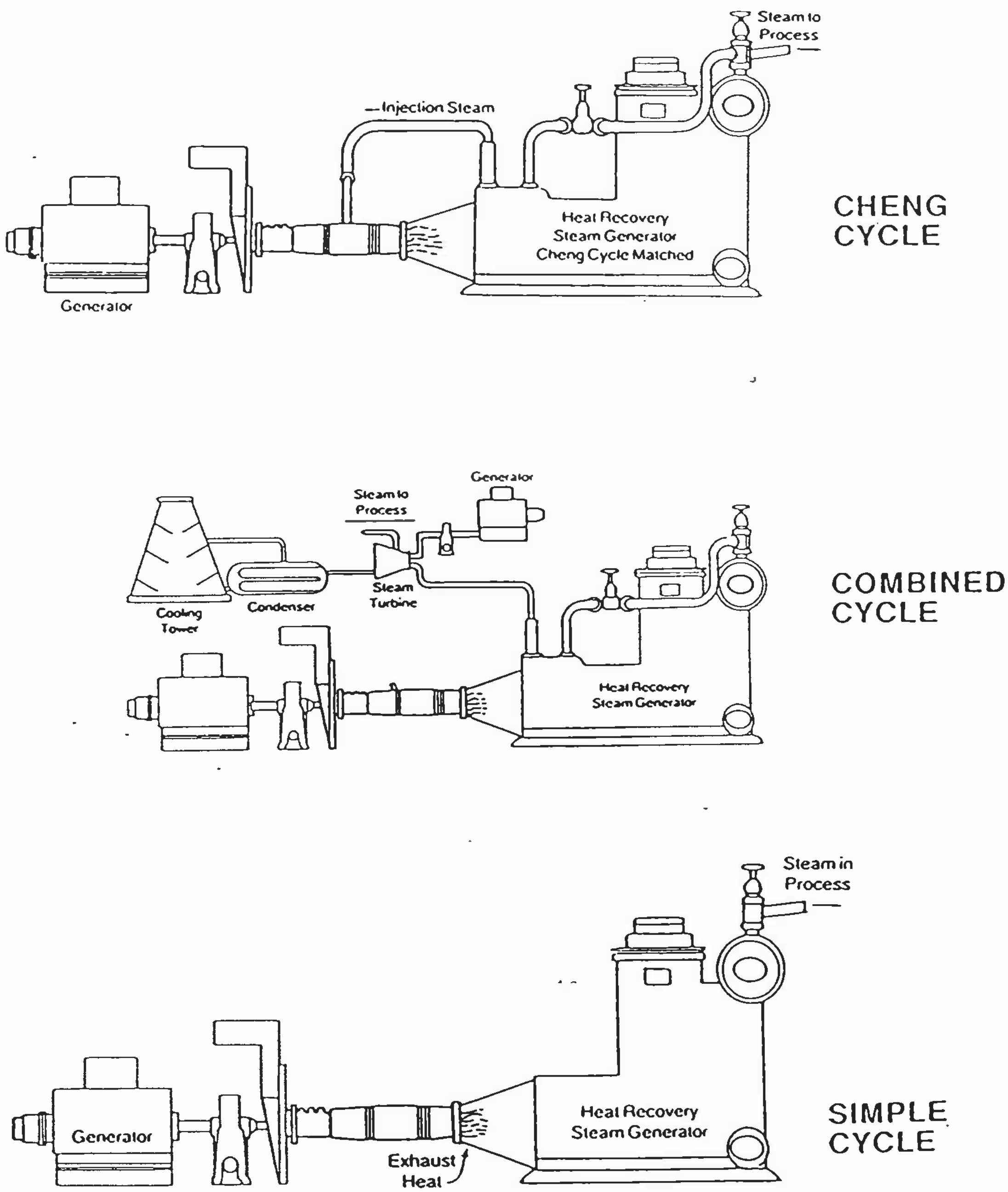
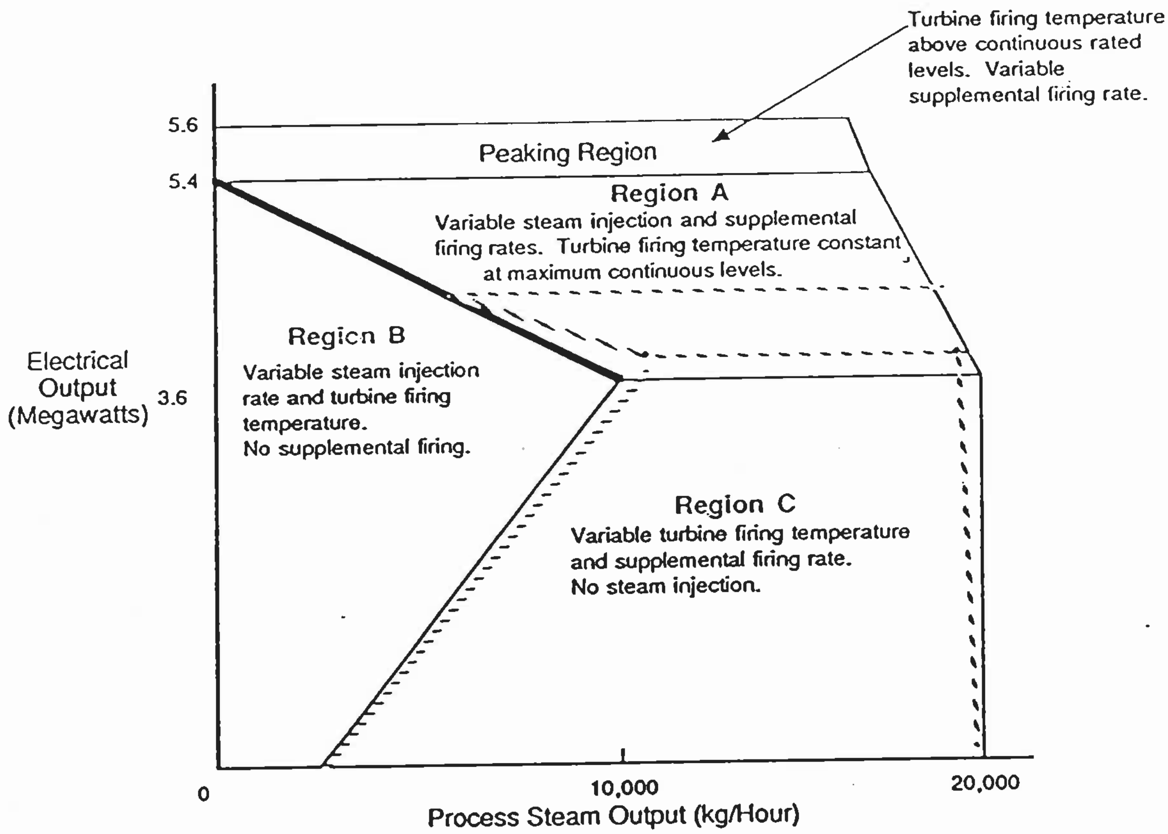
