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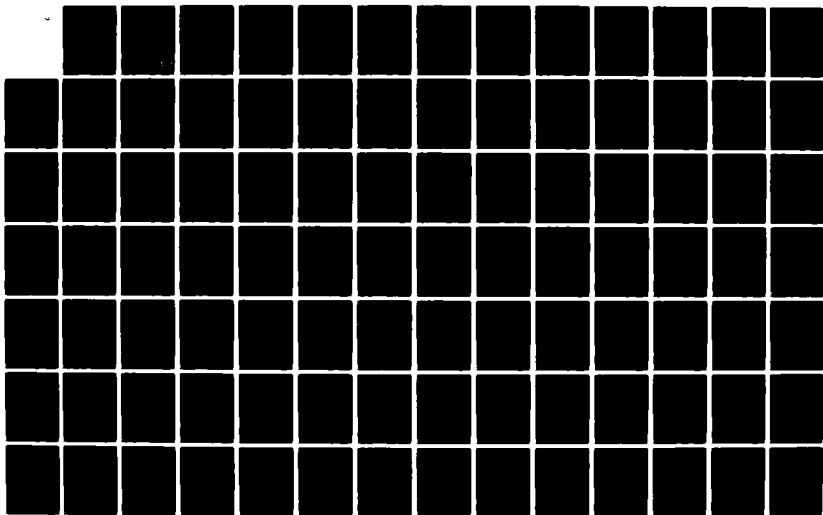
THERMAL ENERGY RECOVERY IN GAS TURBINE ENGINE TEST
CELLS(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA
C A KODRES NOV 83 NCEL-TN-1679

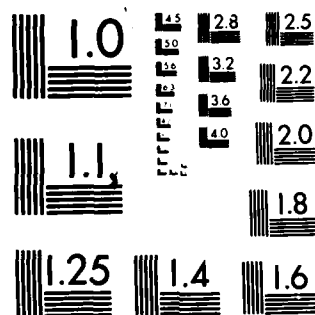
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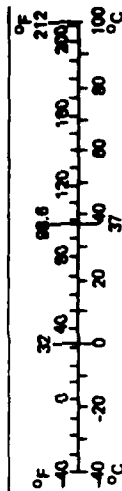
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
in ft yd mi	inches	2.5 30 0.9 1.6	centimeters	cm
	feet		centimeters	cm
	yds		meters	m
	miles		kilometers	km
in ² ft ² yd ² mi ²	square inches	6.5 0.09 0.8 2.6 0.4	square centimeters	cm ²
	square feet		square meters	m ²
	square yards		square meters	m ²
	square miles		square kilometers	km ²
oz lb	acres		hectares	ha
	ounces	28 0.45 0.9	grams	g
	pounds		kilograms	kg
	short tons (2,000 lb)		tonnes	t
tsp Tbsp fl oz c pt qt gal ft ³ yd ³	teaspoons	5 15 30 0.24 0.47 0.95 3.8 0.03 0.76	milliliters	ml
	tablespoons		milliliters	ml
	fluid ounces		milliliters	ml
	cups		liters	l
	pints		liters	l
	quarts		liters	l
	gallons		liters	l
	cubic feet		cubic meters	m ³
°F	cubic yards		cubic meters	m ³
	temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10-286.

Approximate Conversions from Metric Measures

When You Know	Multiply by	To Find	Symbol
millimeters centimeters meters kilometers	0.04 0.4 3.3 1.1 0.6	inches	in
		inches	in
		feet	ft
		yards	yd
square centimeters square meters square kilometers hectares (10,000 m ²)	0.16 1.2 0.4 2.5	miles	mi
		square inches	in ²
		square yards	yd ²
		square miles	mi ²
grams kilograms tonnes (1,000 kg)	0.035 2.2 1.1	acres	ac
		ounces	oz
		pounds	lb
milliliters liters cubic meters	0.03 2.1 1.06 0.28 36 1.3	short tons	st
		fluid ounces	fl oz
		pints	pt
		quarts	qt
Celsius temperature	9/5 (then add 32)	gallons	gal
		cubic feet	ft ³
°C		cubic yards	yd ³
°C	9/5 (then add 32)	Fahrenheit temperature	°F
		temperature	temperature



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>In general, energy recovery is not practical. The exhaust is quickly diluted by the entrained augmentation air, decreasing temperature gradients necessary for heat transfer. Most test cells are used too infrequently to warrant the cost of the hardware. 1

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INTRODUCTION

The energy in the exhaust of a jet engine is immense. To illustrate, with an assumption of only a 25% conversion efficiency, the thermal energy in the exhaust of a J79 engine running at intermediate power is tantamount to the energy required to generate about 280,000 lb/hr of 150-psi steam. To provide a perspective for this magnitude: the average peak steam consumption of the entire Naval Air Station (NAS), Miramar, Calif., on a winter day, is about 35,000 lb/hr.

New jet engines and engines undergoing maintenance or repair are examined in test cells* prior to operational use. In these test facilities, the jet energy is "wasted"; the jet exhaust is diluted and discharged to the atmosphere. Yet, test cells, by their confining geometry, provide an opportunity and, if waterwalls are installed or if heat exchangers are located somewhere in the path of the jet, possibly a means of obtaining part of a vast energy supply.

Operation of Test Cells

Jet engine test facilities have multiple functions: to supply a clean, distortion-free airflow to the engine inlet; to attenuate noise and chemical pollution by the jet; to decrease the kinetic energy of the jet exhaust; and to cool the exhaust sufficiently before dumping either to the atmosphere or to acoustical or environmental treatments.

Although the physics of test cells is extremely complex, their concept is simple; the jet exhaust entrains the cooler surrounding air, losing its energy to this secondary flow, which it carries along through the augmenter. This concept is shown schematically on Figure 1.

The actual mass flow rate of the augmentation airflow is important to the functions of the test cell. Too little augmentation airflow: (1) allows the exhaust gas to recirculate back around to the engine inlet, resulting in hot spots and performance degradation; (2) allows the test cell to heat up; and (3) also results in an excess density of visible emittants, possibly violating Ringelmann number restrictions. Too much air entrainment induces excessive pressure gradients along and across the test cell augmenter, creating structural problems. Too much augmentation airflow can also cause errors in engine thrust measurements (Ref 1).

*No distinction will be made between hush houses, where the engine remains mounted on the aircraft, and test cells, where the engine is tested off the aircraft.

Scope

For several reasons, very little thought has been given to test cell energy recovery.* First, jet engines are rarely tested for long durations. A few hours per day of test cell usage is maximum. Second, the dilution of the jet exhaust with the augmentation air decreases temperature gradients and, therefore, the potential for heat transfer from the exhaust. Even a 25% energy conversion efficiency is unlikely with most test cells. Finally, there are side effects to energy recovery that affect the ability of a test cell to perform its functions.

Waterwalls will decrease jet exhaust temperatures, beginning exactly at the nozzle. The environmental ramifications are, generally, bad. If combustion was complete, lower gas temperatures would decrease equilibrium concentrations of both NO_x and CO. At the higher power settings, however, combustion continues out into the augmenter. (Afterburning jets exhaust as much as 10% of their fuel (Ref 1).) Premature cooling of the exhaust will slow any combustion reactions still taking place. Unburned hydrocarbons, carbon monoxide, even raw fuel, could be carried into the atmosphere. The effect on particulates is uncertain; it can be presumed that changing the combustion chemistry will change the particulate concentration.

Lowering gas temperatures also changes the flow characteristics of the jet, changing kinetic energy, noise generation, and augmenter pressure gradients.

Some side effects of augmenter energy recovery are beneficial. Waterwalls will eliminate burnout problems of the liners and acoustic pads. Waterwalls will also decrease structural thermal shock by damping out temperature fluctuations at startup, shutdown, and while changing power settings.

Convection, water tube heat exchangers located close to the nozzle will introduce the same problems as waterwalls. In addition, the pressure gradient across the device could induce engine back pressure problems. Convection heat exchangers located further down the augmenter tube will have little effect on augmenter gas temperatures, but high engine back pressures still have to be faced.

Regardless, such a large energy source should be investigated. This report summarizes the first step: an analytical study of the economics of test cell energy recovery. The study is limited to thermal energy recovery; other forms of energy, such as kinetic energy, are not included. Side effects are also neglected. The analyses of the side effects will be lengthy; if test cell energy recovery is not economically feasible, an examination of side effects is moot.

Both steam and electricity are considered as products of energy recovery--steam directly and electricity off a Rankine cycle. Four possible heat exchanger** configurations are analyzed (see Figure 1):

*FFV, the Swedish aerospace company, has done some work in this area, including the construction of a small energy recovery system.

**The terms "heat exchanger" and "boiler" will be used interchangeably.

1. Convection, water tube heat exchanger located in the exhaust path at the augments exit
2. Waterwalls located near the augments inlet where the primary mode of heat transfer would be radiation
3. Waterwalls located near the augments exit (for this configuration, the primary mode of heat transfer would probably be convection)
4. Convection, water tube heat exchanger located near the nozzle of the engine

The plan-of-attack is to select several test cells in the San Diego area, evaluate their energy recovery potential, and then generalize the results, reinforced with parametric studies.

TEST CELL SIMULATION

The major burden is determining how much heat can be transferred from the jet exhaust to waterwalls or to a water tube heat exchanger. Once determined, steam generation and, subsequently, the economics of energy recovery can easily be computed. Sizes, shapes, wall constructions, and flow rates of test cells are almost limitless. The obvious approach to the analyses is to formulate and utilize a flexible mathematical model.

The complexities in modelling test cells are manifest. Re-examine Figure 1 and consider the following augments characteristics: multiple, nonconcentric flows, each at a different velocity; turbulence; flow separation; all three modes of heat transfer, simultaneously; extreme changes in temperatures and, thus, variable properties; and nonsymmetric, three dimensional geometries. In addition, some tests are of short duration, resulting in a highly transient situation. These complexities lead to a transient nonlinear problem with coupled energy, mass, and momentum transfer. Numerical techniques are necessary.

Even so, to make a test cell simulation attainable, assumptions must be made. The first assumption is to restrict the analyses to the augments duct. Jet and augmentation flows are treated as boundary conditions. For this present work, the emphasis is on heat transfer. The modelling tactics will be to describe fluid flow empirically but use first principles to determine heat transfer rates. With this in mind, the following additional assumptions are made:

1. Flows are one-dimensional, passing through a cylindrical augments
2. Steady state, steady flow is stipulated
3. Both the jet and augmentation air are ideal gases

4. Flow within the jet and within the augmentation air can be considered turbulent and perfectly mixed
5. Pressure gradients along the augmeter are negligible compared with temperature gradients and can be neglected
6. The jet nozzle is located exactly at the inlet to the augmeter tube
7. The augmeter walls are black, the jet is gray, and the augmentation air is transparent to thermal radiation
8. Axial radiation along the jet has a negligible effect on temperatures; all radiation is from jet to wall or from wall to wall
9. Heat transfer between the jet and the augmentation air is negligible compared with enthalpy changes due to mixing
10. Radiation from the jet to any heat exchanger located past the augmeter exit is negligible

Jet flow through the augmeter is empirically modelled using the curve fits of Becker et al. (Ref 2). Their data are from cold jets, and their test rig is smaller than test cells, necessitating some modification to the empirical constants. Specifically, Becker's relationships have been adjusted to be able to predict the arrival of the jet to the wall at locations observed experimentally at the hush houses, NAS Miramar (Ref 3 and 4).

To model the heat transfer, the augmeter tube is divided into axial segments, with the jet, augmentation flow, and inner and outer liners considered as separate sections. Temperature is assumed constant throughout each section-segment. Flows are perfectly mixed. Conservation of energy is then applied to each segment of each section, and the resulting equations, along with the equations of continuity, are solved simultaneously to determine temperatures and heat fluxes along the augmeter assembly. Due to the nonlinearities, an iterative technique is necessary; the Gauss-Seidel method, with relaxation, is employed for this purpose.

A detailed derivation of the model, including a discussion of the assumptions and the accuracy of the simulation, is enclosed as Appendix A.

ENERGY RECOVERY ECONOMICS

By supposition, a waterwall or a convection, water tube heat exchanger is added to the augmeter. Once potential test cell steam (or electricity) generation has been determined, its accumulated value is computed and compared with the initial cost of the waterwalls or water tube boiler, i.e., a savings-to-investment ratio (SIR) is calculated.

Appendix B includes a description of the relationships used to calculate SIR.

SAN DIEGO TEST CELL ENERGY RECOVERY

Five test cells located in the San Diego area are examined to determine their potential for energy recovery. These cells are selected to provide a variety of sizes and applications, ranging from a hush house down to a 2-foot-diam cell used for testing helicopter engines. Specifications and operating characteristics are summarized in Appendix C.

For these sites, energy is recovered in the form of 350°F saturated steam.* The energy recovery potential of each cell is illustrated by means of two figures. First, the accumulated present value of the generated steam is plotted against the economic life of the steam generation equipment. A Navy average is used for the value of the steam. Predictions of discount and escalation rates are employed (Ref 5). The second approach is to estimate the cost of the energy recovery equipment and plot the energy recovery potential as an SIR (again against the economic life of the equipment).

Hush House No. 1, NAS Miramar

Figures 2 and 3 show the potential for energy recovery in the NAS Miramar Hush House No. 1. The augmentor is large and approximately elliptical, with an overall length of 90 feet and a cross-section minor axis of about 11 feet. A water tube boiler at the augmentor exit (Configuration No. 1 of Figure 1) and both waterwall configurations are examined. These figures reflect testing of both the TF30 (F-14A) and J79 (F-4) at intermediate or afterburning. Although other engines are tested, the TF30 and J79, together, account for about 75% of the total hush house usage.

To summarize: the generation of steam in this facility is not economically feasible. Waterwalls produce very little steam and, in addition, generate this small amount very uneconomically. A large water tube heat exchanger, such as the 220,000 ft² device studied here, can generate plenty of steam during afterburning (A/B), as much as 95,000 lb/hr, but A/B testing is limited, and these large boilers are very expensive. This particular heat exchanger's estimated cost is about \$6 million; thus, the SIR is low.

"A" Test Cell, NAS Miramar

The NAS Miramar "A" test cell, with an augmentor cross-sectional diameter of about 6 feet, can be classified as a "mid-sized" facility.

The economics of thermal energy recovery from this test cell is summarized on Figures 4 and 5. Waterwalls located near the augmentor inlet are not economically feasible. Waterwalls placed along the last 20 feet of the augmentor, however, are feasible although the steam generation is low (see Figure 4). For this configuration, the SIR reaches one after about 22 years. Water tubes placed near the augmentor

*Steam generation at 350°F, 138 psia is assumed throughout this work.

exit are economically feasible, and the steam generation rate is high, averaging 480,000 lb/hr at A/B and about 40,000 lb/hr at intermediate power settings. The SIR reaches one after 7 years.

Steam loads at NAS Miramar average about 30,000 lb/hr. Therefore, 480,000 lb/hr is considerably more steam than the base can consume. Thermal energy is not easily stored; a customer for the excess steam is necessary. If not found, much of the steam generated during A/B testing would not be used, and the above water tube SIR is inflated.

The TF30 is the only engine tested, yet this cell has had a very high frequency of A/B testing - 62.6 total hours in 1982 - and this accounts for much of the positive energy recovery economics. The practicality of installing some type of energy recovery system depends, to a very large extent, on continuing this schedule into the future.

Test Cell 11, NARF North Island

Test Cell 11 is a small cell used to test the T58 helicopter engine. The diameter of the augments is about 2-1/2 feet; its length is 10 feet.

Figures 6 and 7 summarize the energy recovery capability of this cell. Again, the installation of waterwalls is not economically feasible. The use of water tubes placed at the exit to the augments is economically feasible, with the SIR reaching one after 10 years. Approximately 8,000 lb/hr of steam is generated in a 6,600 ft² water tube heat exchanger, only a dribble compared with the steam load at NAS North Island.

Test Cell 14, NARF North Island

Test Cell 14 is a mid-sized facility used, primarily, to test the J79 gas turbine engine. The specifications of this cell are similar to those of the NAS Miramar "A" test cell.

The economics of energy recovery from cell 14 are illustrated by Figures 8 and 9. This cell is used infrequently, and any form of energy recovery is economically unfeasible.

Test Cell 19, NARF North Island

Test Cell 19 is also a mid-sized cell used to test the J79. It has an augments cross-sectional diameter of about 8 feet with a length of almost 80 feet.

Figures 10 and 11 show the potential for energy recovery in Test Cell 19. Both waterwalls and water tubes are economically marginal (i.e., within possible error in estimating the cost of the equipment). The steam generation rate is moderate. A 115,000 ft² water tube boiler will generate an average of 20,000 lb/hr of steam during intermediate power tests and about 310,000 lb/hr during A/B.

A comparison with the NAS Miramar "A" test cell is informative. Although Test Cell 19 is used more frequently, 210* hr/yr compared with about 135 hr/yr for the Miramar test cell, much less energy recovery

*Intermediate and afterburning only. Idle and part power settings do not produce temperature gradients high enough for thermal energy recovery and are not considered.

potential exists. The J79 exhausts somewhat less than the TF30, but the major difference is the low A/B testing, only 18 hr/yr in Test Cell 19 compared with more than 62 hr/yr in the Miramar "A" test cell.

PARAMETRIC STUDY OF TEST CELL ENERGY RECOVERY

A perusal of the five cells just analyzed plus the others described in Appendix C suggests that the test cells can be segregated into three size categories for parametric examination: large, mid-sized, and small. The distinction is based upon augmentor diameter. Large test cells will be represented by NAS Miramar Hush House No. 1, mid-sized cells by the NAS Miramar "A" test cell, and small cells by NARF North Island Test Cell 11.

Again, both the accumulated present value of the steam and SIR will be used as measures of feasibility. Perhaps somewhat redundant, the value of the steam is an indication of steam generation magnitudes while SIR is an indication of economics. Both figures are included also for documentation purposes. They can be used to evaluate test cells not specifically covered.

Large Test Cells

It was not emphasized in the discussion of NAS Miramar Hush House No. 1, but energy can be recovered in the large test cells, by water-walls or by downstream water tubes, only during afterburning tests. All other engine power settings are nonproductive. This is illustrated by Figures 12 and 13, which isolate the energy recovery capabilities of the different power settings. Augmentor exit water tubes are employed in these figures. This is the most efficient energy recovery configuration for Hush House No. 1. Note that some of the hush houses are capable of simultaneously testing two engines.

Although the A/B steam generation rate is potentially high, perhaps 100,000 lb/hr while testing the TF30, the total hours of A/B testing is very low. A testing frequency of 180 hr/yr, or an average of 0.5 hr/day, was assumed for Figures 12 and 13. This schedule is characteristic of intermediate power tests in the San Diego cells, but afterburner tests are conducted less frequently and are of a much shorter duration. An A/B test frequency of 30-40 hr/yr is a better estimate, thus, a 25-year SIR of 0.1, rather than 0.5 (see Figure 13).

The absence of any potential for energy recovery during gas turbine intermediate power tests can be attributed to the high augmentation air flow rates inherent in the large test cells. Augmentation air flows are typically 1,200 to 1,500 lb/sec compared with 400 to 500 lb/sec through mid-sized cells. The engine exhaust is cooled down to about 200°F by the time it reaches the wall; it is even cooler when it reaches the augmentor exit. At this temperature, the exhaust cannot, of course, be used to generate 350°F steam.

Energy recovery will never be economically feasible in the large test cells unless a system capable of recovering energy during intermediate power testing is employed. Either of two methods can accomplish this:

1. Recover the energy from the gas turbine exhaust before it is mixed with the augmentation air and cooled
2. Transfer the energy from the 200°F exhaust/air mixture to some highly volatile working fluid and use this fluid to generate electricity

The first method requires placing the heat exchanger up near the nozzle of the engine, Configuration No. 4 of Figure 1. Figures 14 and 15 parametrically examine this configuration when employed on large test cells. Figure 14 shows the potential of a 500 ft² heat exchanger. Approximately 85 2-inch-diam water tubes stretch across the augmentor just behind the test engine, probably near the maximum number of tubes that could reasonably be placed there. Note that it takes an average of 4 hr/day of testing to make this heat exchanger feasible.

Figure 15 sets the daily test cell operation at 0.5 hr/day and illustrates the effect of increasing heat transfer area (i.e., increasing the number of water tubes). It takes about 4,000 ft² of surface area to be economically feasible.* This is equivalent to 700 tubes stretched across the augmentor. In addition to the design problems innate to this configuration, the pressure drop across 700 tubes would probably induce unacceptable engine back pressures. Configuration No. 4 is not workable.**

The second method of recovering energy, employing a working fluid with a low boiling point to generate electricity, is the topic of a subsequent section.

Mid-Sized Test Cells

The examination of the San Diego cells, particularly the NAS Miramar "A" test cell, showed that energy recovery in mid-sized test cells could be economically feasible with a favorable test schedule. Steam can be generated from the exhaust of gas turbines tested at intermediate power in mid-sized cells. Augmentation air flow rates are moderately low, and the exhaust temperature is still about 400°F to 450°F when it reaches the augmentor wall.

Both water tubes and downstream waterwalls can generate steam; but the upstream waterwalls (Configuration No. 2) are of no use. Radiation from jet to the upstream walls is maximum; however, convection heat transfer from these walls to the cold augmentation air is also maximum (see Figures A-4, A-5, and A-6). There is little net heat transferred.

Figures 16 through 19 parametrically show the potential for energy recovery from engines being tested at intermediate power in the mid-sized cells. A comparison of Figures 16 and 17 with Figures 18 and 19 discloses the superiority of the water tubes over the waterwalls. Figures 16

*Probably more since the cost of the heat exchanger was not increased with heat transfer area.

**The mid-sized and small test cells already have the potential to generate steam at intermediate. For them, there is no need to consider such a radical configuration.

and 18 show the water tubes generate about 60 times more steam (actually, 40,000 lb/hr compared with only 700 lb/hr by the waterwalls). Figures 17 and 19 show the water tube configuration has an SIR about four times higher. The superiority of water tubes exists with all sizes of test cells and can be attributed to the smaller heat transfer surface area of the waterwalls.

Yet, for even the downstream water tube heat exchanger to be economically feasible for mid-sized test cell energy recovery, about 1 hr/day of intermediate testing is required. This frequency, 365 hr/yr, is about twice the usage averaged by the San Diego facilities. More than a trace of A/B testing is still required in order to make energy recovery feasible.

A huge amount of steam can be generated when gas turbines are tested at A/B power settings in a mid-sized cell. Figure 20 is analogous to Figure 17 except that the engines are being tested while afterburning rather than at intermediate. Examining these two figures together is enlightening. They show the combinations of intermediate and A/B testing that, roughly, make energy recovery feasible in mid-sized cells, for example, 0.5 hr/day (180 hr/yr) of intermediate power testing with an SIR of about 0.3 after 25 years combined with 0.05 hr/day (18 hr/yr) of A/B testing with an SIR of about 0.7.

Small Test Cells

Energy recovery in small test cells involves different limitations than energy recovery in the larger cells. There is little or no augmentation air; therefore, temperature gradients are higher. However, engines tested in these cells are much smaller; there is much less thermal energy available for steam generation. Also there is no afterburning. It follows that steam can usually be generated in these cells but not very much of it.

Figures 21 and 22 summarize the energy recovery potential of small test cells. Steam is being generated at a rate of about 8,000 lb/hr. The 25-year break-even SIR occurs when test cell usage reaches about 36 hr/yr. A steam generation rate of only 8,000 lb/hr for perhaps 1/2 hr/day would not contribute much toward satisfying the steam load on the base and, despite any favorable SIR, would not warrant the tribulations involved in maintaining the boiler.

Thermal energy recovery in small test cells might become more attractive if several of them could be combined. The steam generation rate would not improve, unless several cells could be scheduled for testing at the same time, but the steam output would be steadier, and the total steam contribution much higher (for example, cells 9, 10, 11, and 12 at NARF North Island are all within a space of 60 feet and could, conceivably, all be ducted to a single heat exchanger).

ENERGY RECOVERED AS ELECTRICITY

The energy recovery analyses presented to this point were conducted with steam as the product. Electricity could also have been produced. Local conditions might make one or the other more valuable at a particular site, but, by using Navy averages for the values of energy, supply

and demand can be expected to prevail. Similar results would be anticipated from similar analyses using either steam or electricity as the product of energy recovery.

Two situations have been encountered, however, in which the generation of electricity would seem to be preferable. The first occurs when trying to recover energy from a large cell testing a gas turbine at intermediate power. Engine exhaust temperatures, diluted by the high augmentation air flow, are too low to generate 350°F steam. Since energy recovery during intermediate power testing is essential if the concept is to be economically feasible, some other product must be found. It was suggested that the energy in the jet exhaust could be transferred to some highly volatile working fluid (at high pressures but low temperatures) and this fluid expanded through a turbine to generate electricity.

The second situation in which the generation of electricity would appear to be preferable occurs during A/B testing in mid-sized cells located on the smaller Navy bases. The problem is excess steam. If a large water tube boiler is employed, as much as 500,000 lb/hr of 350°F steam can be generated from the exhaust of a TF30 during afterburning tests. This is more steam than many facilities can consume. Yet, for energy recovery to be feasible in mid-sized cells, the energy of afterburning engines must be utilized. Either the steam must be stored or a customer found for the excess. Neither is practical. Thermal energy is not easily stored, and potential customers for the steam would probably not be interested in such an erratic, unpredictable source. The generation of electricity rather than steam may be a solution to the problem. Many utility companies will buy (or compensate for) electricity generated locally.

Thus, the feasibility of energy recovery in the form of electricity is examined for the large and mid-sized test cells. These analyses are conducted by again employing the numerical model. It is assumed that electricity will be generated off a Rankine cycle, with energy supplied from the jet exhaust through waterwalls or through a water tube heat exchanger. A hypothetical organic fluid is substituted for the steam*; otherwise, the analyses are identical to previous efforts. The heat transfer efficiency is inherent in the model. Efficiencies of the other Rankine cycle components are stipulated,

$$\eta_{\text{pump}} = 0.75$$

$$\eta_{\text{turbine}} = 0.85$$

$$\eta_{\text{generator}} = 0.90$$

and multiplied by the energy recovered from the exhaust to provide a magnitude for electricity generation.

*The organic fluid is assumed to vaporize at 120°F with a heat of vaporization of 145 Btu/lb.

Figures 23 and 24 show the potential for energy recovery, as electricity, from jet engines being tested at intermediate power in the large cells. An improvement over steam is shown as would be expected (energy recovery in the form of 350°F steam was negligible). The improvement is small, however. A 25-year break-even requires a 4 hr/day intermediate power test frequency, about eight times the average of the San Diego cells. Too much A/B testing is still necessary in order to make energy recovery economically feasible in the large cells.

The generation of electricity in mid-sized cells shows somewhat more promise. When testing at intermediate, there is little difference in the economics of energy recovery with electricity or with steam as the product. Figures 16 and 17 can be used to evaluate energy recovery within reasonable accuracy. With the working fluid assumed* for this study, the generation of electricity from the energy in the exhaust of afterburning engines is less favorable. Figures 25 and 26 show the potential for generating electricity in mid-sized cells testing engines at A/B. The SIR for electricity generation is roughly one-third the SIR calculated for an analogous system generating steam. Still, the energy recovered as electricity from afterburning engines is equivalent to the energy required to generate 160,000 lb/hr of steam. This is quite significant if all this energy can now be used.

Economic feasibility is determined by energy recovery during both intermediate and afterburning tests. An example was provided earlier to illustrate the feasibility of energy recovery as steam in mid-sized cells. It is informative to repeat this same example with electricity as the product. Generating steam, 0.5 hr/day of intermediate testing combined with 0.05 hr/day of afterburning tests yields an energy recovery SIR of one after 25 years. Generating electricity (from Figures 17 and 26), 0.5 hr/day of intermediate testing must be combined with 0.15 hr/day (54 hr/yr) of A/B testing to yield the same SIR.

The generation of electricity in the NAS Miramar "A" test cell, a cell with a high frequency of afterburning tests, would be expected to be feasible, and it is. This cell is used an average 0.2 hr/day (72.9 hr/yr) for intermediate power tests, yielding an SIR of 0.25 after 25 years; and used approximately 0.17 hr/day (62.6 hr/yr) for A/B tests, yielding an SIR of 0.85. Thus, the total savings-to-investment ratio reaches about 1.1 after 25 years.

CONCLUSIONS

Thermal energy recovery is not economically feasible in hush houses and large test cells. The augmentation air flow rates are very high, rapidly cooling the engine exhaust and eliminating temperature gradients necessary for steam generation. Electricity generation off an organic Rankine cycle, although economically better, still requires too much test cell usage to be feasible.

*The selection of an optimum organic fluid is itself a major task, the choice varying with cell geometry, test schedule, and other conditions.

Energy recovery in most small test cells is unfeasible. These facilities are normally used for testing a single class of gas turbine; the hours of operation are limited. Even if the S/R is favorable, the engines are small and steam or electricity generation is so low that it would not be worth the effort. An exception might occur if energy recovery systems for several small cells could be combined (e.g., ducting the augmentor exit gases of several cells to a single heat exchanger).

Energy recovery in the mid-sized cells is marginal, with the feasibility depending upon cell usage and energy loads. Steam generation rates can be excellent because augmentation flows are lower than in the large cells, yet mid-sized cells are often used for testing the larger engines. If the Naval facility is small, steam generation rates may even exceed the steam demand, particularly when testing afterburning. When this occurs, the generation of electricity is an alternative to be considered.

A water tube boiler located outside the augmentor exit, Configuration No. 1 of Figure 1, is the only practical choice for an energy recovery heat exchanger. Augmentor waterwalls and water tubes inside the augmentor have too small a heat transfer surface area. The steam generation potential is much too low.

COMMENTS

Boiler design problems have not been examined, but they will tend to discourage thermal energy recovery. Boilers do not function particularly well when subjected to cyclic operation. Not only is the incessant mechanical expansion and contraction of the pressure components a difficult design problem, but the water swell occurring at each start up presents a control problem and certainly results in a significant quantity of boiler water wastage. Tube or waterwall chemical corrosion can be expected. Surface erosion is also probable. A gas velocity of 150 ft/sec is about the practical limit that the heat exchanger components could withstand. If the heat exchanger is outside the augmentor, the engine exhaust can be slowed to acceptable velocities before entering the device. For waterwalls and for water tubes inside the augmentor, heat transfer surface erosion would be a very serious problem. In addition, water tubes inside the augmentor would have to withstand blasts of 3,000°F exhaust whenever afterburning tests were conducted.

Although not intentionally included in these analyses, some knowledge of potential side effects was acquired as a byproduct of the heat transfer calculations. The only energy recovery configuration that has a significant effect on flow characteristics inside the augmentor is upstream water tubes (Configuration No. 4 of Figure 1). It is unlikely that this configuration will ever be employed; the design problems are presumably insurmountable. Very little energy is removed from the jet by waterwalls, and side effects will probably be negligible (compare stack gas temperatures on Table 1 with and without waterwalls). The downstream water tubes, Configuration No. 1, have an appreciable effect on flow characteristics, but only outside the augmentor tube.* Thus, side effects to test cell energy recovery may not be a major factor.

*The effect on engine back pressures could still be a problem.

Stack gas temperatures are another byproduct of the heat transfer calculations. Table 1 summarizes the effect of energy recovery boilers on the temperature of the jet exhaust. As suggested above, the effect of the waterwalls is very small. Convection, water tube configurations, however, significantly lower stack gas temperatures, a beneficial side effect when further environmental or acoustical treatments are necessary.

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NOMENCLATURE

A	Surface area
C_p	Specific heat
C_t	Craya-Curtet Number, Equation A-1
COST	Assumed value of steam, Equation B-1
D	Diameter
D_{EQV}	Equivalent diameter
DISC	Discount rate
e	Boiler effectiveness
ESC	Escalation rate of the cost of steam or electricity, Equation B-2
F, F1	Radiation shape factors
h	Enthalpy
$\hat{h}$	Convective heat transfer film coefficient
k	Coefficient of thermal conductivity
$\dot{M}$	Mass flow rate
$\Delta \dot{M}$	Augmentation flow entrained by the jet
PRICE	Initial cost of waterwalls or heat exchanger, Equation B-3
PV	Present value
$\dot{q}_{COND}$	Conduction heat transfer
$\dot{q}_{CONV}$	Convection heat transfer
$\dot{q}_{RAD}$	Radiation heat transfer
$\dot{q}_{STM}$	Heat transferred from jet and augmentation airflow to the steam
r^*	Ratio of jet nozzle area to cross-sectional area of augments, Equation A-1
R	Radius
R(Z)	Radius at distance Z from the augments inlet

SIR	Savings-to-investment ratio, Equation B-3
T	Temperature
TIME	Average utilization of the test cell, Equation B-1
UA	Product of boiler overall heat transfer coefficient and heat transfer area
VALUE	Value of the steam or electricity generated
V	Velocity
Z	Distance from the augments inlet
α	Radiation absorptivity
Δh_{fg}	Heat of vaporization of steam
ΔT_m	Logarithmic mean temperature difference, Equation A-10
ϵ	Radiation emissivity
μ	Viscosity
ρ	Density
σ	Stefan-Boltzmann constant
η	Efficiency

Subscripts

AUG	Refers to augments tube
GAS	Refers to the mixed jet and augmentation flow
I, J	Segment node designations, see Figure A-1
IL	Refers to inner liner of augments
I→J	From segment "I" to segment "J", etc.
JET	Refers to jet exhaust
JET→IL	From the jet to the inner liner of augments, etc.
N	Number of axial segments of the augments tube, see Figure A-1
NN	Economic life of waterwalls or energy recovery heat exchanger, Equation B-2
OL	Refers to outer liner of augments

REF	Reference, used for defined properties
SEC	Refers to augmentation (secondary) air flow
STACK	Refers to jet and augmentation flow leaving the convection boiler
STM	Refers to steam generated
TUBE	Refers to water tubes of convection heat recovery heat exchanger
∞	Refers to ambient conditions

Abbreviations

A/B	Afterburning
INTER	Intermediate
ORC	Organic Rankine cycle

Table 1. Effect of Gas Turbine Test Cell Energy Recovery on Stack Gas Temperatures

Engine	Type of Energy Recovery Equipment	Total Gas Flow Out the Stack, Jet Exhaust and Cooling Flow (lb/sec)	Avg Stack Gas Temp Without Energy Recovery (°F)	Avg Stack Gas Temp With Energy Recovery (°F)
a. Large Test Cell				
J79 afterburning	(1) With water tubes at augmentor exit, 250,000 ft ²	1,700	420	370
	(2) With waterwalls along last 50 feet of augmentor	1,700	420	415
TF30 afterburning	(1) With water tubes at augmentor exit, 220,000 ft ²	1,450	650	425
	(2) With waterwalls along last 60 ft of augmentor	1,450	650	640
b. Mid-Sized Test Cell				
TF30 at intermediate	(1) Water tubes at augmentor exit, 80,000 ft ²	660	425	370
	(2) Waterwalls along last 20 ft of augmentor	660	425	420
TF30 afterburning	(1) Water tubes at augmentor exit, 80,000 ft ²	660	1,220	560
	(2) Waterwalls along last 20 ft of augmentor	660	1,220	1,205
c. Small Test Cell				
T58 at intermediate	(1) Water tubes at augmentor exit, 6,600 ft ²	20	820	465
	(2) Waterwalls along last 38 ft of augmentor	20	820	810

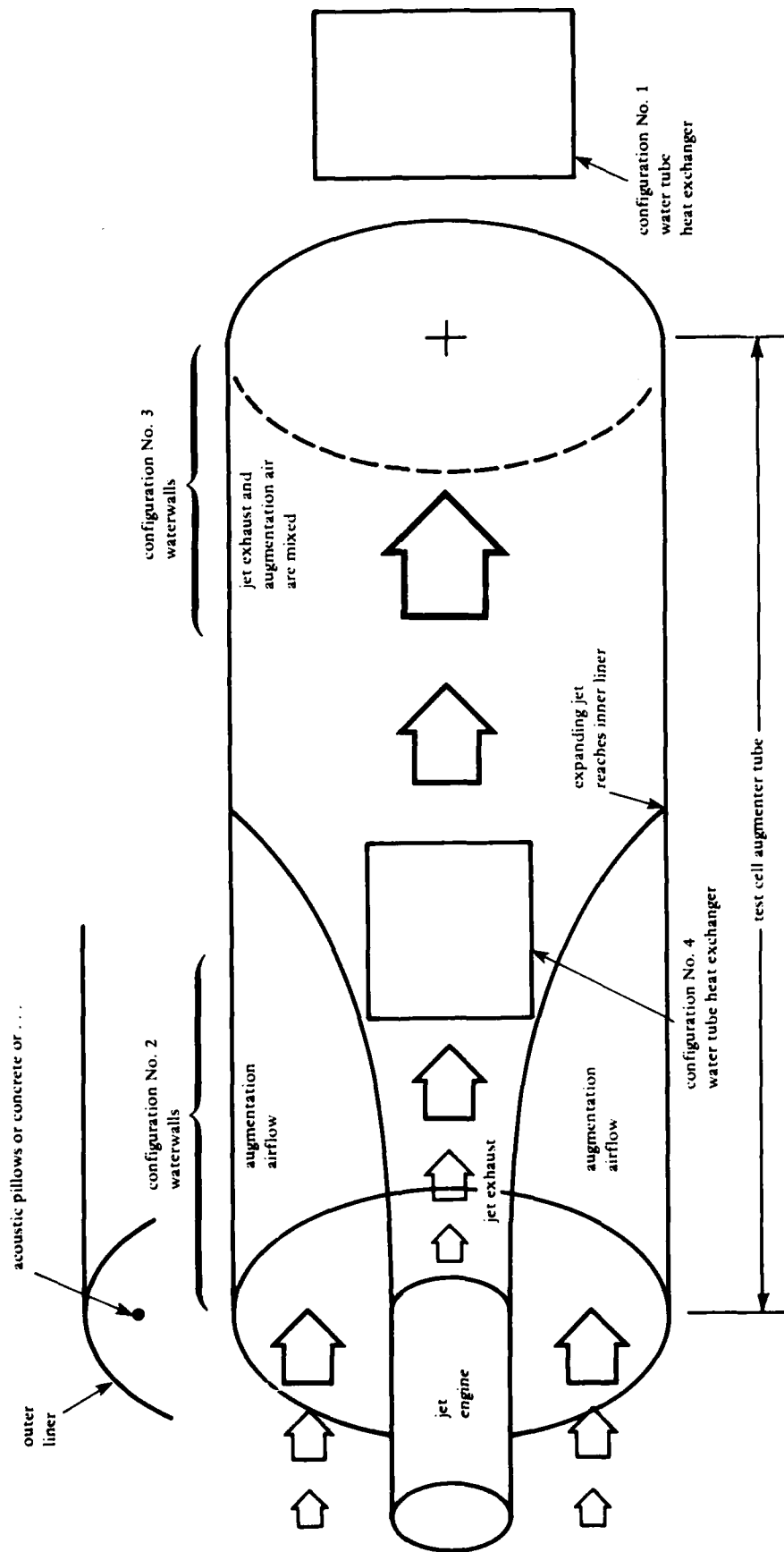
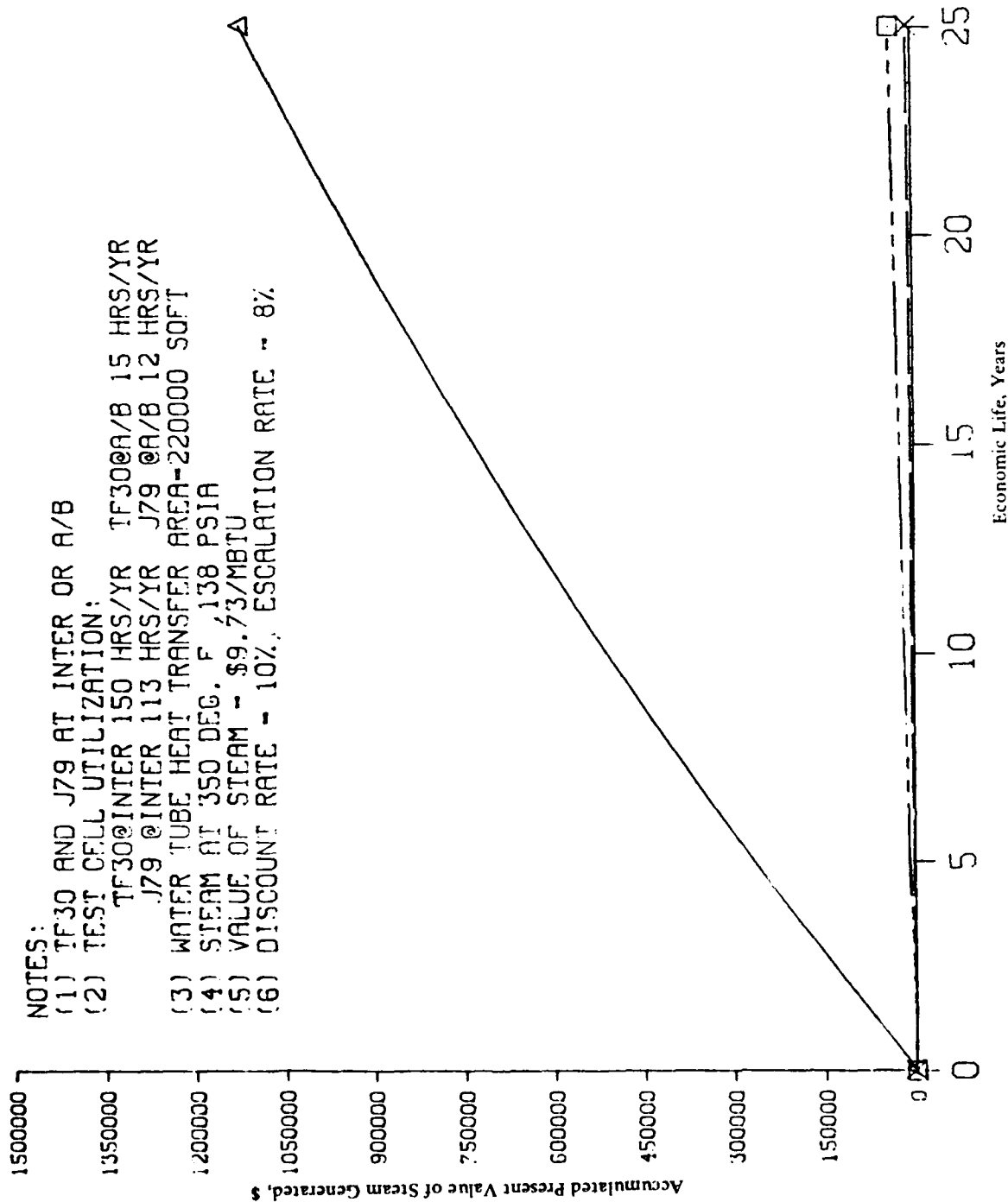


Figure 1. Schematic of gas turbine engine test facility augmenting tube and proposed boiler configurations.