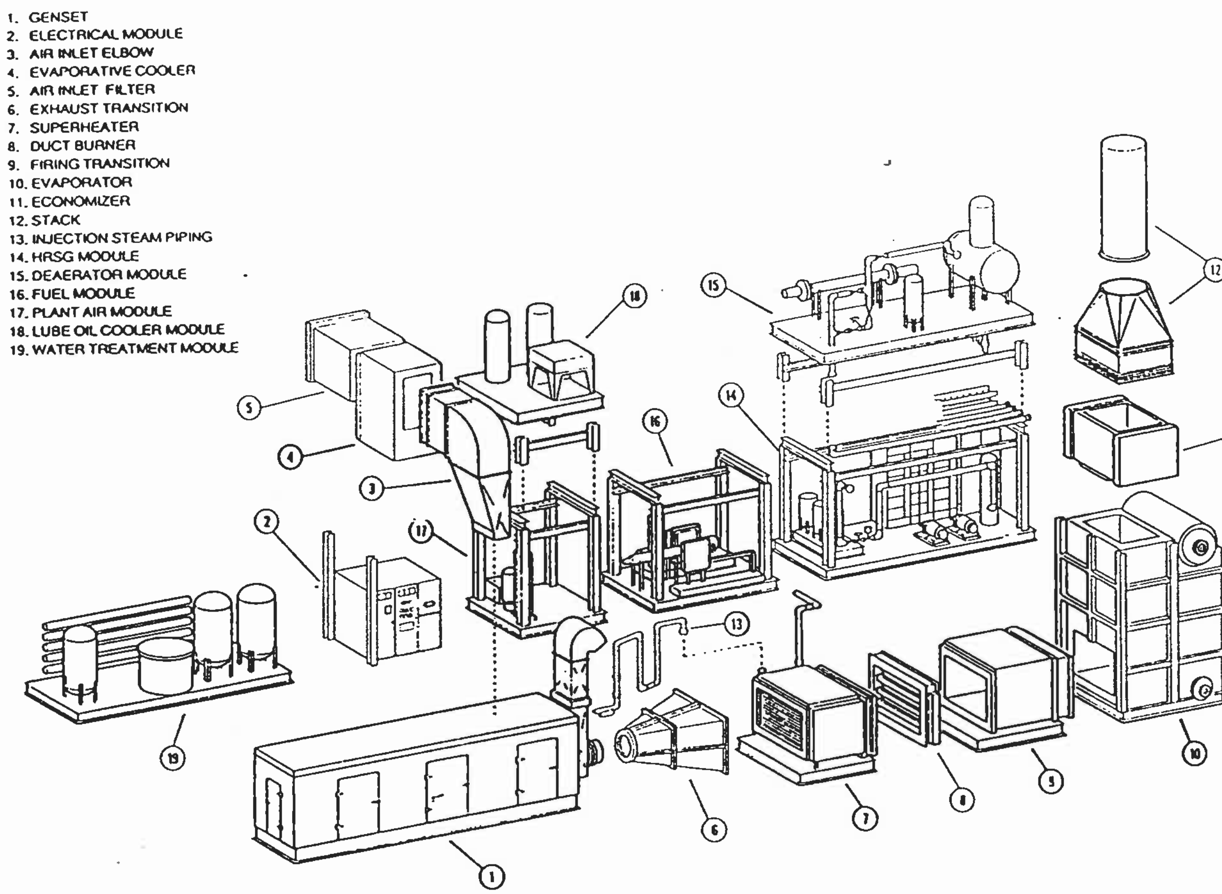


FIGURE 2-2
CHENG CYCLE SERIES 7 OPERATING REGIME



- - - - Systems equipped with optional water injection.

FIGURE 2-3
EXPLODED VIEW OF CHENG CYCLE SERIES 7 PLANT



steam and/or electric power vary on a seasonal or daily basis. Steam not needed for process uses or heating can be injected into the turbine to increase power output and generating efficiency. This allows the Cheng Cycle system to run efficiently even when the steam demands of the host facility drop to zero. In addition, the use of a supplemental burner allows peak electrical production while continuing to follow process steam loads. This additional electrical output can be used for peak shaving operation or for capacity sales to the utility network. The benefits of operating flexibility and additional electrical capacity are gained without the use of steam turbines and associated auxiliaries. The system remains mechanically simple and reliable.

The Cheng Cycle technology was developed by International Power Technology (IPT) of Redwood City, California. IPT holds numerous U.S. and foreign patents covering the methods and apparatus required to configure, operate, and control thermodynamically optimized steam injected gas turbine systems.

The first commercial Cheng Cycle cogeneration plant went into operation in December 1984. Today, seven Cheng Cycle systems totaling over 35 MW of electrical capacity are in commercial operation, and two other units with a capacity of 11 MW are under construction.

IPT has licensed the Western European rights to its Cheng Cycle Series 7 product to Voest-Alpine Maschinenbau Ges.m.b.H. Voest-Alpine is a worldwide manufacturer and industrial technology company headquartered in Linz, Austria. Voest-Alpine sells the system on a turnkey basis, and also sells the major components to others wishing to be turnkey suppliers.

IPT has also granted licenses to U.S. Turbine for the Series 7 in North and South America and to Hitachi Zosen for the Series 7 in Asia. Kawasaki Heavy Industries (Akashi, Japan) is the exclusive licensee worldwide for smaller Cheng Cycle systems. Kawasaki has recently completed demonstration plant testing and has introduced the M1A-13CC, a Cheng Cycle system which produces up to 2.4 MW of electrical power and up to 8600 kg/hour of process steam.

Section 3
Intrinsic Cheng Cycle NOx Control

The injection of large volumes of superheated steam in and around the Cheng Cycle turbine combustion zone for power augmentation has a significant secondary benefit: a reduction in nitrogen oxide (NOx) emissions. Steam injection inhibits NOx formation by lowering peak combustion zone temperatures.

Intrinsic Cheng Cycle NOx removal efficiency is related primarily to steam injection volume. Figure 3-1 shows Cheng Cycle NOx emissions as a function of injection steam rate at maximum turbine inlet temperature (1010 degrees C.). For natural gas firing, NOx is reduced from about 115 ppmvd (15% O_2) without steam injection, to about 25 ppmvd (15% O_2) at maximum steam injection (2.5 kg/sec); a 78% reduction. NOx emissions for distillate fuel firing are typically 60% higher with a base of about 180 ppmvd (15% O_2) reduced to about 40 ppmvd (15% O_2) at maximum injection. Carbon monoxide (CO) and unburned hydrocarbon (UBHC) emissions are largely unaffected by Cheng Cycle injection steam, typically remaining constant within the 5-15 ppmvd (15% O_2) range.

Intrinsic Cheng Cycle NOx removal efficiency is also affected by the location at which steam is introduced into the turbine. Figure 3-2, a cutaway view of the Cheng Cycle Series 7 genset, shows the locations of the two injection steam ports on the 501-KH turbine. Figure 3-3 shows NOx and CO emissions as a function of injection steam rate when all steam is routed through the upstream injection port. Upstream injection improves NOx removal efficiency by about 10% over that achieved in the standard split injection mode. This is because steam injected into the upstream port enters closer to the flame zone than that introduced through the downstream port. It can be seen however, that CO emissions increase dramatically at upstream injection rates above about 70% of maximum, marking an upper limit over which upstream injection causes flame stability problems.