Legend

△ H2O TUBE HEAT TRANSFER

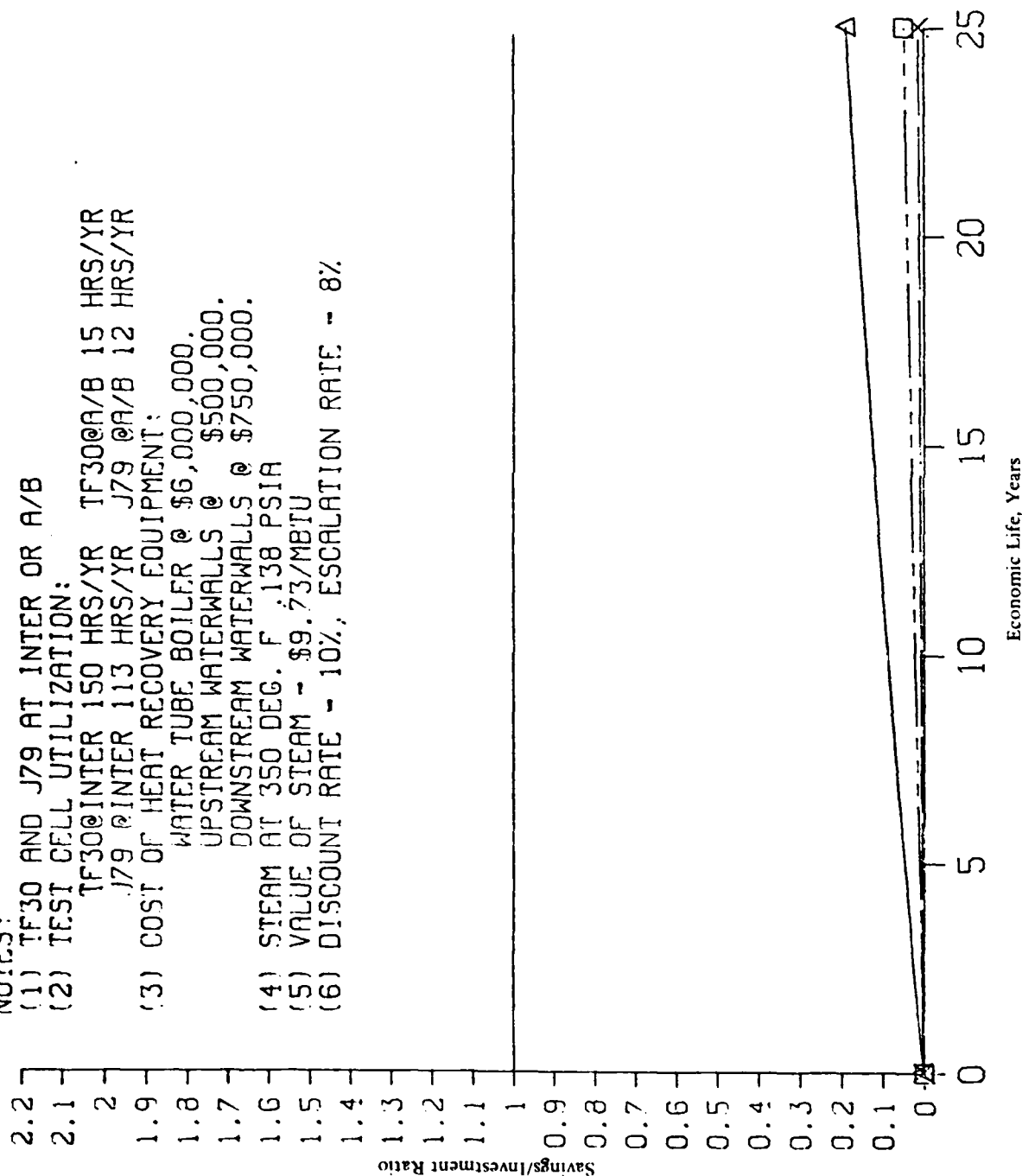
× H2O WALLS 1ST 30FT

□ H2O WALLS 1ST 60FT

Figure 2. Generation of steam in gas turbine engine test facilities: NAS Miramar Hush House No. 1.

NOTES:

- (1) TF30 AND J79 AT INTER OR A/B
- (2) TEST CELL UTILIZATION:
TF30@INTER 150 HRS/YR TF30@A/B 15 HRS/YR
J79 @INTER 113 HRS/YR J79 @A/B 12 HRS/YR
- (3) COST OF HEAT RECOVERY EQUIPMENT:
WATER TUBE BOILER @ \$6,000,000.
UPSTREAM WATERWALLS @ \$500,000.
DOWNSTREAM WATERWALLS @ \$750,000.
- (4) STEAM AT 350 DEG. F. 138 PSIA
- (5) VALUE OF STEAM - \$9.73/MBTU
- (6) DISCOUNT RATE - 10%, ESCALATION RATE - 8%.

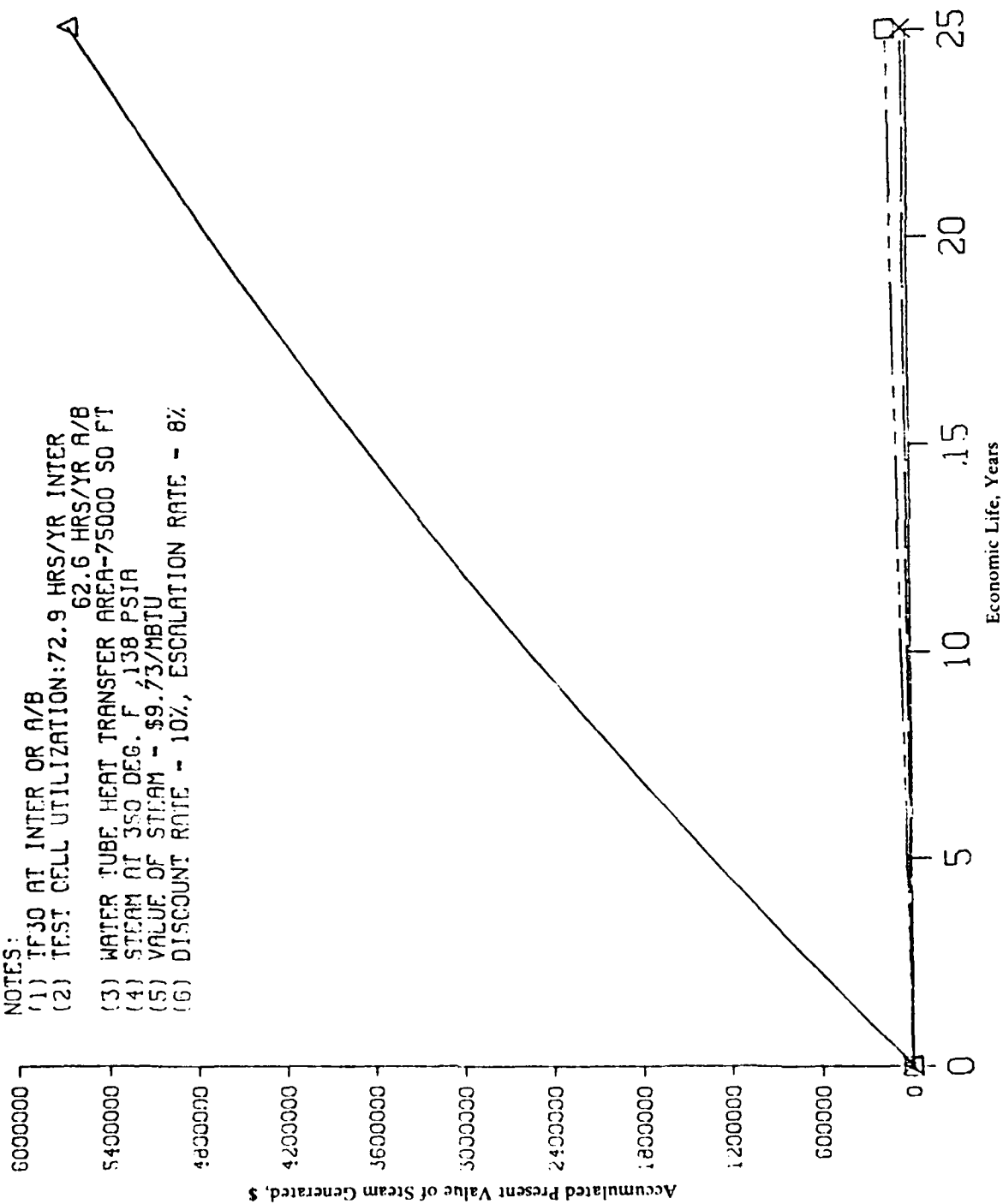


Legend

- △ H2O TUBE
- × H2O WALLS 1ST 30FT
- H2O WALLS LAST 60FT

Figure 3. Economics of gas turbine engine test facility energy recovery: NAS Miramar Hush House No. 1.

NOTES:
 (1) IF 30 AT INTER OR A/B
 (2) TEST CELL UTILIZATION: 72.9 HRS/YR INTER
 62.6 HRS/YR A/B
 (3) WATER TUBE HEAT TRANSFER AREA - 75000 SQ FT
 (4) STEAM AT 350 DEG. F, 138 PSIA
 (5) VALUE OF STEAM - \$9.73/MBTU
 (6) DISCOUNT RATE - 10%, ESCALATION RATE - 8%

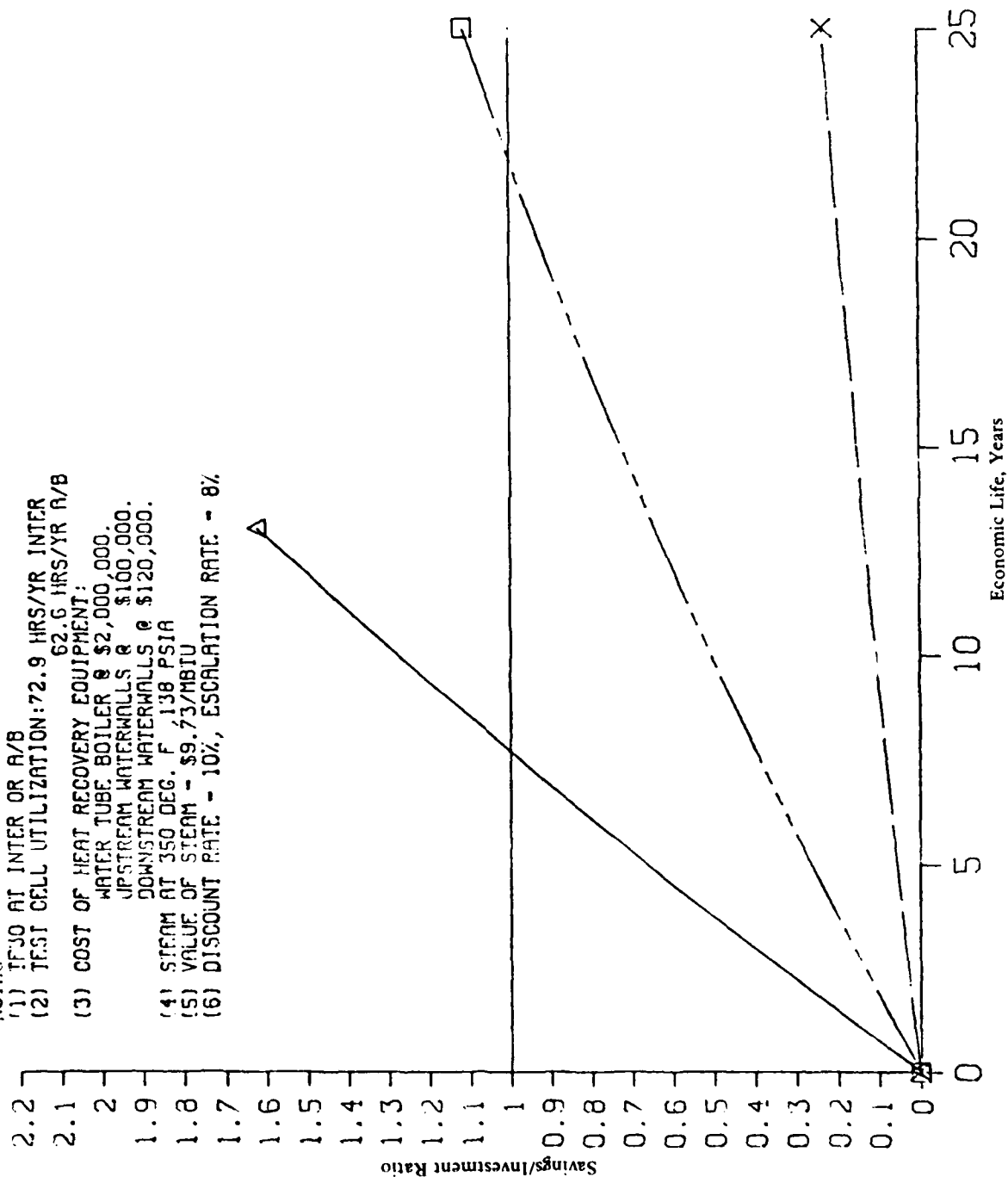


Legend

- △ H2O TUBES (NUCME)
- × H2O WALLS 1ST 15FT
- H2O WALLS 1ST 20FT

Figure 4. Generation of steam in gas turbine engine test facilities: NAS Miramar Test Cell "A".

- NOTES:
- (1) IF30 AT INTER OR A/B
 - (2) TEST CELL UTILIZATION: 72.9 HRS/YR INTER
62.6 HRS/YR A/B
 - (3) COST OF HEAT RECOVERY EQUIPMENT:
WATER TUBE BOILER @ \$2,000,000.
UPSTREAM WATERWALLS @ \$100,000.
DOWNSTREAM WATERWALLS @ \$120,000.
 - (4) STEAM AT 350 DEG. F, 138 PSIA
 - (5) VALUE OF STEAM - \$9.73/MBTU
 - (6) DISCOUNT RATE - 10%, ESCALATION RATE - 8%.

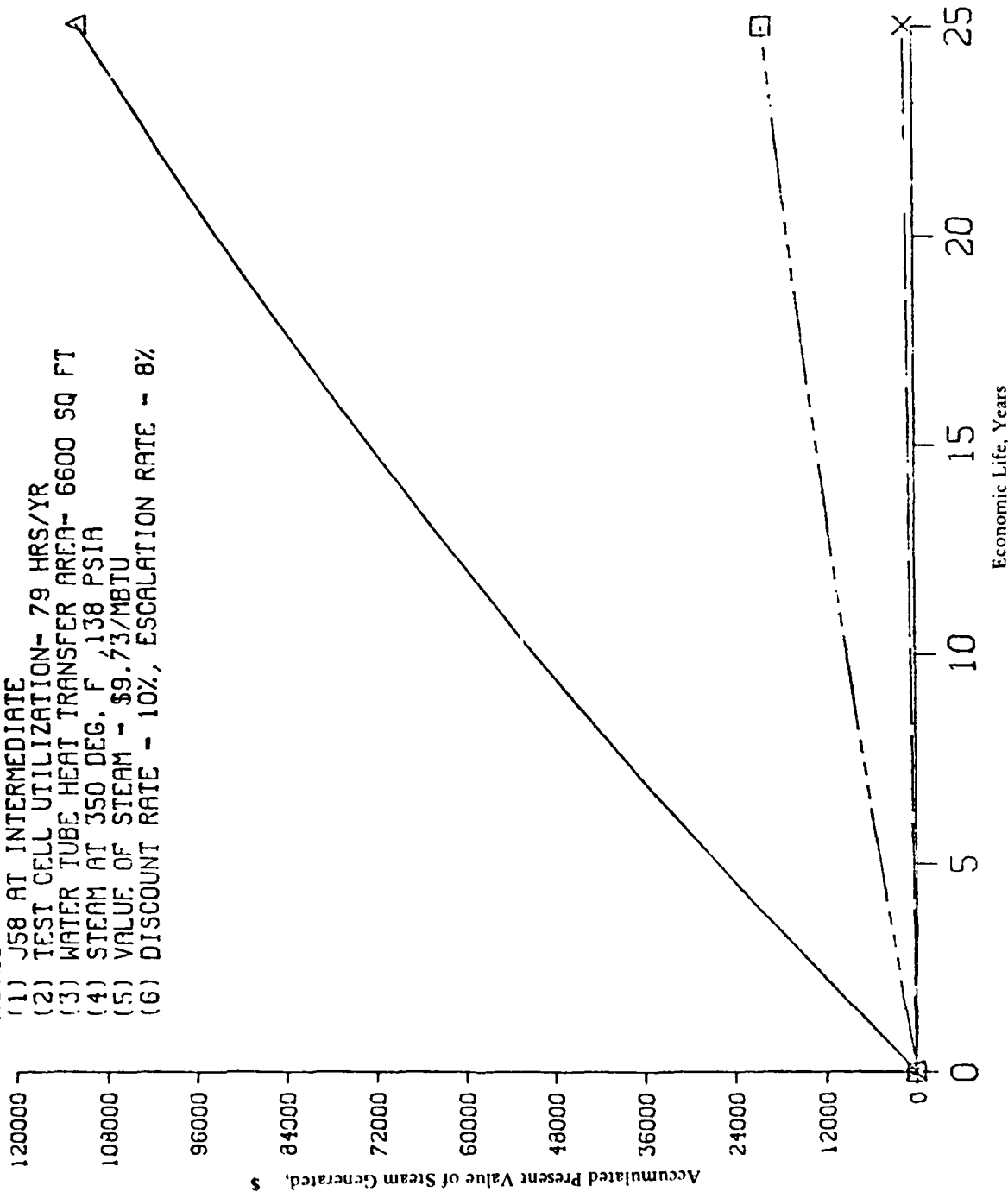


Legend

- Δ H2O TUBE, SAUGHEXIT
- X H2O WALLS 1ST 15FT
- $\square$ H2O WALLS LAST 20FT

Figure 5. Economics of gas turbine engine test facility energy recovery: NAS Miramar Test Cell "A".

NOTES:
 (1) J58 AT INTERMEDIATE
 (2) TEST CELL UTILIZATION- 79 HRS/YR
 (3) WATER TUBE HEAT TRANSFER AREA- 6600 SQ FT
 (4) STEAM AT 350 DEG. F, 138 PSIA
 (5) VALUE OF STEAM - \$9.73/MBTU
 (6) DISCOUNT RATE - 10%, ESCALATION RATE - 8%

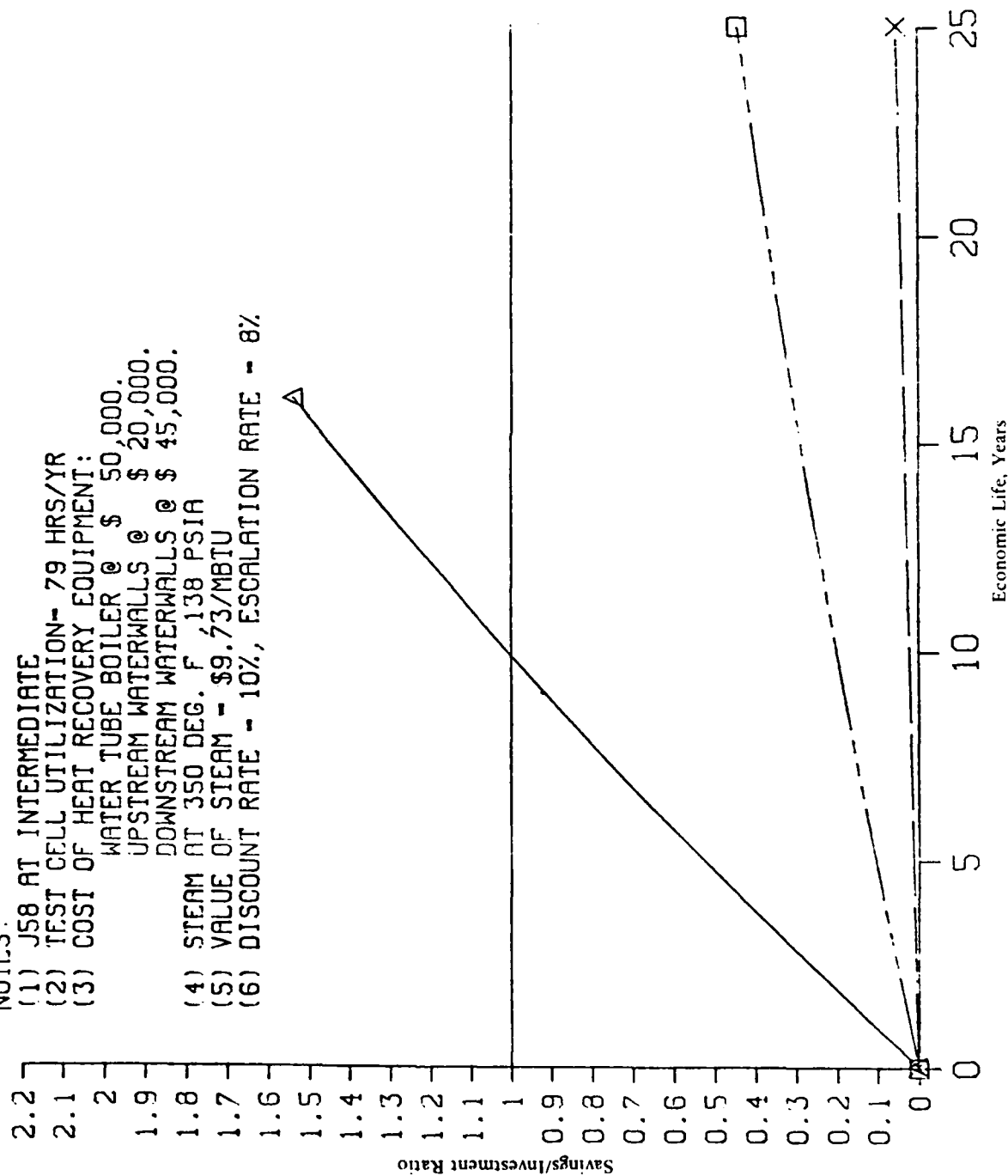


Legend
 Δ H2O TUBE SEAUGHEXIT
 X H2O WALLS 1ST 5 FT
 □ H2O WALLS LAST 38 FT

Figure 6. Generation of steam in gas turbine engine test facilities: NARF/NAS North Island Test Cell 11.