To take advantage of the improved emissions characteristics of upstream injection, the Cheng Cycle Series 7 can be equipped with an optional "staged steam" injection valve package. This package includes control system logic that optimizes the steam injection distribution.

FIGURE 3-1
CHENG CYCLE NOx EMISSIONS
vs.
STEAM INJECTION

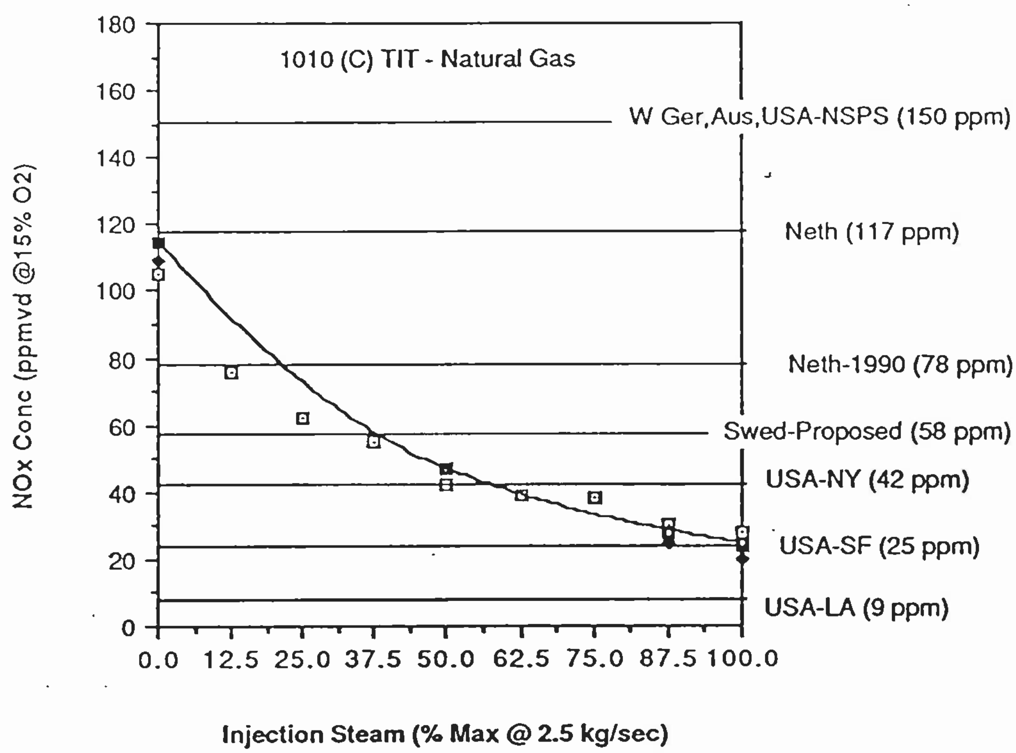


FIGURE 3-2
CHENG CYCLE GENSET EQUIPMENT ARRANGEMENT

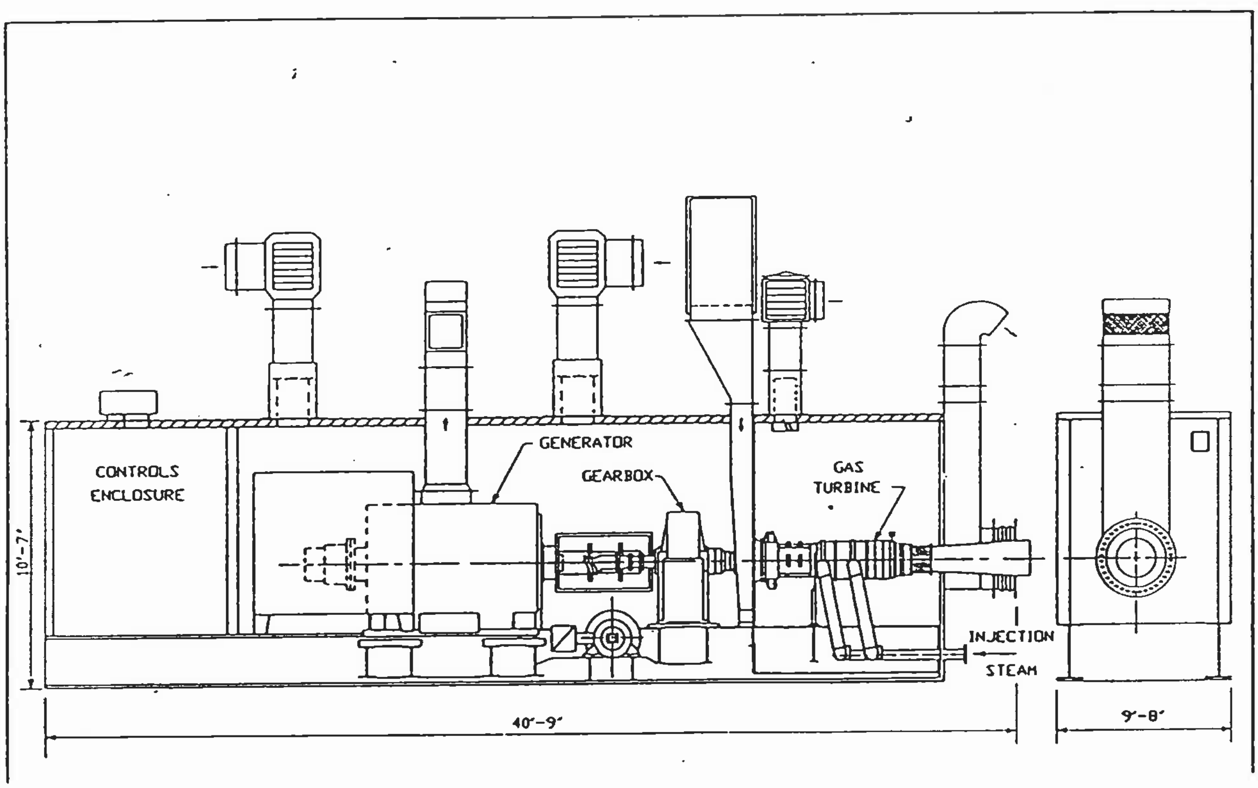
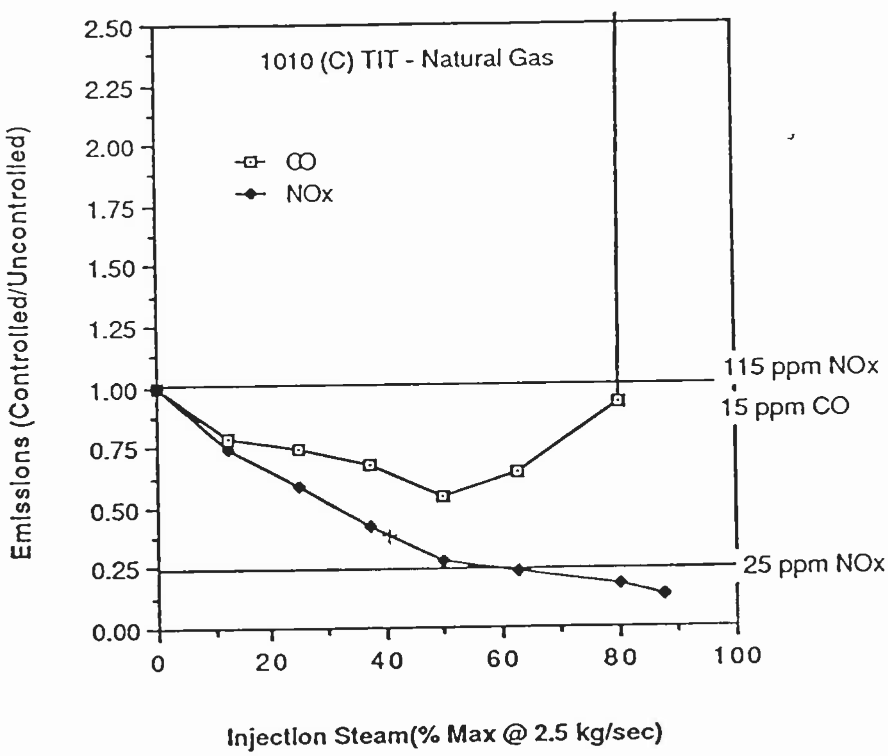


FIGURE 3-3
CHENG CYCLE UPSTREAM INJECTION
vs.
NOx AND CO



Cheng Cycle intrinsic steam injection can eliminate the need for a water injection control system. For instance, the current Dutch gas turbine NOx emission control standard (135 g/GJ) can be met simply by establishing a minimum steam injection setpoint of about 20% of maximum (natural gas firing). This reduces system installation and maintenance cost and complexity and avoids the increased carbon monoxide and hydrocarbon emissions associated with water injection

Section 4
Enhanced Wet NOx Control with Water Plus Steam Injection

Conventional water injection control technology can be used to augment the intrinsic NOx control benefits of Cheng Cycle steam injection. With water injection, high purity water is atomized and injected directly into the turbine combustion zone through the fuel nozzle. The combined flame zone cooling effects of water plus steam injection yields greater NOx reduction than that which can be achieved by either method alone.