NOTES:

- (1) J58 AT INTERMEDIATE
- (2) TEST CELL UTILIZATION - 79 HRS/YR
- (3) COST OF HEAT RECOVERY EQUIPMENT:
 WATER TUBE BOILER @ \$ 50,000.
 UPSTREAM WATERWALLS @ \$ 20,000.
 DOWNSTREAM WATERWALLS @ \$ 45,000.
- (4) STEAM AT 350 DEG. F, 138 PSIA
- (5) VALUE OF STEAM - \$9.73/MBTU
- (6) DISCOUNT RATE - 10%, ESCALATION RATE - 8%



Legend
 Δ H2O TUBES @ AUGMENT
 X H2O WALLS 1ST 5 FT
 □ H2O WALLS LAST 38 FT

Figure 7. Economics of gas turbine engine test facility energy recovery: NARF/NAS North Island Test Cell 11.

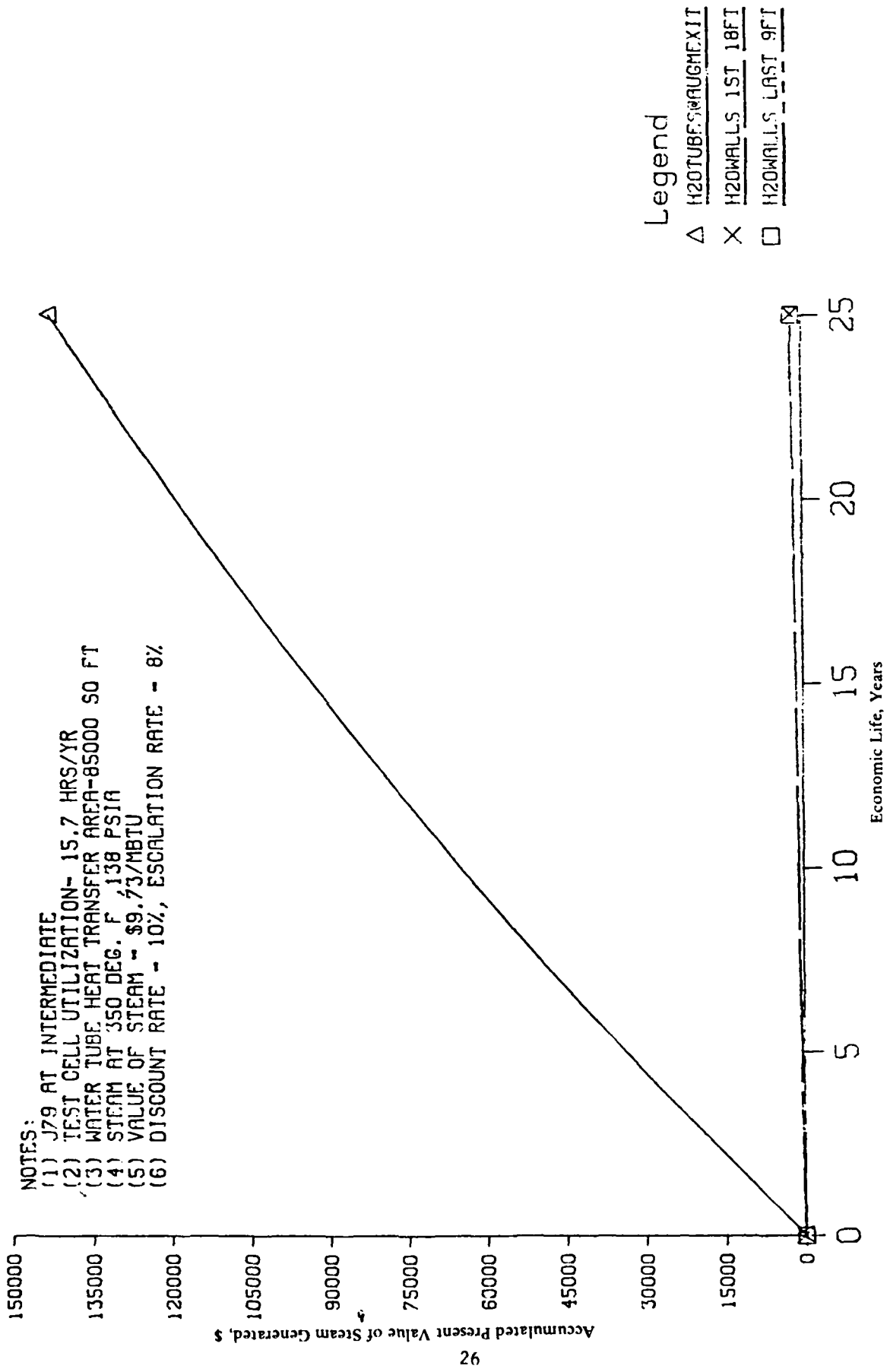
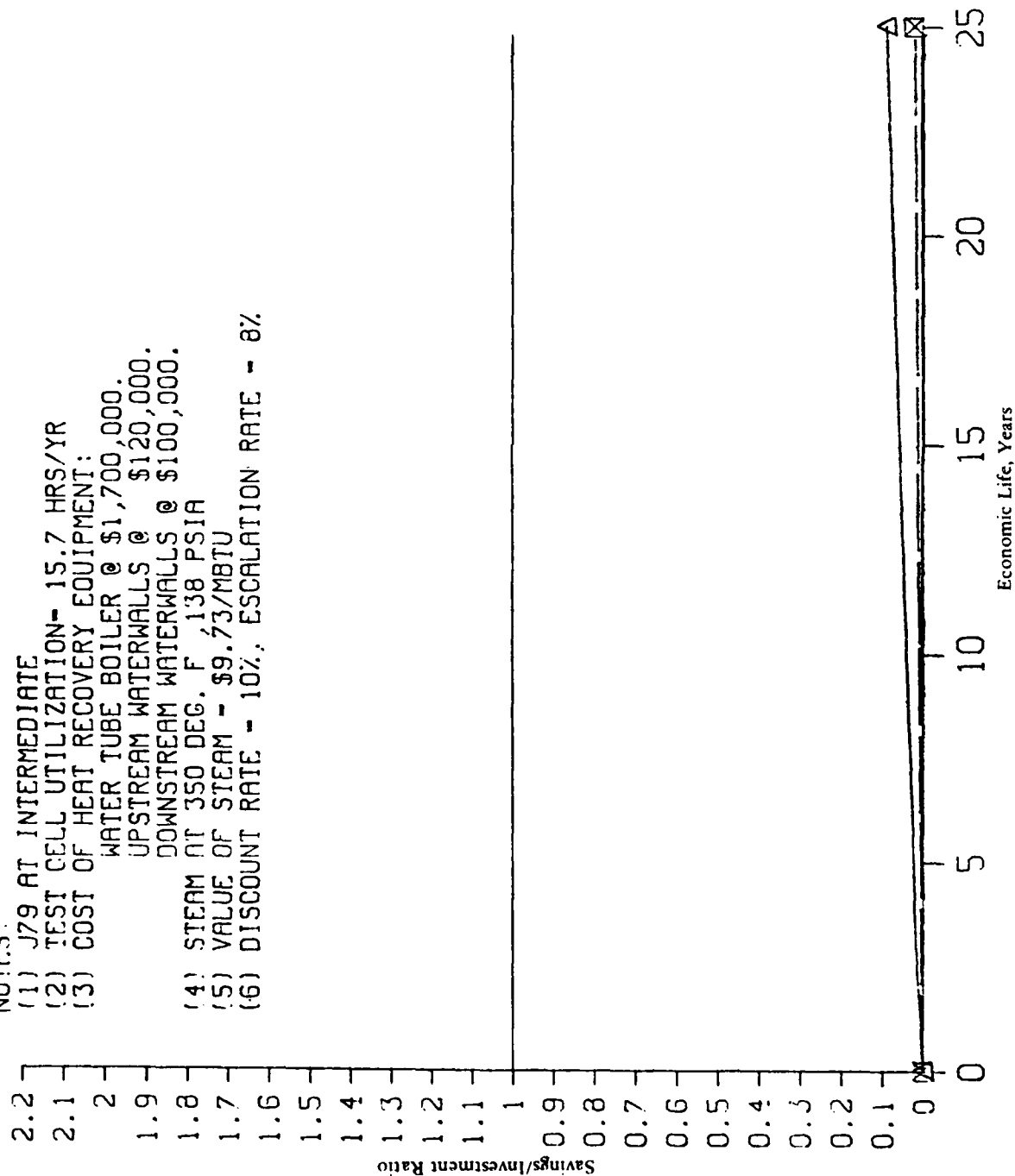


Figure 8. Generation of steam in gas turbine engine test facilities: NARE/NAS North Island Test Cell 14.

NOTES:

- (1) J79 AT INTERMEDIATE
- (2) TEST CELL UTILIZATION- 15.7 HRS/YR
- (3) COST OF HEAT RECOVERY EQUIPMENT:
 WATER TUBE BOILER @ \$1,700,000.
 UPSTREAM WATERWALLS @ \$120,000.
 DOWNSTREAM WATERWALLS @ \$100,000.
- (4) STEAM AT 350 DEG. F, 138 PSIA
- (5) VALUE OF STEAM - \$9.73/MBTU
- (6) DISCOUNT RATE - 10%, ESCALATION RATE - 8%



Legend

- Δ H2O TUBE SEAUGMEX 17
- $\times$ H2O WALLS 1ST 18FT
- $\square$ H2O WALLS LAST 9FT

Figure 9. Economics of gas turbine engine test facility energy recovery: NARF/NAS North Island Test Cell 14.

NOTES:

- (1) J79 AT INTER OR A/B
- (2) TEST CELL UTILIZATION: 196.3 HRS/YR INTER
17.7 HRS/YR A/B
- (3) WATER TUBE HEAT TRANSFER AREA - 115000 SQFT
- (4) STEAM AT 350 DEG. F, 138 PSIA
- (5) VALUE OF STEAM - \$9.73/MBTU
- (6) DISCOUNT RATE - 10%, ESCALATION RATE - 8%

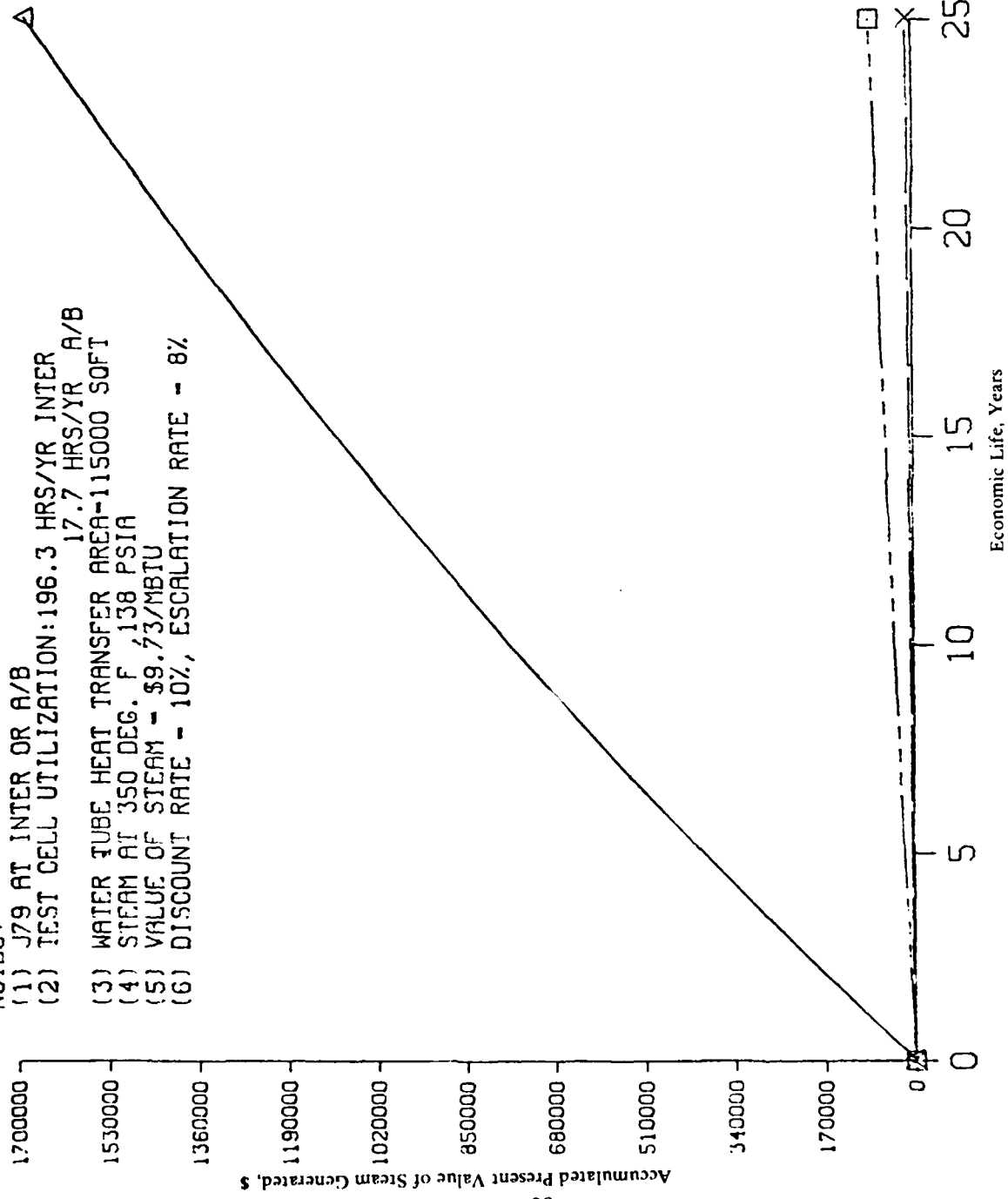


Figure 10. Generation of steam in gas turbine engine test facilities: NARF/NAS North Island Test Cell 19.

NOTES:

- (1) J/9 AT INTER OR A/B
- (2) TEST CELL UTILIZATION: 196.3 HRS/YR INTER
17.7 HRS/YR A/B
- (3) COST OF HEAT RECOVERY EQUIPMENT:
WATER TUBE BOILER @ \$2,000,000.
UPSTREAM WATERWALLS @ \$150,000.
DOWNSTREAM WATERWALLS @ \$200,000.
- (4) STEAM AT 350 DEG. F, 138 PSIA
- (5) VALUE OF STEAM - \$9.73/MBTU
- (6) DISCOUNT RATE - 10%, ESCALATION RATE - 8%

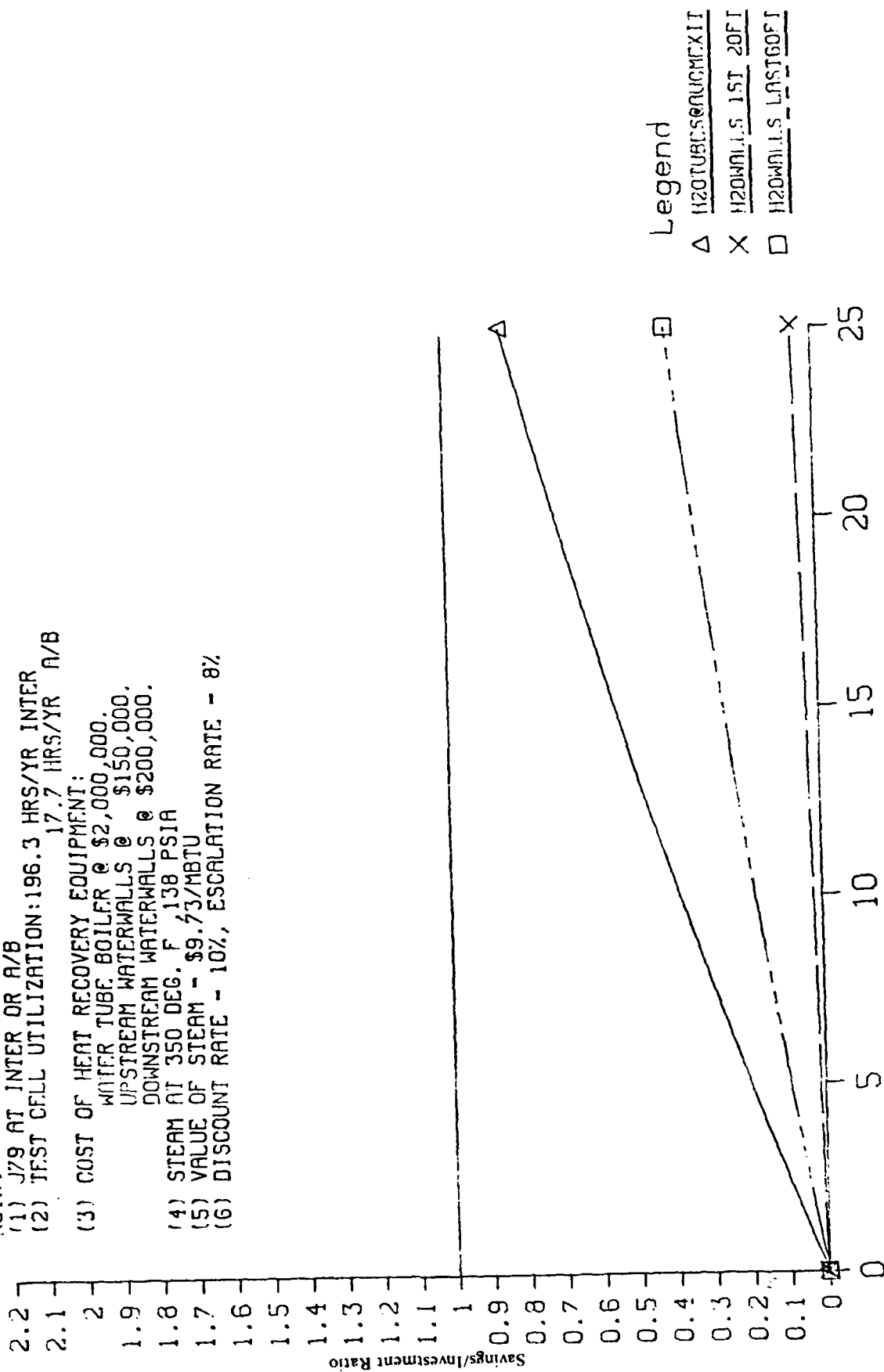
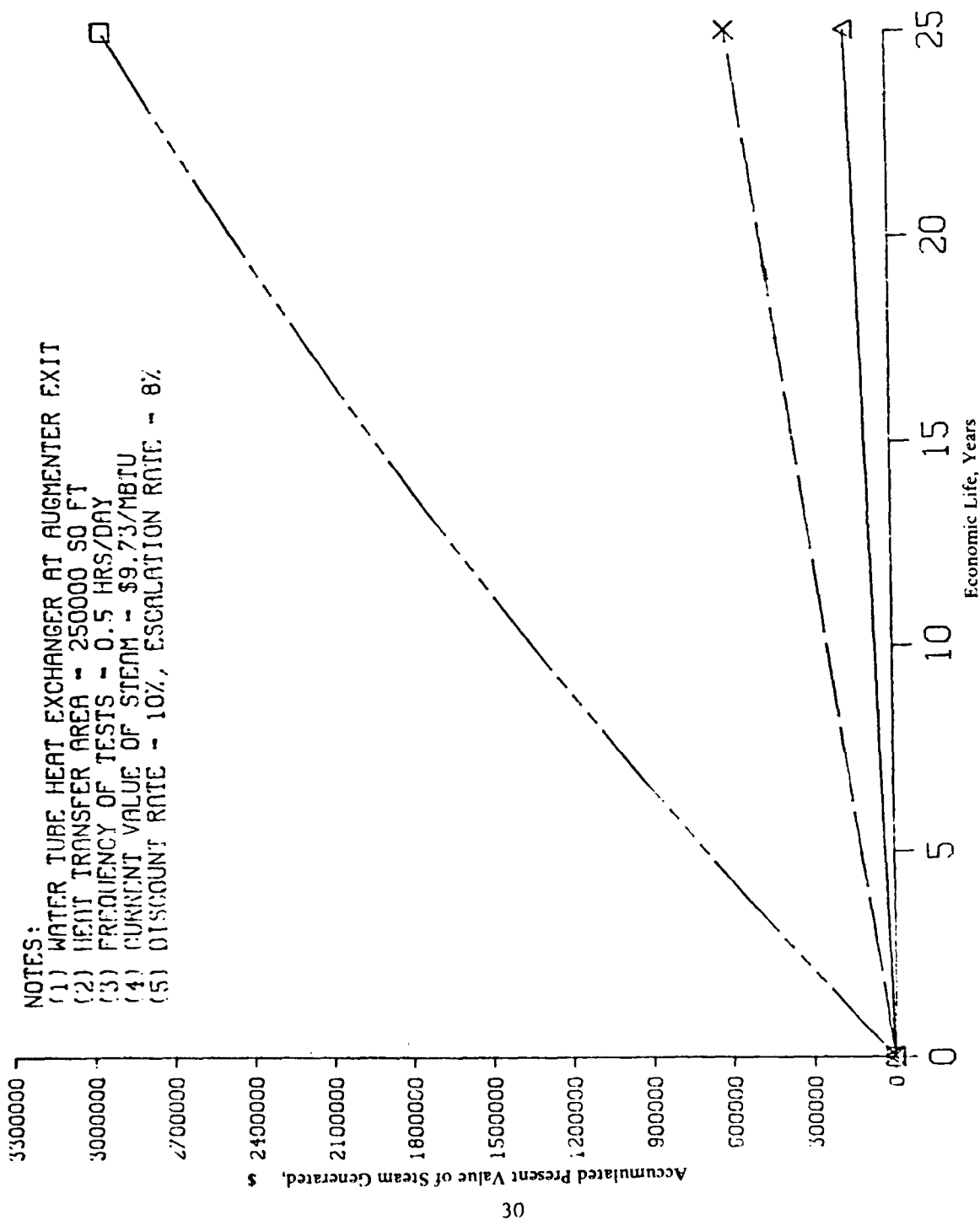


Figure 11. Economics of gas turbine engine test facility energy recovery: NARF/NAS North Island Test Cell 19.

NOTES:
 (1) WATER TUBE HEAT EXCHANGER AT AUGMENTER EXIT
 (2) HEAT TRANSFER AREA - 250000 SQ FT
 (3) FREQUENCY OF TESTS - 0.5 HRS/DAY
 (4) CURRENT VALUE OF STEAM - \$9.73/MBTU
 (5) DISCOUNT RATE - 10%, ESCALATION RATE - 8%



Legend
 Δ 1XJ79@INTER
 X 2XJ79@INTER
 □ 1XJ79@A/B

Figure 12. Effect of engine power setting on the generation of steam in a typical large gas turbine test cell.

2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0

Savings/Investment Ratio

31

NOTES:

- (1) WATER TUBE HEAT EXCHANGER AT AUGMENTER EXIT
- (2) HEAT TRANSFER AREA - 250000 SQ FT
- (3) FREQUENCY OF TESTS - 0.5 HRS/DAY
- (4) BOILER INITIAL COST - \$6,000,000.
- (5) CURRENT VALUE OF STEAM - \$9.73/MBTU
- (6) DISCOUNT RATE - 10%, ESCALATION RATE - 8%

Legend

Δ 1XJ79@INTER

X 2XJ79@INTER

$\square$ 1XJ79@N/B

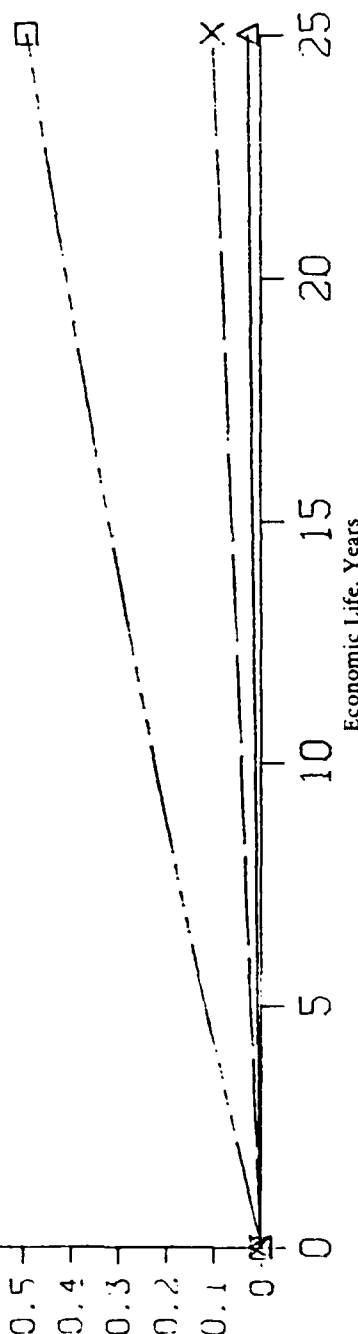


Figure 13. Effect of engine power setting on the economics of energy recovery in a typical large gas turbine test cell.

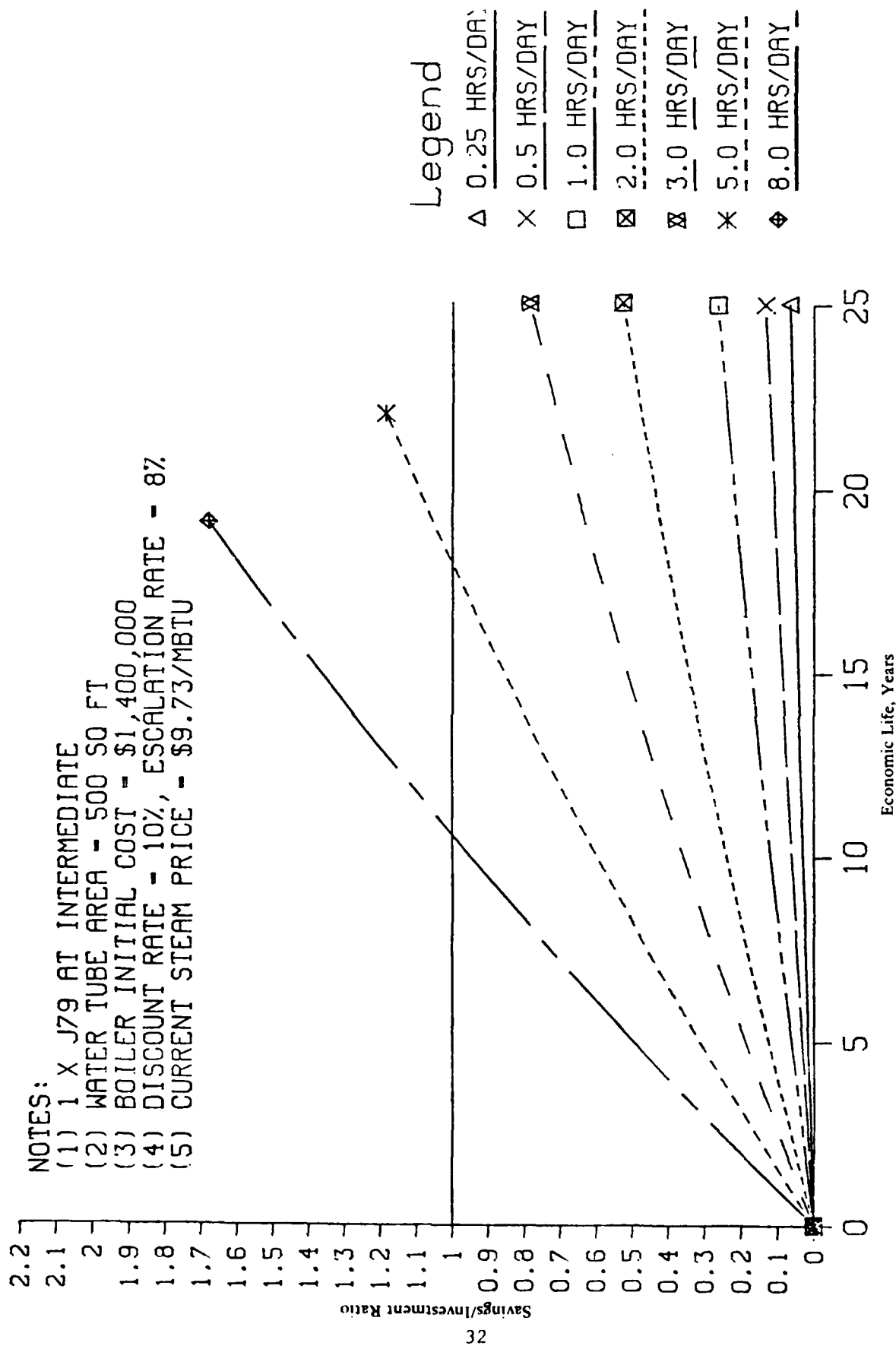


Figure 14. Economics of energy recovery from a typical large gas turbine test cell by using water tubes located near the nozzle.

NOTES:
 (1) WATER TUBES NEAR ENGINE NOZZLE
 (2) J79 AT INTERMEDIATE
 (3) AVERAGE DURATION OF TESTS - 0.5 HRS/DAY
 (4) BOILER INITIAL COST - \$1,400,000
 (5) DISCOUNT RATE - 10%, ESCALATION RATE - 8%
 (6) CURRENT VALUE OF STEAM - \$9.73/MBTU

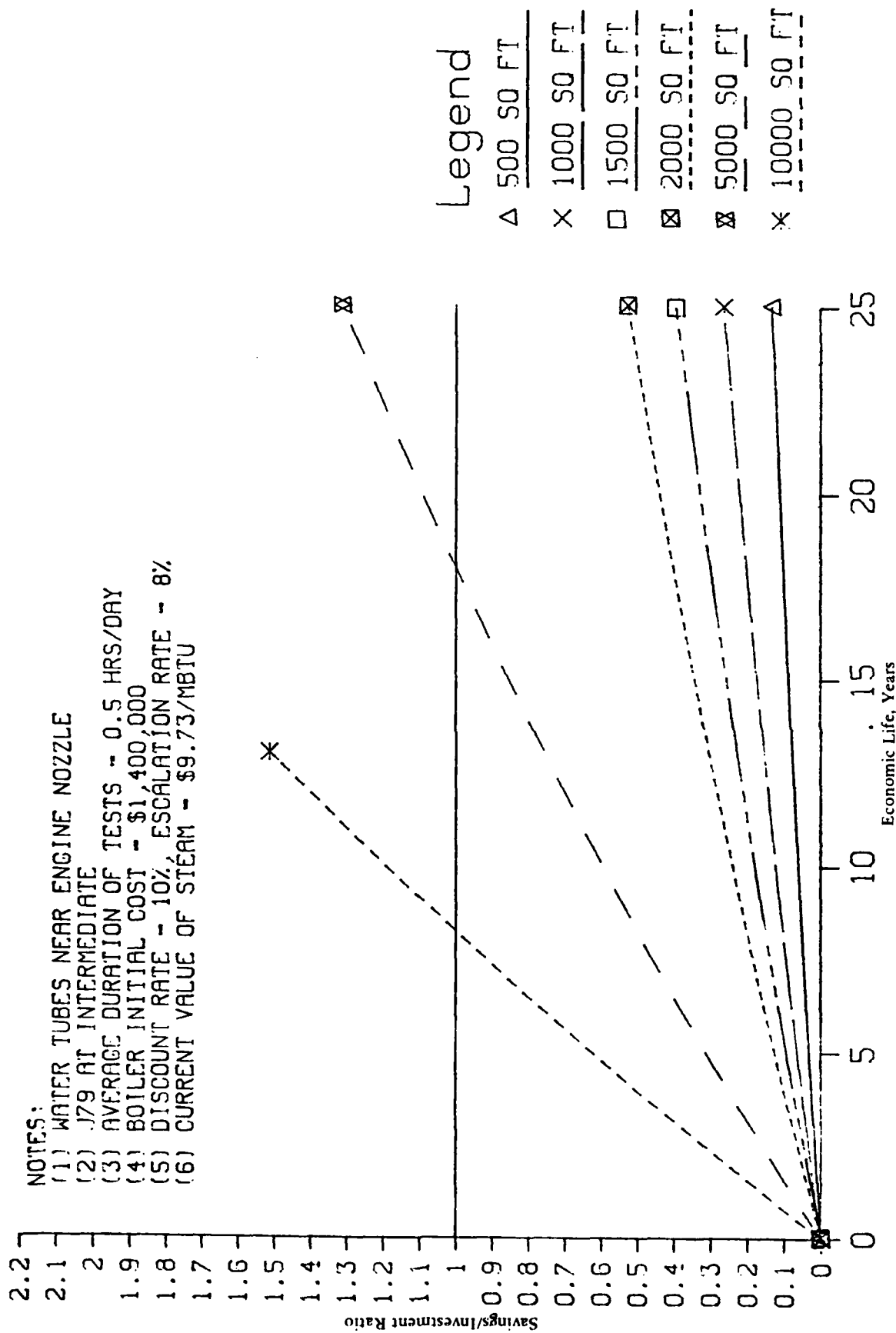


Figure 15. Effect of heat transfer area on energy recovery in a typical large test cell.

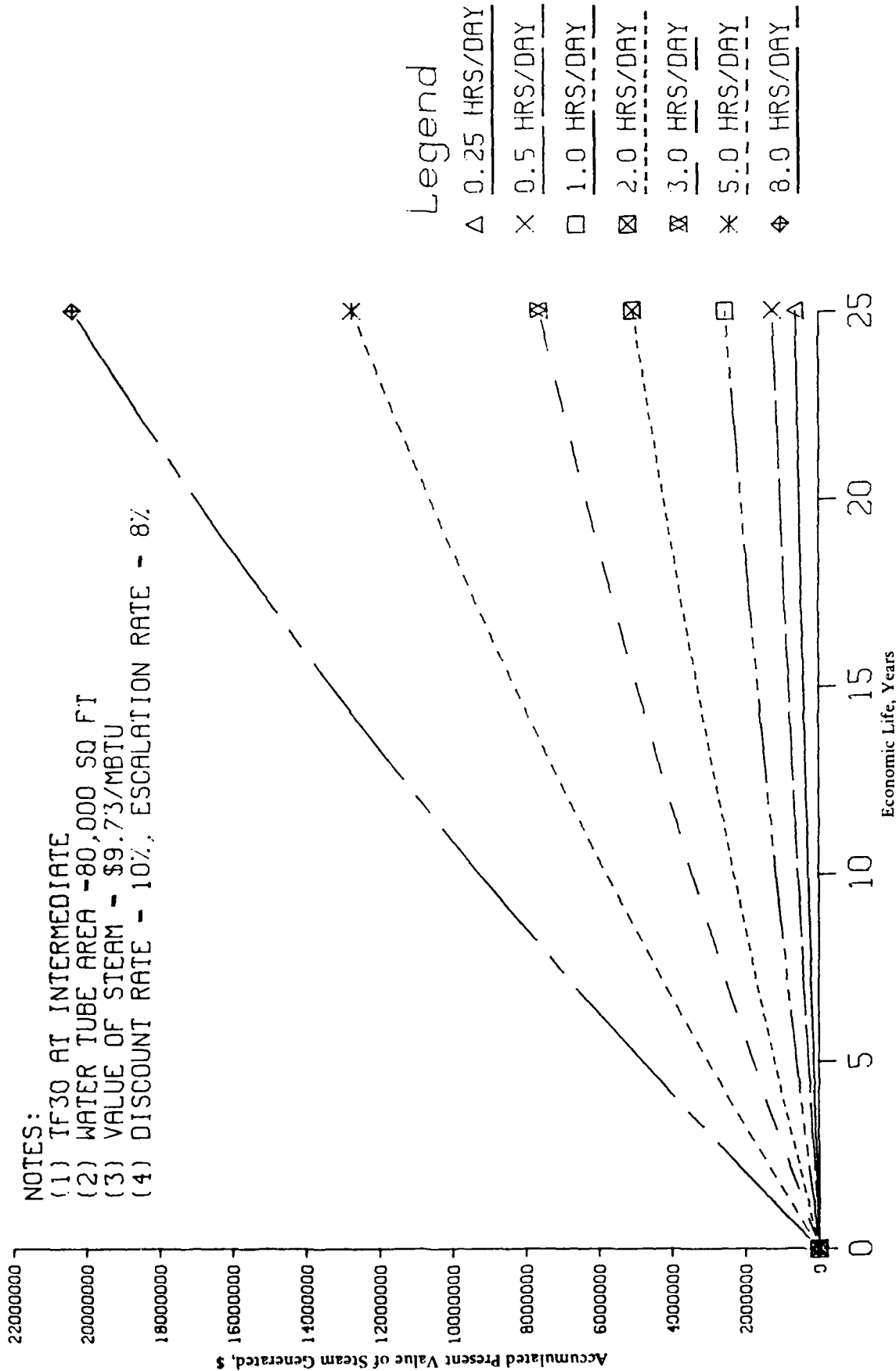


Fig. 16. Steam generation in a typical mid-sized gas turbine test cell by using water tubes located at augments exit.

NOTES:

- (1) TF30 AT INTERMEDIATE
- (2) WATER TUBE AREA - 80,000 SQ FT
- (3) BOILER INITIAL COST - \$2,000,000.
- (4) VALUE OF STEAM - \$9.73/MBTU
- (5) DISCOUNT RATE - 10%, ESCALATION RATE - 8%

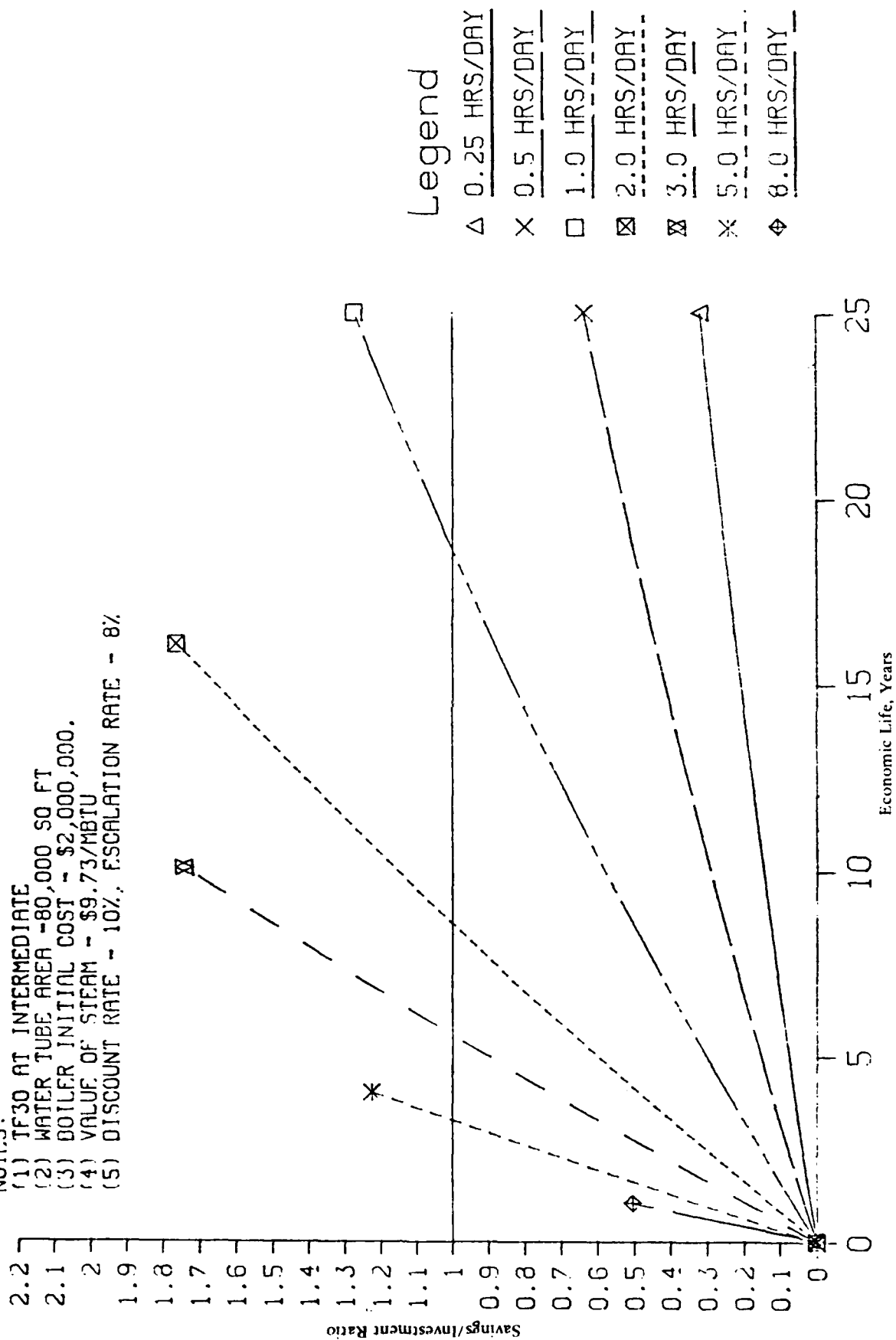


Figure 17. Economics of energy recovery from a typical mid-sized gas turbine test cell by using water tubes located at augmentor exit.