Figure 4-1 shows 501-KH turbine NOx and CO emissions as a function of water injection rate without steam injection. These emission levels are essentially identical to those from the 501-KB5, non-steam injected turbine. CO and unburned hydrocarbon (UBHC) emissions increase dramatically at water injection rates above 0.8 kg water per kg natural gas fuel, marking a threshold above which additional water injection causes flame stability problems. This CO threshold restricts water injection NOx removal efficiency to about 70%, typically yielding exhaust concentrations of about 35 ppmvd (15% O_2) on natural gas firing and 55 ppmvd (15% O_2) on distillate fuel firing. CO and UBHC are increased by no more than about 50% at this threshold, an increase which is generally considered acceptable by regulatory agencies in terms of environmental impact, and turbine manufacturers in terms of flame stability and engine durability.

When water injection is used in combination with Cheng Cycle manifold steam injection, enhanced NOx reduction results from the combined effects of the two systems. This is illustrated in Figures 4-2 and 4-3 which plot NOx and CO emissions as a function of water injection rate at two different points in the Cheng Cycle operating regime.

In Figure 4-2, Cheng Cycle steam injection is at 50% maximum (2.8 lb/sec) with the turbine fired at maximum inlet temperature (1010 degrees C.) on natural gas. The water injection CO threshold (50% increase) occurs at about 0.7 kg water per kg fuel, with an associated NOx removal efficiency of about 87%. This produces an exhaust NOx level of less than 15 ppmvd (15% O_2).