NOTES:

- (1) TF30 AT INTERMEDIATE
- (2) WATERWALLS ALONG LAST 20 FT OF AUGMENTER
- (3) VALUE OF STEAM - \$9.73/MBTU
- (4) DISCOUNT RATE - 10%, ESCALATION RATE - 8%

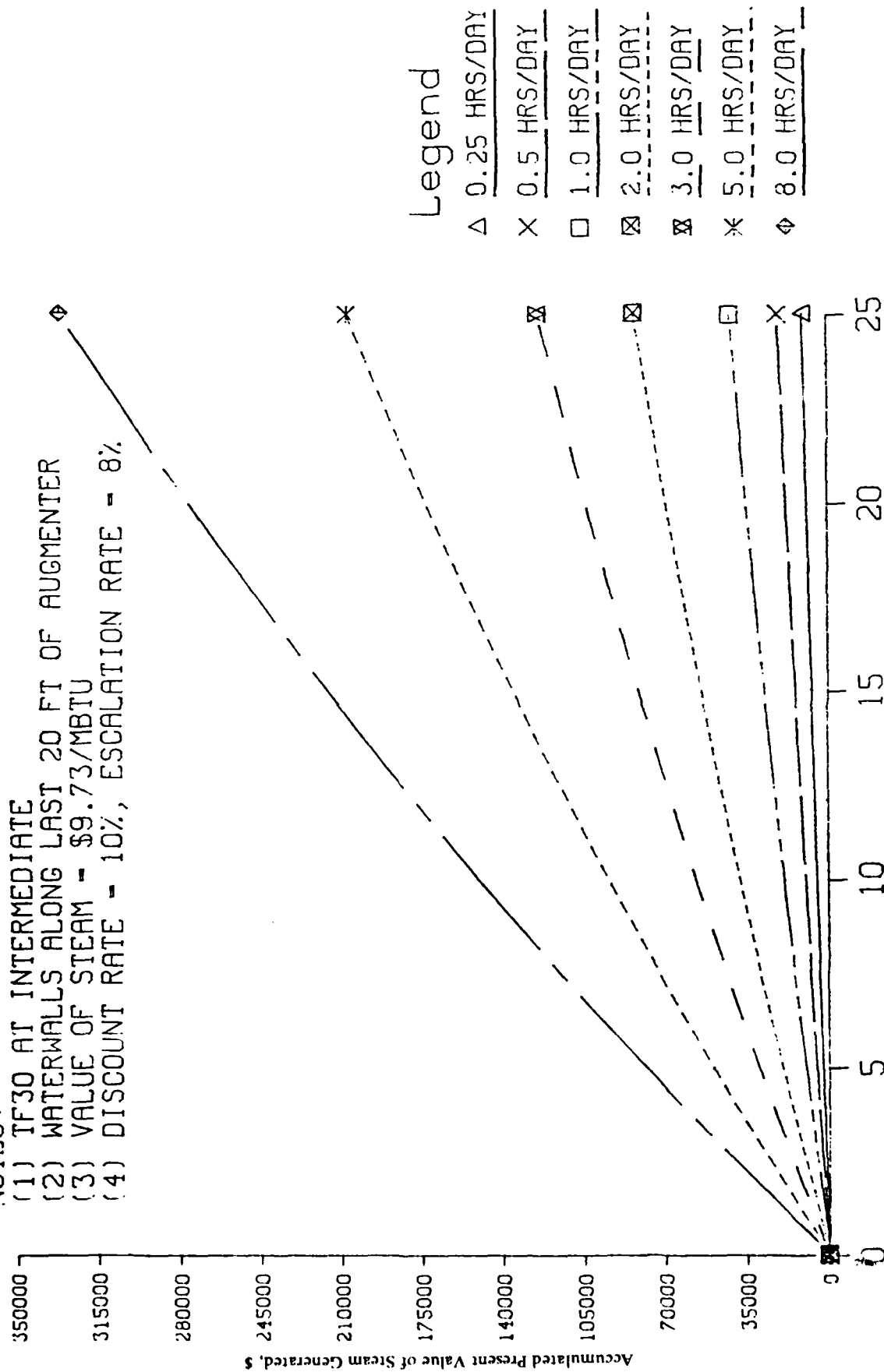


Figure 18. Steam generation in a typical mid-sized gas turbine test cell with waterwalls.

NOTES:

- (1) TF30 AT INTERMEDIATE
- (2) WATERWALLS ALONG LAST 20 FT OF AUGMENTER
- (3) COST OF WATERWALLS - \$130,000.
- (4) VALUE OF STEAM - \$9.73/MBTU
- (5) DISCOUNT RATE - 10%, ESCALATION RATE - 8%.

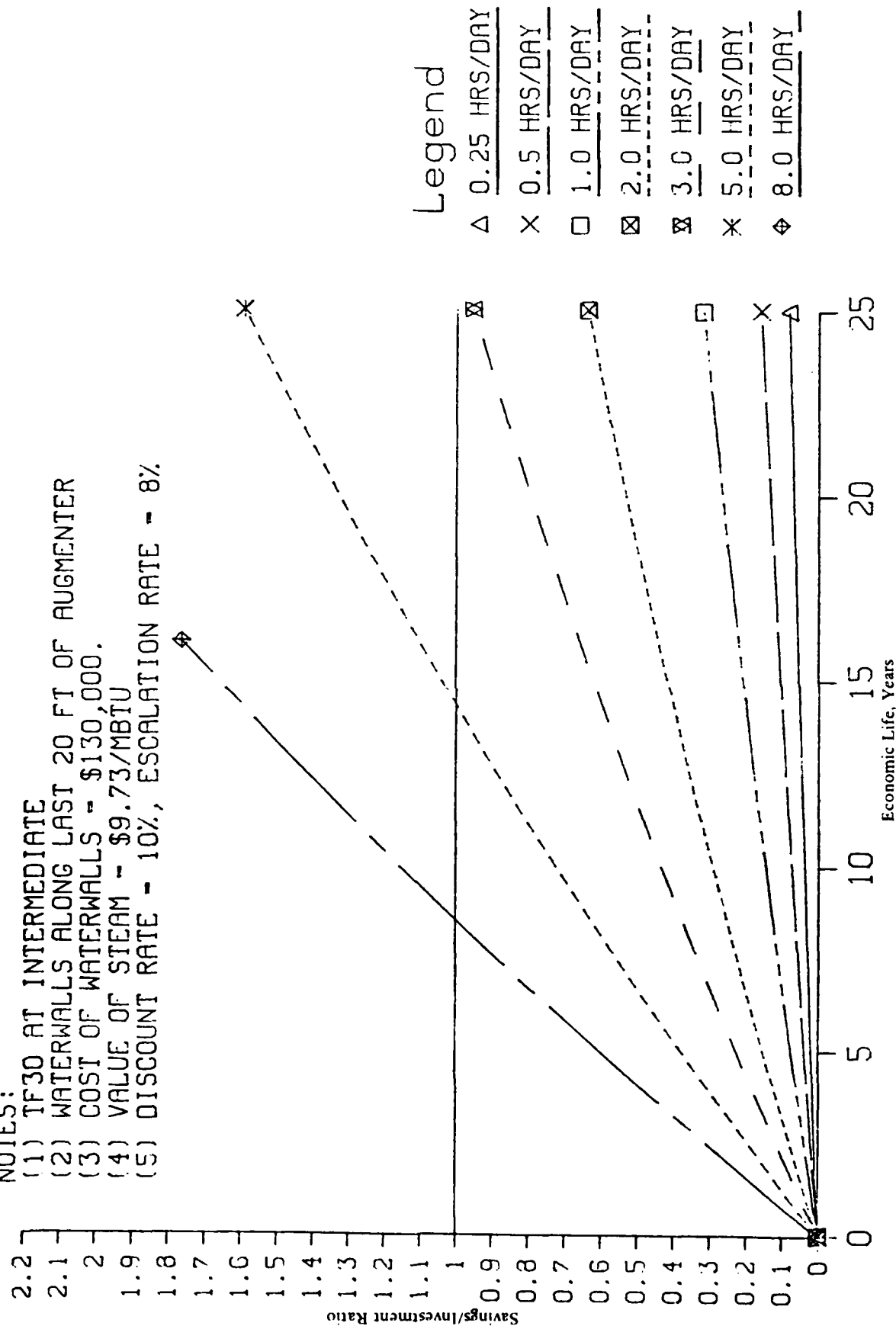
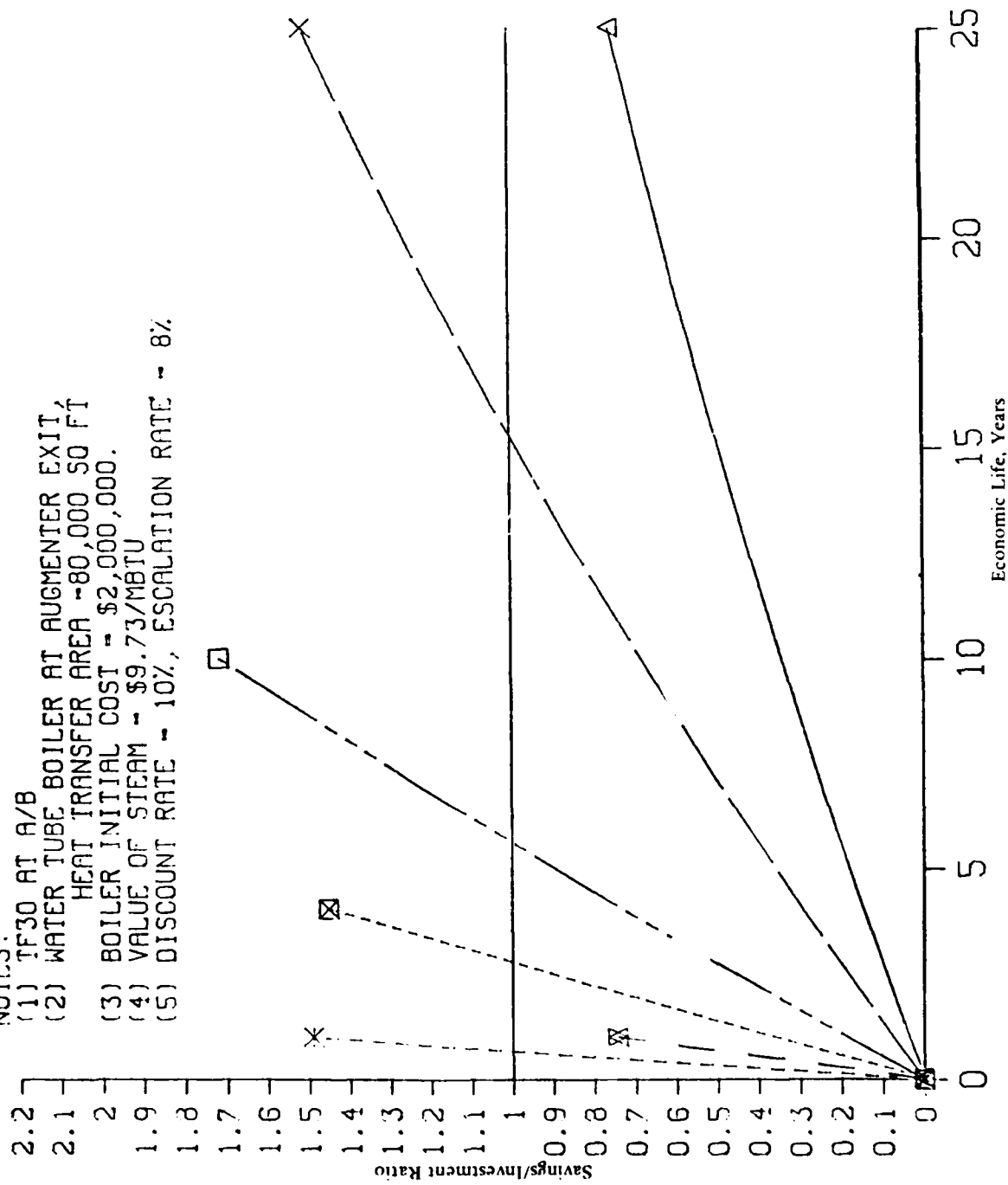


Figure 19. Economics of energy recovery from a typical mid-sized gas turbine test cell with waterwalls.

NOTES:

- (1) TF30 AT A/B
- (2) WATER TUBE BOILER AT AUGMENTER EXIT,
HEAT TRANSFER AREA - 80,000 SQ FT
- (3) BOILER INITIAL COST - \$2,000,000.
- (4) VALUE OF STEAM - \$9.73/MBTU
- (5) DISCOUNT RATE - 10%, ESCALATION RATE - 8%



Legend

- △ 0.05 HRS/DAY
- × 0.10 HRS/DAY
- 0.25 HRS/DAY
- ⊠ 0.5 HRS/DAY
- ⋈ 1.0 HRS/DAY
- × 2.0 HRS/DAY

Figure 20. Effect of afterburning on the economics of energy recovery from a typical mid-sized gas turbine test cell.

NOTES:

- (1) T 58 AT INTERMEDIATE
- (2) HEAT TRANSFER AREA - 6600 SQ FT
- (3) VALUE OF STEAM - \$9.73/MBTU
- (4) DISCOUNT RATE - 10%, ESCALATION RATE - 8%

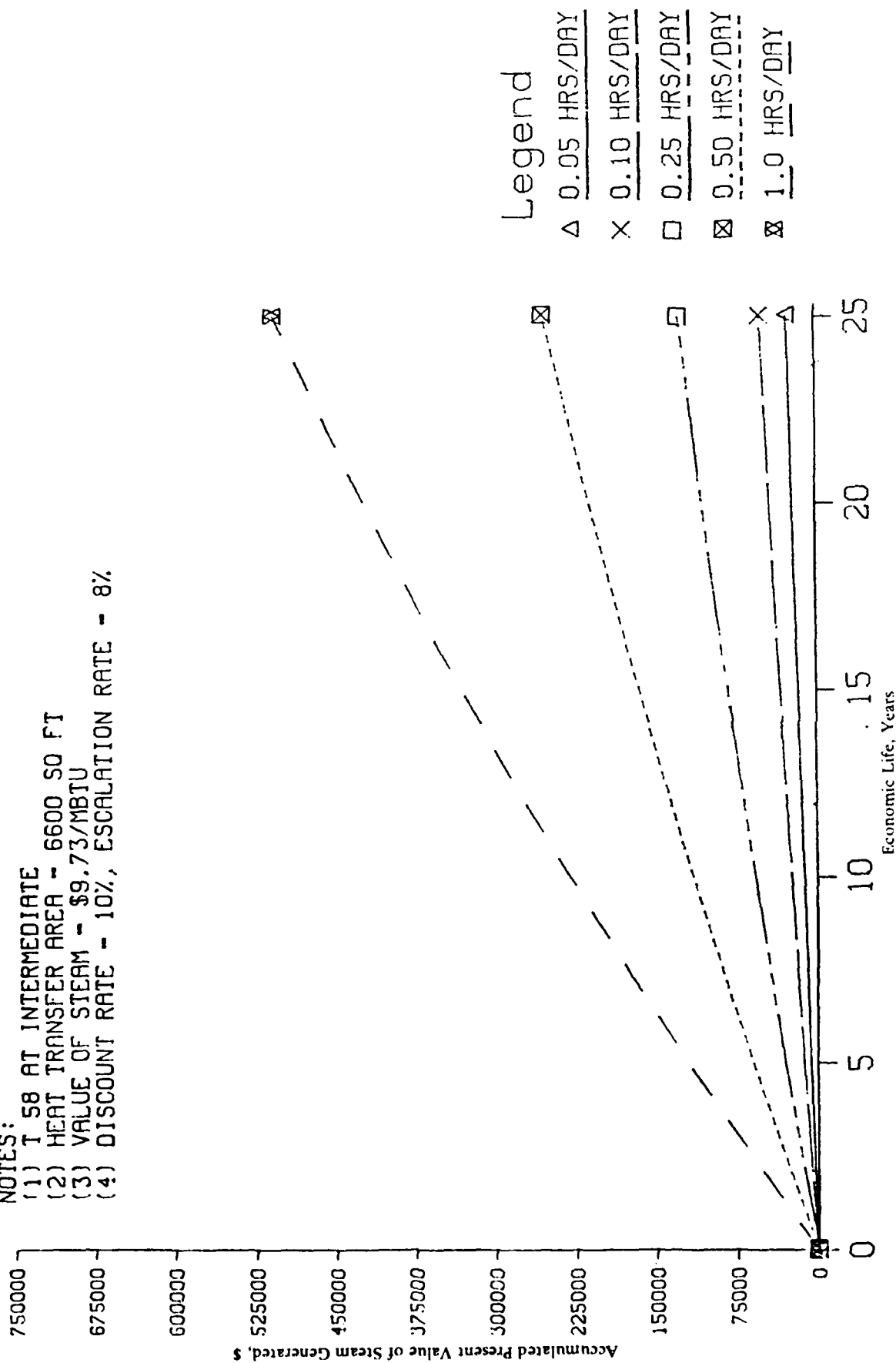
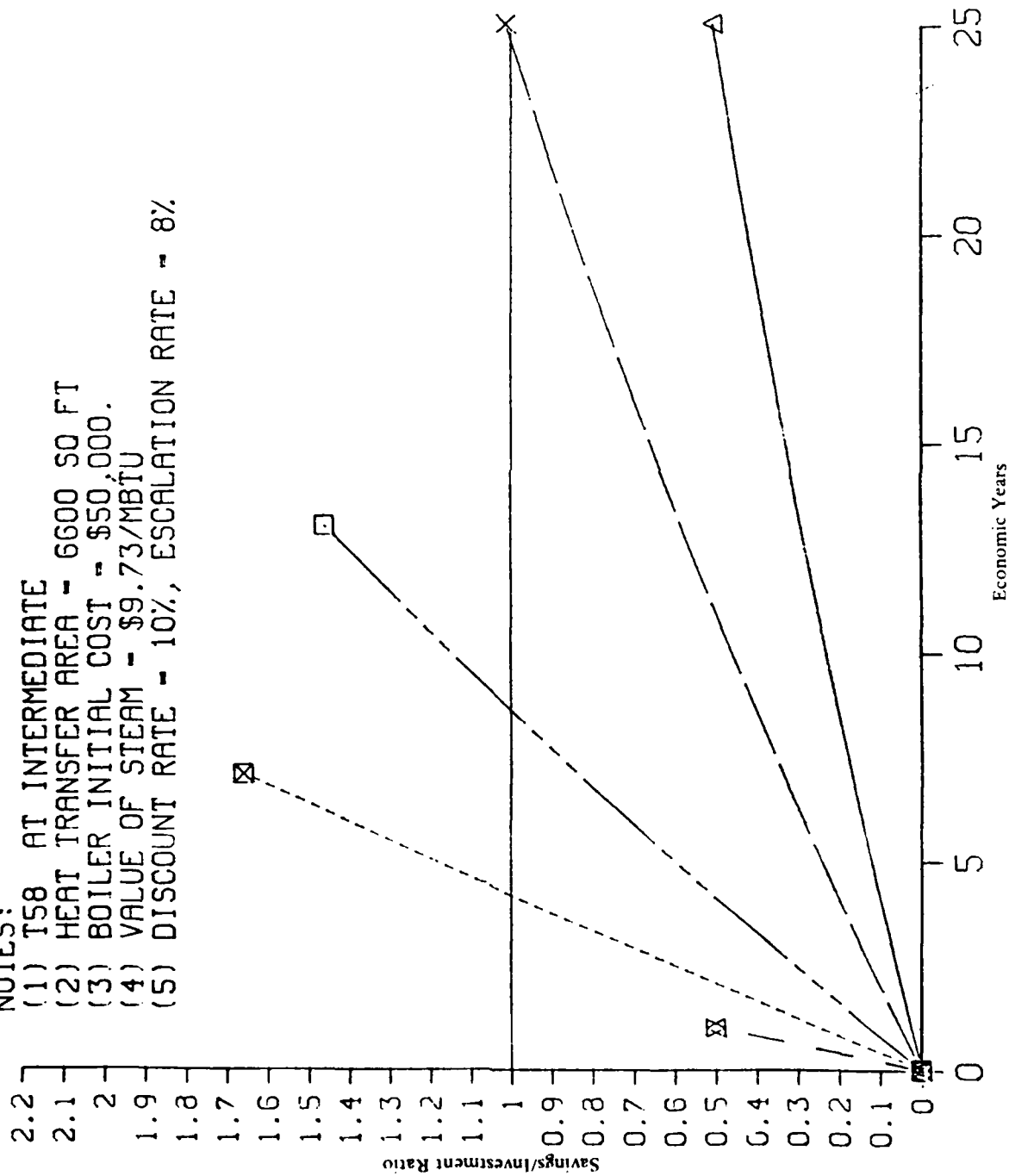


Figure 21. Steam generation in a typical small gas turbine test cell using water tubes at the augments exit.

NOTES:

- (1) T58 AT INTERMEDIATE
- (2) HEAT TRANSFER AREA - 6600 SQ FT
- (3) BOILER INITIAL COST - \$50,000.
- (4) VALUE OF STEAM - \$9.73/MBTU
- (5) DISCOUNT RATE - 10%, ESCALATION RATE - 8%.



Legend

Δ 0.05 HRS/DAY

X 0.10 HRS/DAY

□ 0.25 HRS/DAY

⊠ 0.50 HRS/DAY

⊗ 1.0 HRS/DAY

Figure 22. Economics of energy recovery from a typical small gas turbine test cell using water tubes at the augmentor exit.

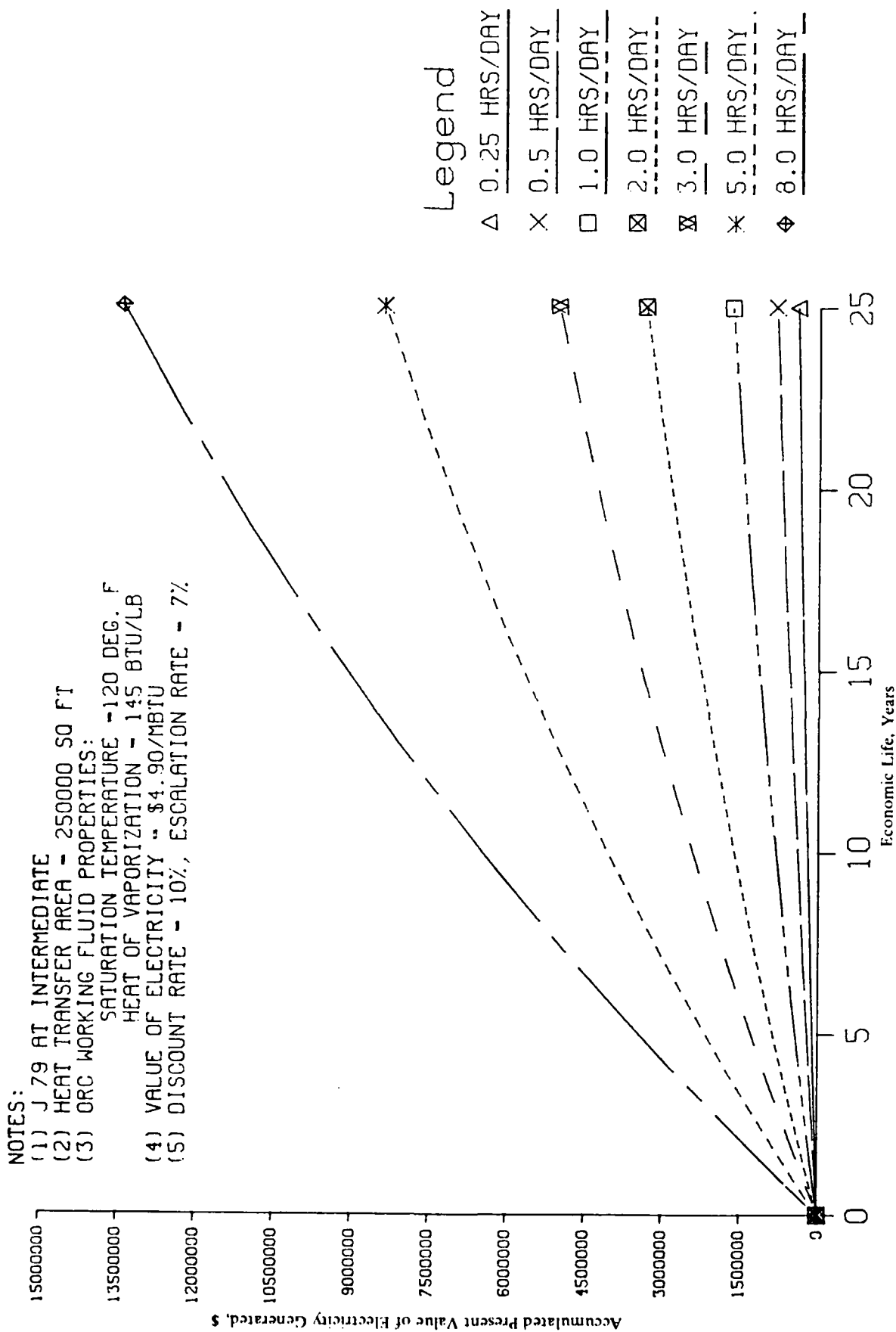
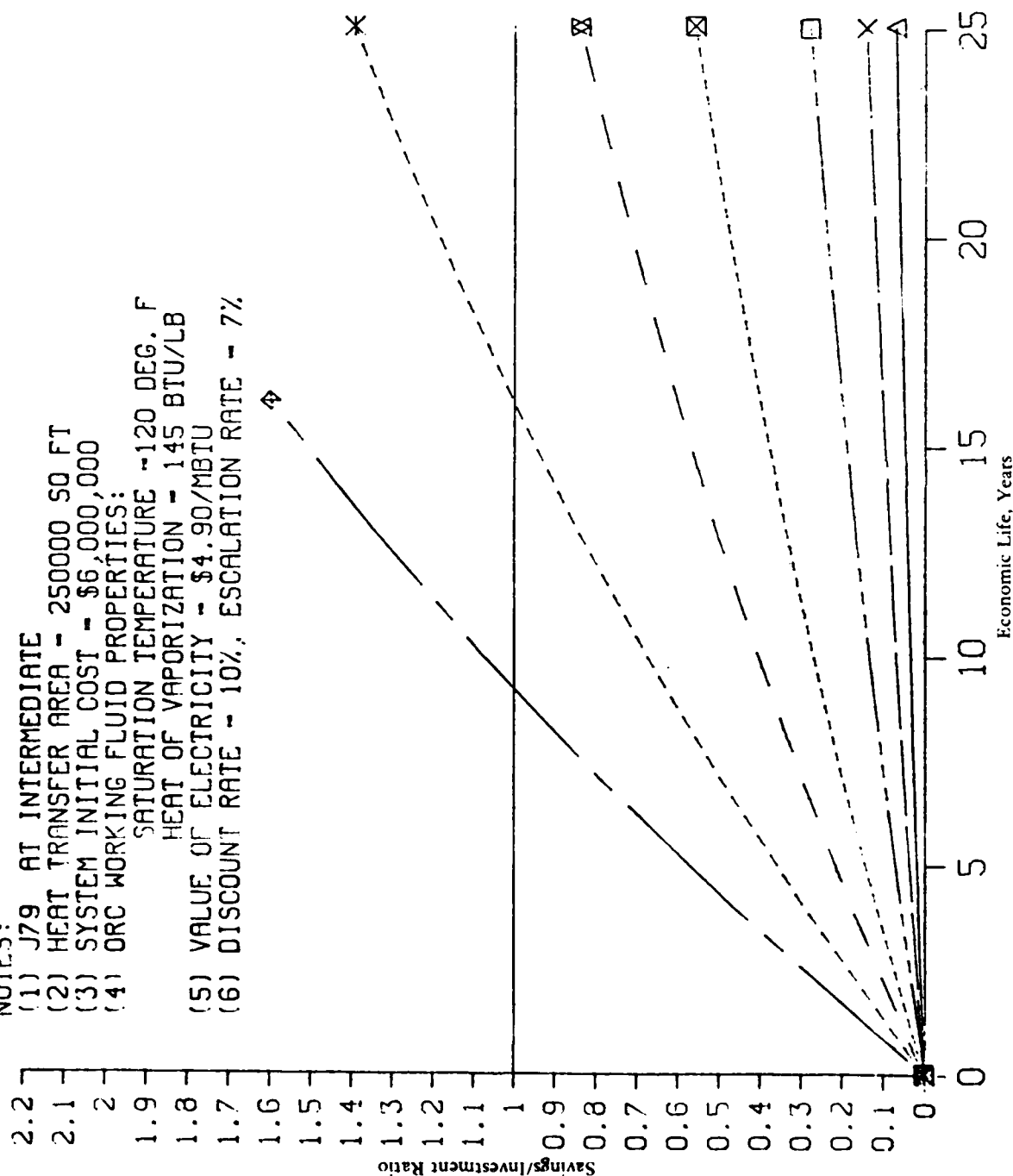


Figure 23. Generation of electricity from thermal energy recovered in a typical large gas turbine test cell using water tubes at the augmentor exit.

NOTES:

- (1) J79 AT INTERMEDIATE
- (2) HEAT TRANSFER AREA - 250000 SQ FT
- (3) SYSTEM INITIAL COST - \$6,000,000
- (4) ORC WORKING FLUID PROPERTIES:
SATURATION TEMPERATURE - 120 DEG. F
HEAT OF VAPORIZATION - 145 BTU/LB
- (5) VALUE OF ELECTRICITY - \$4.90/MBTU
- (6) DISCOUNT RATE - 10%, ESCALATION RATE - 7%



Legend

- △ 0.25 HRS/DAY
- × 0.5 HRS/DAY
- 1.0 HRS/DAY
- ⊠ 2.0 HRS/DAY
- ⊗ 3.0 HRS/DAY
- * 5.0 HRS/DAY
- ◇ 8.0 HRS/DAY

Figure 24. Economics of electricity generation from thermal energy recovered in a typical large gas turbine test cell using water tubes at the augmentor exit.

NOTES:

- (1) TF30 AT A/B
- (2) HEAT TRANSFER AREA - 80000 SQ FT
- (3) ORC WORKING FLUID PROPERTIES:
SATURATION TEMPERATURE - 120 DEG. F
HEAT OF VAPORIZATION - 145 BTU/LB
- (4) VALUE OF ELECTRICITY - \$4.90/MBTU
- (5) DISCOUNT RATE - 10%, ESCALATION RATE - 7%.

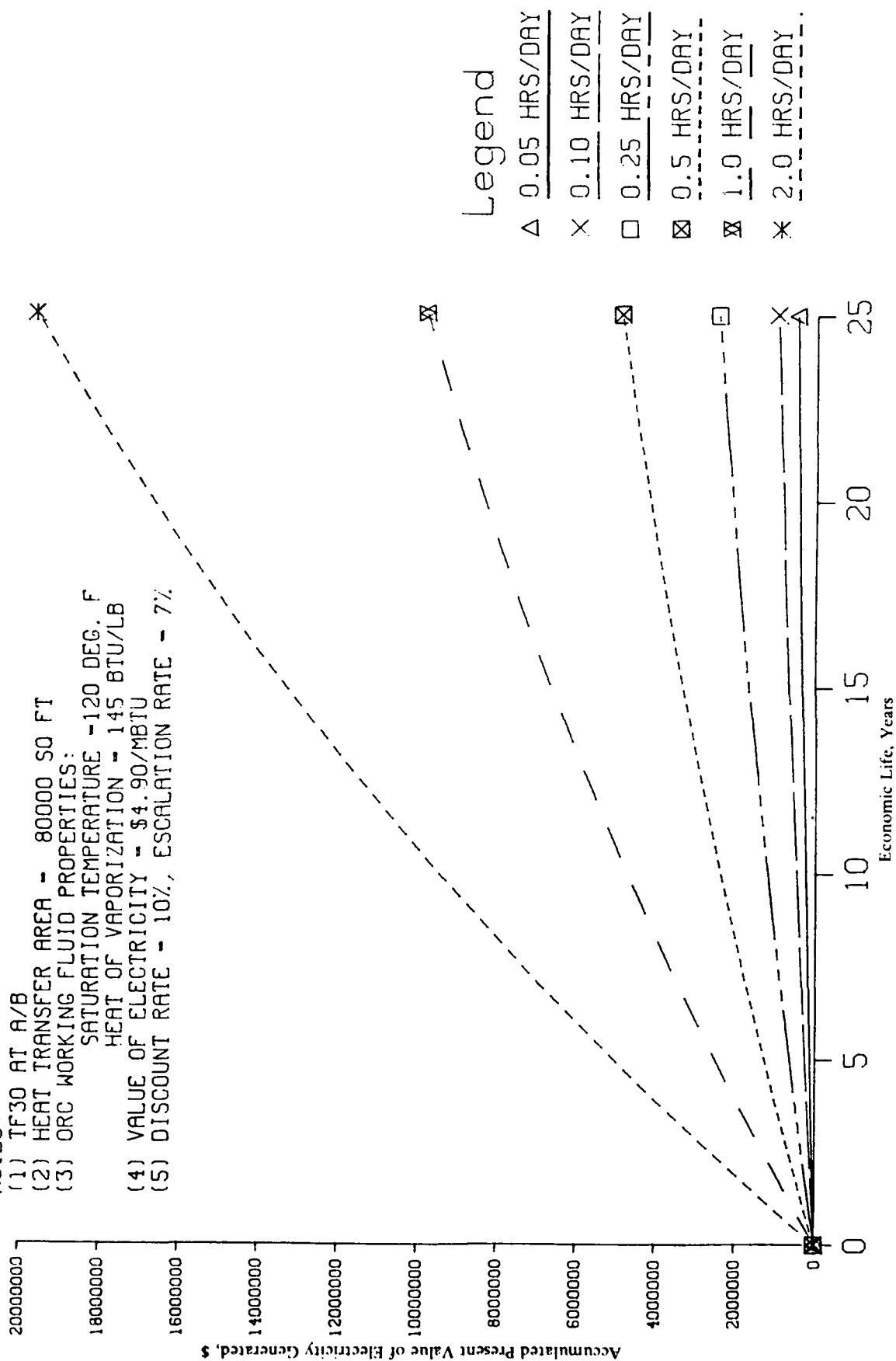
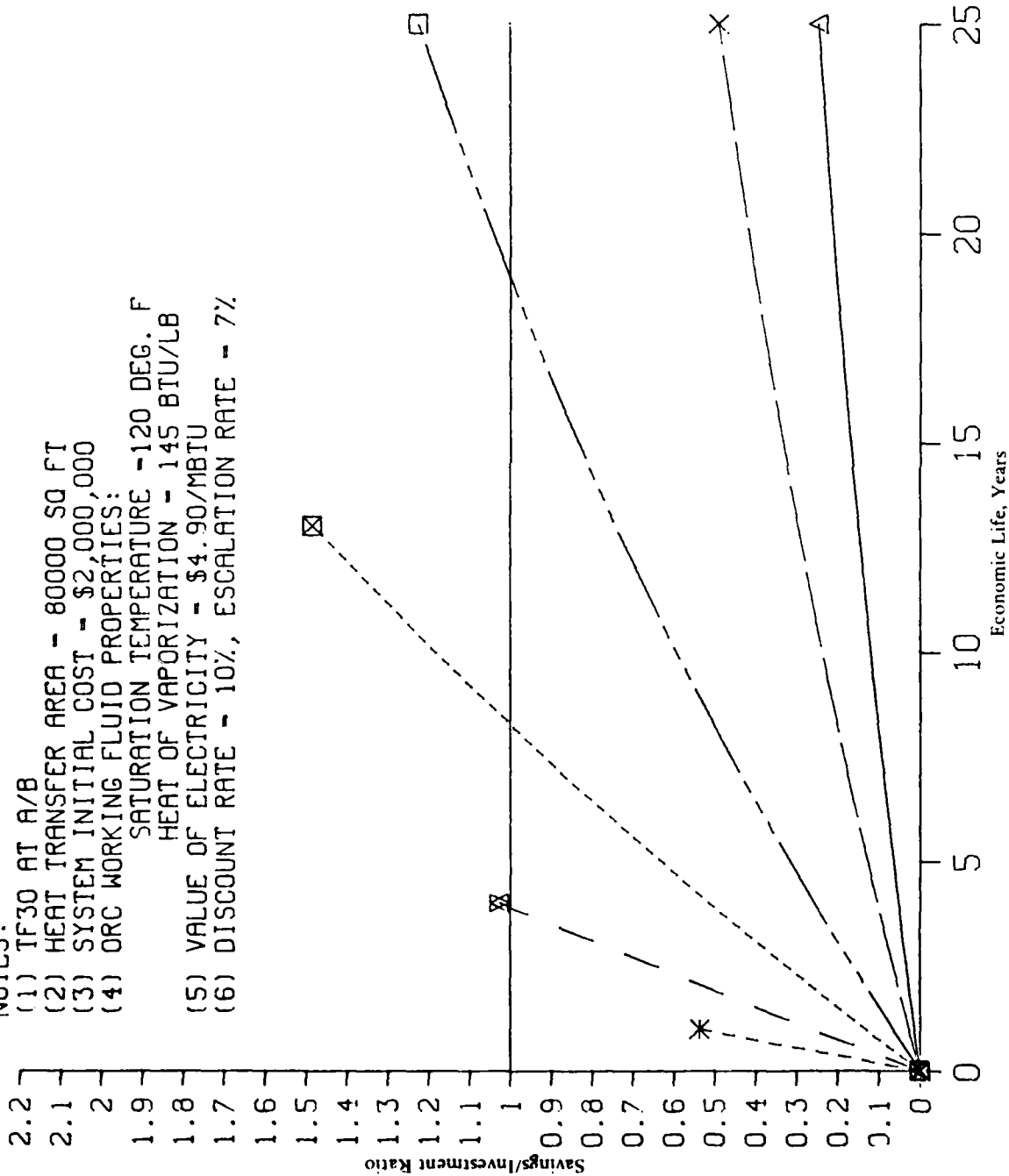


Figure 25. Generation of electricity from thermal energy recovered in a typical mid-sized gas turbine test cell using water tubes at the augments exit.

NOTES:

- (1) TF30 AT A/B
- (2) HEAT TRANSFER AREA - 80000 SQ FT
- (3) SYSTEM INITIAL COST - \$2,000,000
- (4) ORC WORKING FLUID PROPERTIES:
SATURATION TEMPERATURE -120 DEG. F
HEAT OF VAPORIZATION - 145 BTU/LB
- (5) VALUE OF ELECTRICITY - \$4.90/MBTU
- (6) DISCOUNT RATE - 10%, ESCALATION RATE - 7%.



Legend

- △ 0.05 HRS/DAY
- × 0.10 HRS/DAY
- 0.25 HRS/DAY
- ⊠ 0.5 HRS/DAY
- * 1.0 HRS/DAY
- * 2.0 HRS/DAY

Figure 26. Economics of electricity generation from thermal energy recovered in a typical mid-sized gas turbine test cell using water tubes at the augments exit.

Appendix A

SIMULATION OF A JET ENGINE TEST CELL AUGMENTER TUBE

The problems inherent in simulating the operation of test cell augmenter tubes are extremely complex. Re-examine Figure 1 and consider the following augmenter characteristics: multiple, nonconcentric flows at different velocities; turbulence; flow separation; all three modes of heat transfer, simultaneously; extreme changes in temperature and, thus, variable properties; and nonsymmetric three-dimensional geometries. In addition, some tests are of short duration, resulting in a highly transient situation; e.g., testing with afterburners might involve 30-second cycles with 3,000°F exhaust. These complexities lead to a transient, nonlinear problem with coupled energy, mass, and momentum transfer.

To make an augmenter simulation attainable, assumptions are necessary. For this present work, the emphasis is on heat transfer. Can enough steam be generated, via energy transferred from the jet exhaust, to warrant the purchase of a boiler? The modelling tactics will be to simulate the fluid flow (mass and momentum) empirically but use first principles to determine heat transfer. For this plan-of-attack, the following assumptions are made:

1. Flows are one-dimensional, passing through a cylindrical augmenter
2. Steady state, steady flow is stipulated
3. Both the jet and augmentation air are ideal gases

4. Flow within the jet and within the augmentation air can be considered turbulent and perfectly mixed
5. Pressure gradients along the augmeter are negligible compared with temperature gradients and can be neglected
6. The jet nozzle is located exactly at the inlet to the augmeter tube
7. The augmeter walls are black, the jet is gray, and the augmentation air is transparent to thermal radiation
8. Axial radiation along the jet has a negligible effect on temperatures; all radiation is from jet to wall or from wall to wall
9. Heat transfer between the jet and the augmentation air is negligible compared with enthalpy changes due to mixing
10. Radiation from the jet to any heat exchanger located past the augmeter exit is negligible

The validity of several of the assumptions and the accuracy of the resulting simulation are discussed in a subsequent section.

SIMULATING THE JET EXHAUST

The jet is empirically modelled using the curve fits of Becker et al. (Ref 2). Their data are from cold jets, and their test rig is smaller than test cells, necessitating some modification to the empirical constants. Specifically, these relationships have been adjusted to be able to predict the arrival of the jet to the wall at locations observed experimentally at the hush houses, NAS Miramar (Ref 3 and 4).

Following Becker's technique, jet flow geometry is extrapolated from the NAS Miramar data by means of a nondimensional similarity parameter usually referred to as the Craya-Curtet number, C_t , a ratio of the kinematic to dynamic mean inlet velocities,

$$C_t \equiv \frac{r^{*2} V_{JET}(0) + (1-r^{*2}) V_{SEC}}{\left\{ r^{*2} V_{JET}(0) + (0.5-r^{*2}) V_{SEC}^2 - 0.5 \left[r^{*2} V_{JET}(0) + (1-r^{*2}) V_{SEC} \right]^2 \right\}^{1/2}} \quad (A-1)$$

where: r^* = ratio of jet nozzle area to cross-sectional area of the augmeter tube

$V_{JET}(0)$ = velocity of jet at the augmeter inlet

V_{SEC} = velocity of augmentation (secondary) airflow

Then, for $0 < C_t \leq 0.7$,

$$R_{JET}(Z) = R_{JET}(0) + 0.131 Z \left\{ 1 - \left[Z / (Z_R R_{AUG}) \right]^{5/3} \right\} \quad (A-2)$$

where: $Z_R \equiv 4.07 \exp(3.54 C_t)$

$R_{JET}(Z)$ = radius of jet at a distance Z from the augmeter inlet

R_{AUG} = radius of augmeter tube

and for $0.7 < C_t$,

$$R_{JET}(Z) = R_{JET}(0) + 0.126 Z \quad (A-2')$$

The geometry of the jet is fully defined by Equations A-1 and A-2. Although it appears that fluid properties are being neglected, it should be noted that the augmentation airflow rate is input directly, rather than calculated. This partially introduces properties of both the jet and augmentation air through the variable V_{SEC} .

A final flow relationship is acquired by employing the assumptions of an isopiestic ideal gas

$$\rho T = \text{constant}$$

(A-3)

where: ρ = density

T = gas temperature

SIMULATING THE HEAT TRANSFER

To model the heat transfer, the augments tube is first divided into axial segments, with the jet, augmentation flow, and inner and outer liner* sections lumped separately as illustrated on Figure A-1. Temperature is assumed constant throughout each section-segment; flows are perfectly mixed.