FIGURE 4-1
WATER INJECTION vs. NOx and CO
IN THE 501-KB5 TURBINE

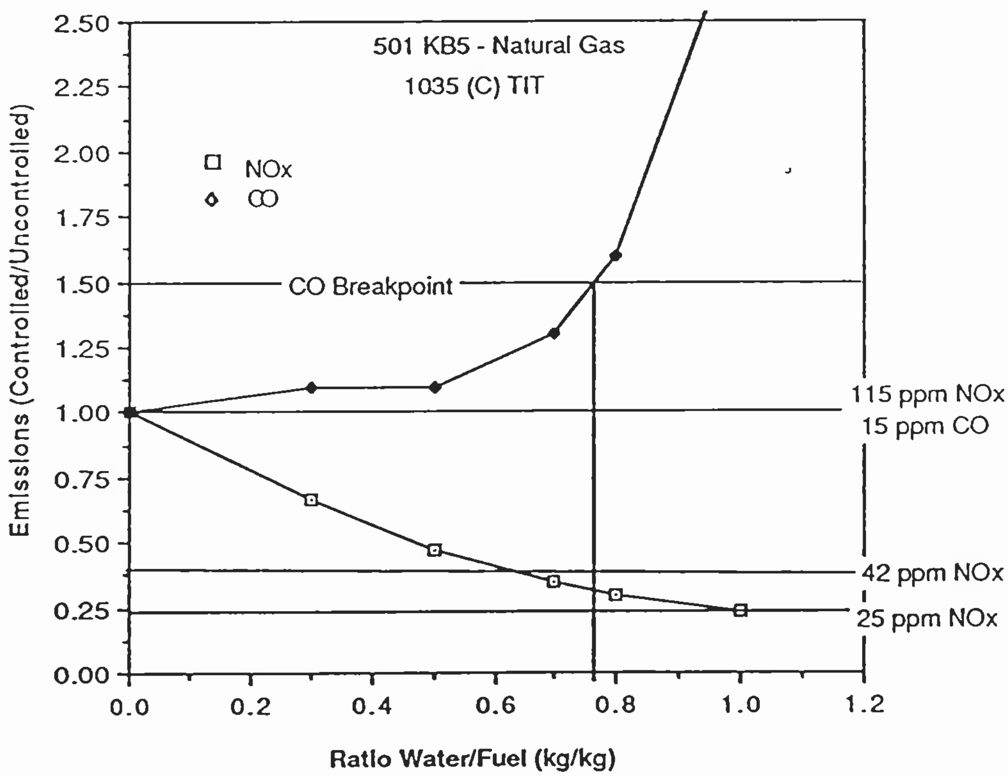


FIGURE 4-2
50% CHENG CYCLE STEAM INJECTION
PLUS WATER INJECTION

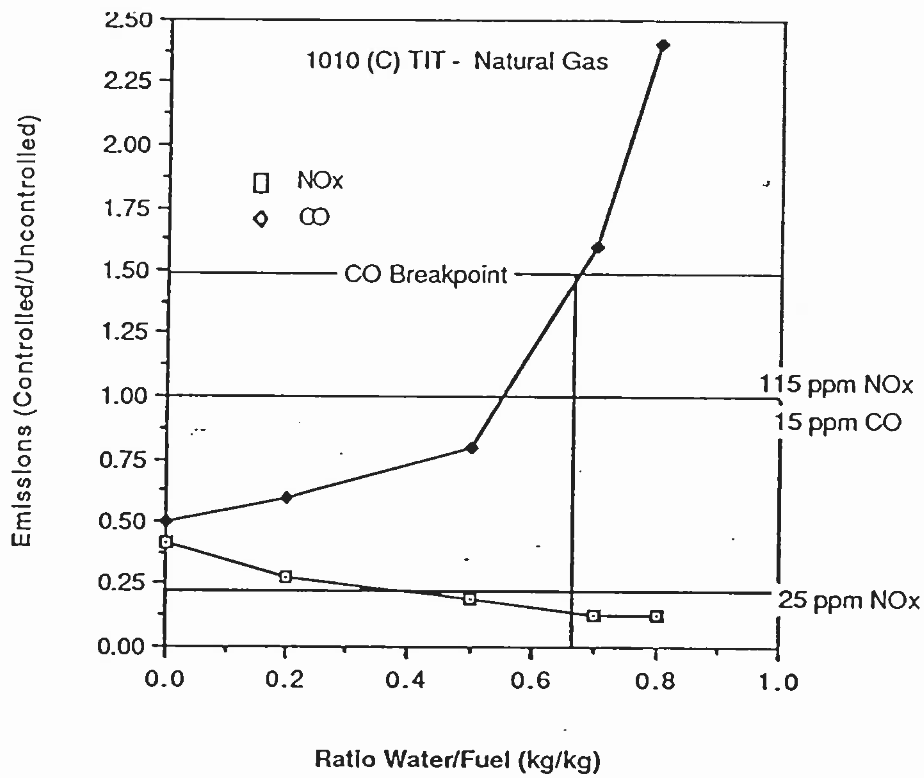
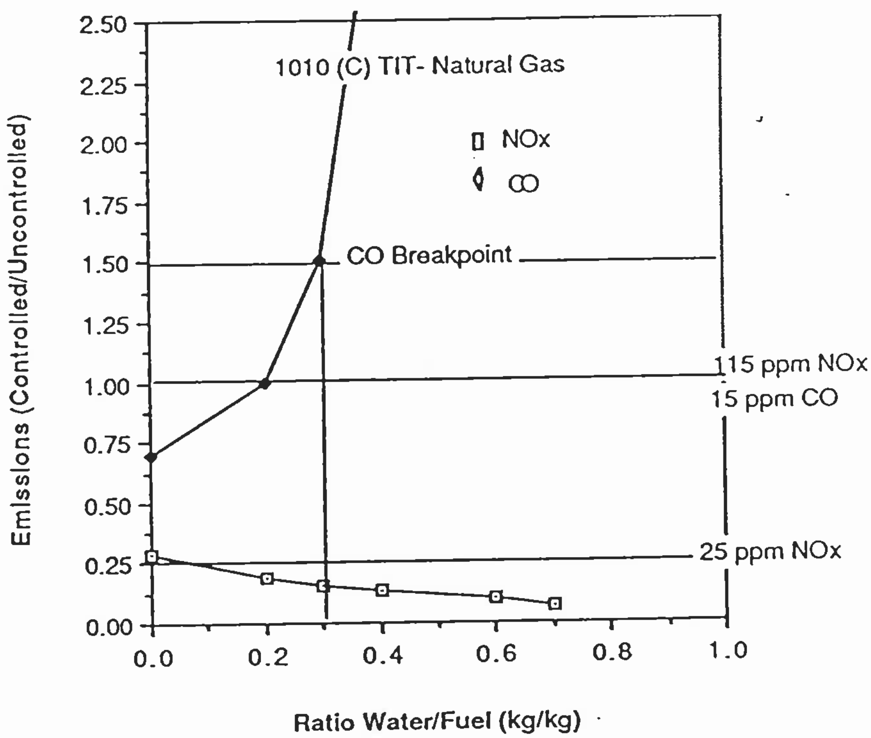


FIGURE 4-3
100% CHENG CYCLE STEAM INJECTION
PLUS WATER INJECTION

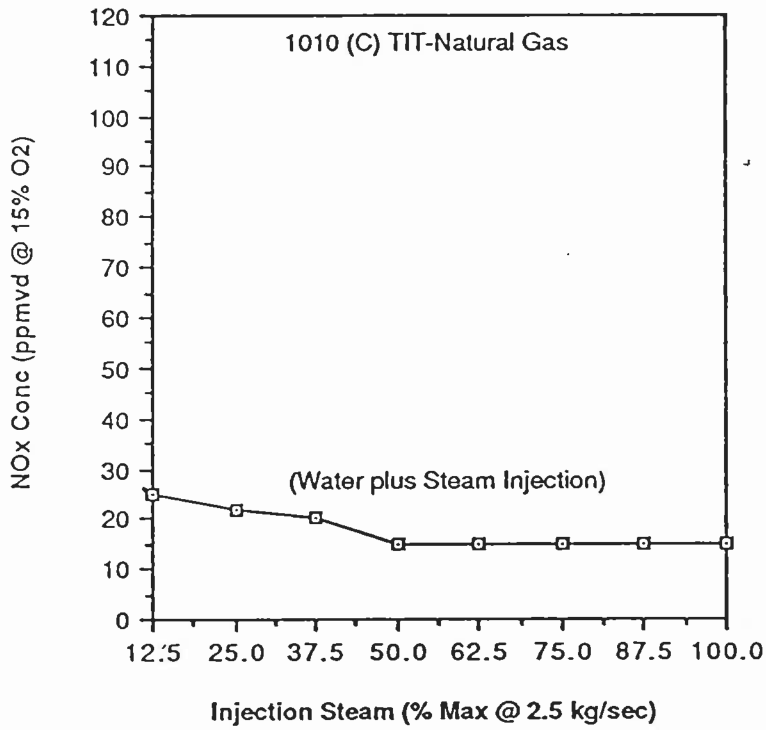


In Figure 4-3, the Cheng Cycle system is operated at the maximum steam injection rate (2.5 kg/sec) with the turbine fired at maximum inlet temperature (1010 degrees C.) on natural gas. Here the water injection CO threshold occurs at about 0.3 kg water per kg fuel, with an associated exhaust NOx reduction of about 85%.

To take advantage of the enhanced NOx reduction capabilities of combined water plus steam injection, the Cheng Cycle Series 7 turbine can be equipped with an optional water injection control package. This package includes a sophisticated control system with control logic that proportions water injection to turbine fuel and injection steam flow. The control logic can be set so the unit will comfortably meet specific regulatory emission limits, or it can be tuned for maximum NOx reduction capability.

Figure 4-4 plots NOx emissions as a function of steam injection rate with the water injection control logic tuned for achieving maximum NOx reduction. For maximum NOx control, water injection rates are adjusted to just reach the CO breakpoint (50% increase) at the associated injection steam rate. Exhaust NOx emissions are in the range of 15-25 ppmvd (15% O_2) for natural gas firing, and 25-40 ppmvd (15% O_2) for distillate fuel firing.

FIGURE 4-4
CHENG CYCLE NOx EMISSIONS
WITH ENHANCED WET NOx CONTROL



Section 5
Additional Developments in Allison Wet NOx Control Technology

Two-Piece low emission combustion can liners

Allison has recently introduced a new line of two-piece "low emission" combustion can liners. These two-piece liners are structurally superior and have improved fuel combustion characteristics, compared to the previous one-piece design. Though they do not directly reduce NOx emissions, these new liners benefit the wet NOx control system in two ways: (1) They produce lower baseline carbon monoxide (CO) and unburned hydrocarbon (UBHC) levels and (2) they better resist wet NOx control CO and UBHC increases.

Recent source test data from the Cheng Cycle facilities at Hershey Chocolate Company and SRI International which are equipped with the two-piece liners revealed exhaust CO levels in the range of 2–7 ppmvd (15% O_2) throughout the normal turbine operating range with combined water and steam injection (natural gas firing).

Nozzle steam injection

Allison has recently introduced a new gas/gas fuel nozzle that can be used to inject saturated steam into the combustion zone when firing gaseous fuels. This system, referred to as "nozzle steam injection," provides excellent wet NOx control capability. It is currently installed on an Allison model 501-KB5 gas turbine in Japan, which fires propane as its primary fuel.

The nozzle steam injection system can replace water injection for gas fuel firing while offering higher NOx removal capability. Preliminary data indicate a CO breakpoint at levels significantly higher than with water injection, with an associated improvement in NOx reduction. It is anticipated that nozzle steam injection in combination with Cheng Cycle manifold steam injection, will yield very high NOx removal efficiencies. At this time, however, it must be emphasized that there are very little performance and emission data available for the system, with the only existing commercial installation operating on propane gas, a non-conventional fuel.

A limitation to nozzle steam injection application is that it is currently restricted to gas fuel firing only. This is a significant restraint where back-up diesel fueling is required.

Other research and development efforts

Other wet NOx control technology developments actively being pursued by Allison engineers include the following:

- -Water/Fuel Premix - A system for premixing water with gaseous fuels in a special chamber upstream of the standard fuel nozzle. This system is expected to significantly improve water injection NOx reduction capability by allowing higher water injection feed rates.

- -Dual fuel-nozzle steam injection - This system will eliminate the current liquid fuel firing restraint for nozzle steam injection.