Mass flow rates through each segment are determined from the geometry of the jet; i.e., from Equation A-2.

$$\dot{\Delta M}_I = \pi \rho_{\text{SEC},I} V_{\text{SEC},I} \left(R_{\text{JET},I}^2 - R_{\text{JET},I-1}^2 \right)$$

$$\dot{M}_{\text{JET},I+1} = \dot{M}_{\text{JET},I} + \dot{\Delta M}_I$$

$$\dot{M}_{\text{SEC},I+1} = \dot{M}_{\text{SEC},I} - \dot{\Delta M}_{I+1}$$

where: $\dot{\Delta M}_I$ = augmentation flow entrained by the jet in segment "I"

$\dot{M}_{\text{JET},I}$ = mass flow rate of jet through segment "I"

$\dot{M}_{\text{SEC},I}$ = mass flow rate of augmentation air through segment "I"

$\rho_{\text{SEC},I}$ = density of augmentation air

$R_{\text{JET},I}$ = radius of segment "I" of the jet

Conservation of energy is then applied to each segment of each section. For the jet exhaust (see Figure A-2),

*Some augmenters do not have liners but are of solid construction. For this configuration, the inner and outer "liners" in the model represent the inside and outside of the wall.

$$\begin{aligned}
& \dot{M}_{JET,I+1} \left(h_{JET,I+1} - h_{REF} + \frac{v_{JET,I+1}^2}{2} \right) + \dot{q}_{RAD,I,JET \rightarrow IL} \\
& - \dot{M}_{JET,I} \left(h_{JET,I} - h_{REF} + \frac{v_{JET,I}^2}{2} \right) \\
& - \Delta \dot{M}_I \left(h_{SEC,I} - h_{REF} + \frac{v_{SEC,I}^2}{2} \right) = 0
\end{aligned}$$

or, using the ideal gas approximation after applying conservation of mass to eliminate the reference enthalpies,

$$\begin{aligned}
& \dot{M}_{JET,I+1} \left(c_{P,JET,I+1} T_{JET,I+1} + \frac{v_{JET,I+1}^2}{2} \right) + \dot{q}_{RAD,I,JET \rightarrow IL} \\
& - \dot{M}_{JET,I} \left(c_{P,JET,I} T_{JET,I} + \frac{v_{JET,I}^2}{2} \right) \\
& - \Delta \dot{M}_I \left(c_{P,SEC} T_{SEC,I} + \frac{v_{SEC,I}^2}{2} \right) = 0
\end{aligned}$$

where: $T_{JET,I}$ = temperature of jet in segment "I"

$c_{P,JET,I}$ = specific heat of the jet exhaust in segment "I"

$T_{SEC,I}$ = temperature of augmentation air in segment "I"

$c_{P,SEC,I}$ = specific heat of augmentation air in segment "I"

The radiation from jet segment "I" to the wall, $\dot{q}_{RAD,I,JET \rightarrow IL}$, is determined by summing the net radiation between this segment and all sections of the wall,

$$\dot{q}_{RAD,I,JET \rightarrow IL} = \sum_{J=1}^N \sigma A_{JET,I} F_{I,J} \left(\epsilon T_{JET,I}^4 - \alpha T_{IL,J}^4 \right)$$

where: $T_{IL,J}$ = temperature of augmenter inner liner segment "J"
 $A_{JET,I}$ = surface area of jet segment "I"
 σ = Stefan-Boltzmann constant
 $F_{I,J}$ = shape factor for radiation from jet segment "I" to inner liner segment "J"
 $\epsilon = \epsilon(I, T_{JET,I})$ = emissivity of jet segment "I"
 α = absorptivity of jet segment "I"
 $= \epsilon(T_{JET,I}/T_{IL,J})^{0.5}$ (Ref 6)
 N = number of axial segments of the augmenter tube

For the augmentation airflow (see Figure A-3),

$$\begin{aligned}
 & \dot{M}_{SEC,I+1} \left(C_{P,SEC} T_{SEC,I+1} + \frac{V_{SEC,I+1}^2}{2} \right) \\
 & + \Delta \dot{M}_{I+1} \left(C_{P,SEC} T_{SEC,I+1} + \frac{V_{SEC,I+1}^2}{2} \right) \\
 & - \dot{M}_{SEC,I} \left(C_{P,SEC} T_{SEC,I} + \frac{V_{SEC,I}^2}{2} \right) + \dot{q}_{CONV,I,IL \rightarrow SEC} = 0
 \end{aligned}
 \quad \dots \dots \dots (A-5)$$

where: $\dot{q}_{CONV,I,IL \rightarrow SEC}$ = convection heat transfer from the inner liner to augmentation air segment "I"
 $h = \hat{h} A_{AUG} (T_{IL,I} - T_{SEC,I})$
 $\hat{h} = \hat{h}(I, V_{SEC,I})$ = convective film coefficient of segment "I"
 $A_{AUG} = A_{AUG,I}$ = surface area of liner in contact with augmentation air segment "I"

Conservation of energy across segments of the inner and outer liners are handled in a similar manner. For the inner liner,

$$\dot{q}_{COND,I \rightarrow I-1,IL} + \dot{q}_{COND,I,IL \rightarrow OL} + \dot{q}_{CONV,I,IL \rightarrow SEC} + \dot{q}_{RAD,I \rightarrow J,IL} - \dot{q}_{COND,I+1 \rightarrow I,IL} - \dot{q}_{RAD,I,JET \rightarrow IL} = 0 \quad (A-6)$$

where: $\dot{q}_{COND,I \rightarrow I-1,IL}$ = conduction along the inner liner
 $= kA_{IL}(T_{IL,I} - T_{IL,I-1})/\Delta Z$

$\dot{q}_{COND,I,IL \rightarrow OL}$ = conduction between inner and outer liners

$\dot{q}_{RAD,I \rightarrow J,IL}$ = radiation between different segments of the inner liner

$$\dot{q}_{RAD,I \rightarrow J,IL} = \sum_{J=1}^N \sigma A_{AUG} F_{I,J} (1 - \epsilon) (T_{IL,I}^4 - T_{IL,J}^4)$$

where: $F_{I,J}$ = shape factor for radiation from inner liner segment "I" to inner liner segment "J"

k = effective coefficient of thermal conductivity, includes liner, acoustic pillows, concrete, etc. (where applicable)

A_{IL} = cross sectional area of inner liner, acoustic pads, etc.

ΔZ = spacing between nodes

Finally, for the outer liner,

$$\dot{q}_{COND,I \rightarrow I-1,OL} + \dot{q}_{CONV,I,OL \rightarrow \infty} - \dot{q}_{COND,I+1 \rightarrow I,OL} - \dot{q}_{COND,I,IL \rightarrow OL} = 0 \quad (A-7)$$

where: $\dot{q}_{CONV,I,OL \rightarrow \infty}$ = convection heat transfer off outer skin of augmenter
 $= \hat{h}_{\infty} A_{\infty} (T_{OL,I} - T_{\infty})$

Equations A-4 through A-7 for all sections, along with Equation A-3 and the Equation of Continuity, are solved simultaneously to determine temperatures throughout the augmenter assembly. When the jet reaches the wall, conservation of augmentation flow energy is deleted, and the

other equations are modified accordingly. Due to the nonlinearities, an iterative technique is necessary, and the Gauss-Seidel method, with relaxation, is employed for this purpose. Figure A-4 illustrates typical predicted augmenter temperature profiles.

The heat transfer characteristics perhaps need further discussion. Radiation was modelled by considering each jet segment as a separate gas mass and applying the mean beam length approximation suggested by Hottel (Ref 6). With this approximation, radiation from irregular geometries is related to radiation from a gas hemisphere by extrapolation using a fictitious dimension called the mean beam length.

Emissivity of the jet is a function of its geometry (mean beam length), composition, and temperature. Geometry is easily acquired from the node spacing and from Equation A-2. Composition of each segment is determined by inputting the weight fraction of the radiators, CO_2 , H_2O , and CO , at the engine nozzle and then progressively diluting the jet with augmentation air. Temperature is the problem; the interdependency with temperature necessitates including the emissivity calculations in the temperature iteration. The gas emissivity data of Hottel were curve-fitted to provide a continuous relationship as a function of mean beam length, composition, and temperature. Figure A-5 shows typical emissivities calculated in this manner.

Very little work has been done in the area of convection heat transfer to confined jets. Kang et al. (Ref 7) have experimentally determined some Nusselt numbers, but their tests are not comprehensive enough to provide the foundation for any correlation. Thus, conventional relationships (Ref 8) for turbulent flow through a cylinder had to be employed, substituting the equivalent diameter of the augmentation flow for the diameter of the cylinder,

$$\hat{h} = \frac{14 k_{\text{SEC}}}{D_{\text{EQV}}^{0.2}} \left(\frac{v_{\text{SEC}} \rho_{\text{SEC}}}{\mu_{\text{SEC}}} \right)^{0.8}$$

where: $\hat{h}$ = film coefficient of convective heat transfer between augmentation airflow and the inner liner

k_{SEC} = thermal conductivity of augmentation air

$$\begin{aligned}\mu_{\text{SEC}} &= \text{viscosity of augmentation air} \\ D_{\text{EQV}} &= \text{equivalent diameter of augmentation flow} \\ &= 2 (R_{\text{AUG}} - R_{\text{JET}})\end{aligned}$$

This convection coefficient varies with equivalent diameter of the augmentation flow and, therefore, varies from segment to segment. Properties of the augmentation flow vary with temperature, requiring the film coefficient calculations to also be included in the iteration. Figure A-6 shows typical calculated coefficients.

BOILER SIMULATION

To simulate waterwalls, the temperature of the outer liner is set equal to the saturation temperature of the steam; and all heat resistance, except the metal, is removed from between the two liners. This is equivalent to neglecting the resistance to heat transfer on the boiling water side of the walls, a good approximation since this resistance is several orders of magnitude less than the resistance to convection and radiation from the jet exhaust. The steam generation is then determined directly from a summation of the energy transferred to the outer liner.

Simulation of convection, water tube boilers is more difficult. Conservation of energy is applied to the jet and augmentation flow through the heat exchanger, to the water/steam flow through the heat exchanger, and to the overall heat exchanger. These relationships are, in the same order,

$$\dot{q}_{\text{STM}} = \dot{M}_{\text{GAS}} C_{P,\text{GAS}} (T_{\text{GAS}} - T_{\text{STACK}}) \quad (\text{A-8})$$

$$\dot{q}_{\text{STM}} = \dot{M}_{\text{STM}} \Delta h_{fg} \quad (\text{A-9})$$

$$\dot{q}_{\text{STM}} = UA \Delta T_M \quad (\text{A-10})$$

where: $\dot{M}_{GAS}$ = sum of jet and augmentation air
 $\dot{M}_{STM}$ = steam generation
 $\dot{q}_{STM}$ = heat transferred from jet and augmentation airflow to the steam
 T_{GAS} = temperature of gas entering the boiler
 T_{STACK} = temperature of gas exiting the boiler
 UA = product of boiler overall heat transfer coefficient and heat transfer area
 Δh_{fg} = heat of vaporization of steam
 ΔT_m = logarithmic mean temperature difference

$$\text{where: } \Delta T_m = \frac{T_{GAS} - T_{STM}}{\ln \left(\frac{T_{GAS} - T_{STM}}{T_{STACK} - T_{STM}} \right)}$$

T_{STM} = saturation temperature of steam

resulting in Equations A-8, A-9, A-10 and the four unknowns: $\dot{q}_{STM}$, $\dot{M}_{STM}$, T_{STACK} , and UA . The final relationship is determined by stipulating a boiler effectiveness*, e,

$$e = \frac{T_{GAS} - T_{STACK}}{T_{GAS} - T_{STM}}$$

If boiler effectiveness is known, steam generation and the other unknowns can be calculated. Furthermore, if the boiler tube configuration is also stipulated, the heat transfer characteristics can be estimated. For example, if the boiler is to be of a staggered tube configuration (Ref 8),

$$U \approx \hat{h}_{TUBE} = 0.287 \frac{k_{JET}}{D_{TUBE}} \left(\frac{\rho_{JET} V_{JET} D_{TUBE}}{\mu_{JET}} \right)$$

*A value $e = 0.76$ is assumed throughout these analyses.

where: $\hat{h}_{TUBE}$ = convection film coefficient between jet exhaust and water tubes

D_{TUBE} = outer diameter of water tubes

It should be noted that the resistance to heat transfer through the tube walls and to the boiling water are being neglected. With this equation, an estimate of boiler heat transfer area is also acquired because UA is known. Properties are determined by assuming the jet exhaust behaves identically to air and applying the Eucken equations (Ref 9),

$$k_{JET}, \mu_{JET} \propto \frac{T_{JET}^{1.5}}{225 + T_{JET}}$$

ACCURACY OF THE AUGMENTER MODEL

To evaluate the simulation, predicted augmenter inner liner temperatures are compared with measured values. The accuracy of these temperatures makes a valid benchmark since they indicate the accuracy of the simulation of heat transfer to the walls and, by supposition, to a waterwall heat exchanger. The same reasoning applies to the augmenter exit gas temperature, but here the modelling involves only simple mixing of gases, and little error is likely. Regardless, these temperatures can be examined concurrently by noting that, due to high wall resistance, there is little difference between gas and wall temperatures near the augmenter exit. This trend is illustrated in Figure A-4.

An abundance of data are not available with which to make this comparison. The hush houses at the NAS Miramar have been studied extensively. These facilities were used to develop the empirical model of the jet exhaust, however. It is suspect to use the same sites to evaluate the model. Nevertheless, they will be used. The hush house at the Marine Corps Air Station El Toro, although studied less extensively, provides a better accreditation.

The comparisons are made on Figures A-7 through A-9. Predicted and measured temperatures are within $\pm 50^{\circ}\text{F}$ of each other. The exception is the TF30 engine undergoing afterburning tests where the simulation of inner liner temperatures is in error by more than 200°F . Not enough temperatures have been measured near the augmentor inlet to verify the existence of the radiation peaks shown on the figures.

Several sources of error are obvious, each related to the assumptions. First, the hush houses are not cylindrical but elliptical. Although the distance from the nozzle to the nearest augmentor wall was used as an effective radius, the effects of this cross section on flow characteristics could not be accounted for. The steady state assumption is possibly not valid for the afterburning tests which tend to be of short duration. Actual inner liner temperatures could be much higher or much lower than steady state temperatures, depending upon wall thickness, specific heat, and thermal conductivity as well as time. Jet exhaust and secondary entrained air are certainly not perfectly mixed at the nozzle. A hot core of exhaust will survive for some distance, tending to damp out both the radiation peak and convection valley predicted by the model and illustrated on Figures A-7 through A-9. Finally, the jet nozzle is not located exactly at the augmentor inlet but some 10 feet back inside the hush houses.

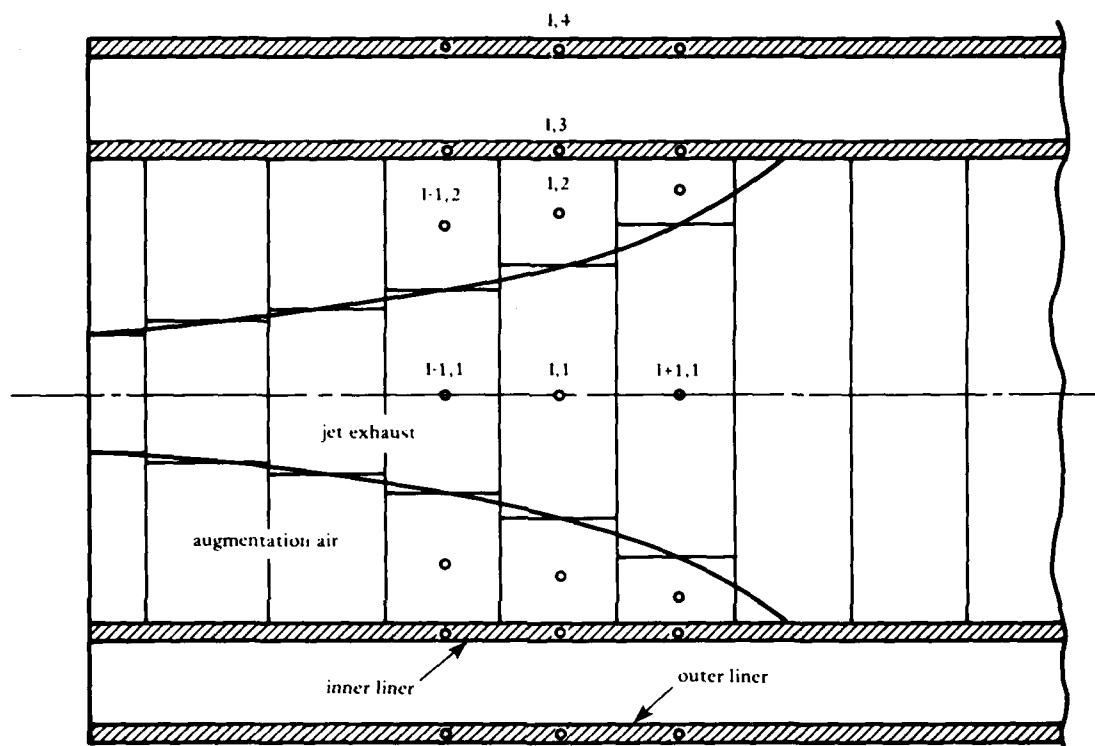


Figure A-1. Dividing the augmenter into segments

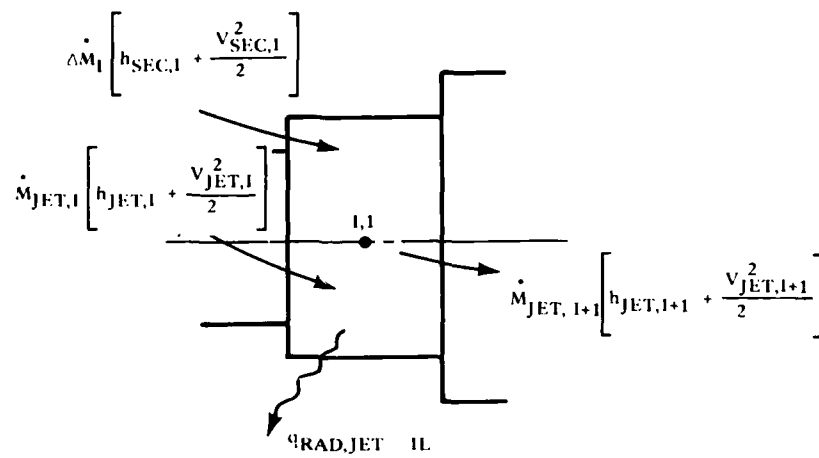


Figure A-2. Conservation of energy across segment of jet exhaust.

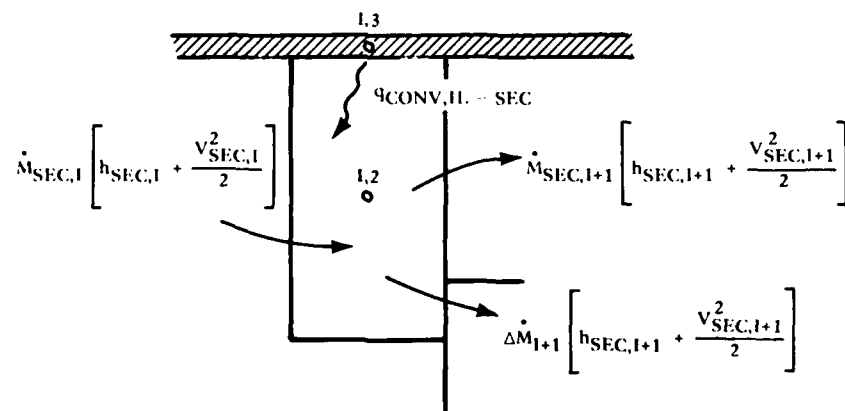


Figure A-3. Conservation of energy across segment of augmentation air.

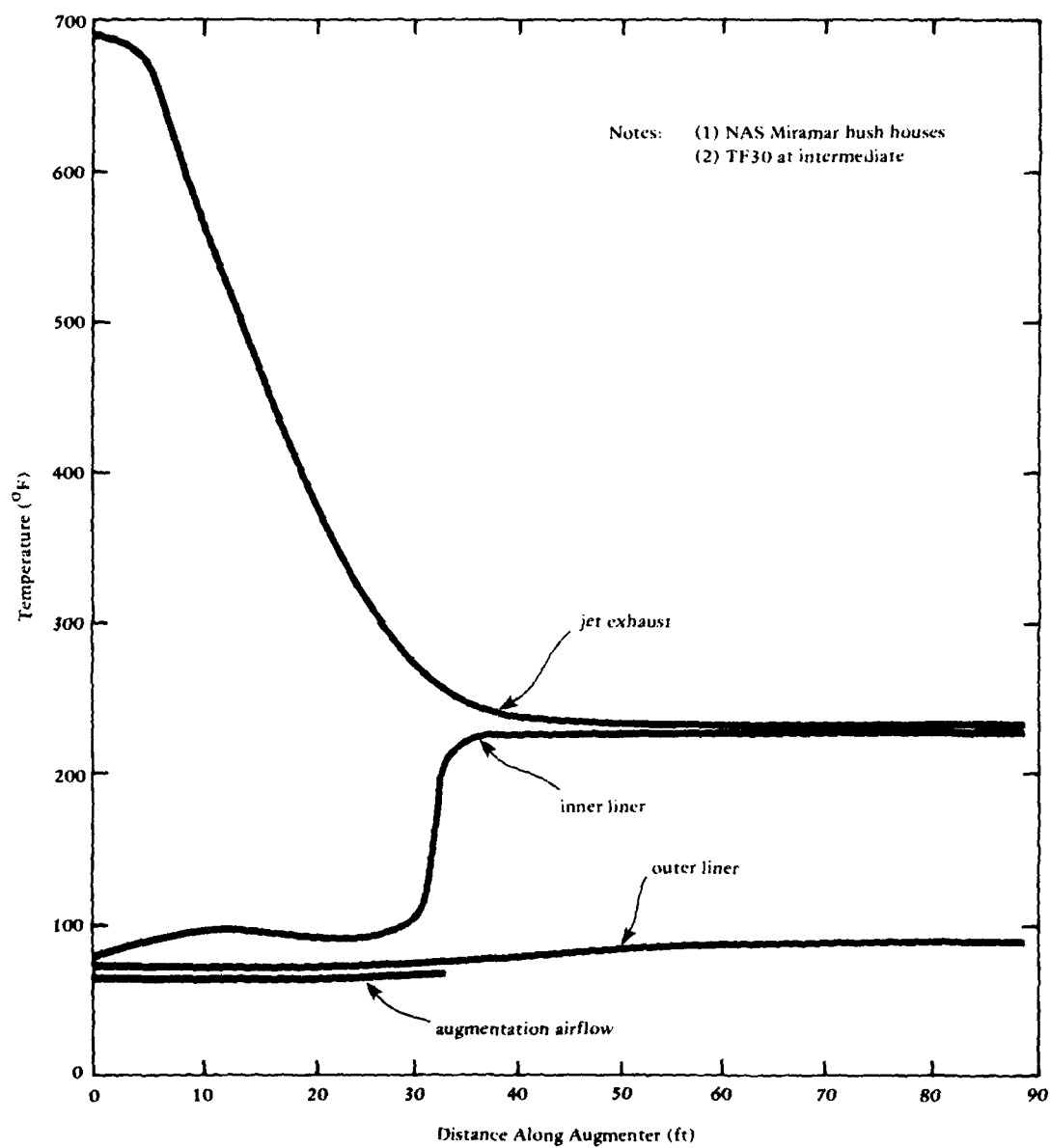


Figure A-4. Typical predicted temperature profiles along the augmenter.

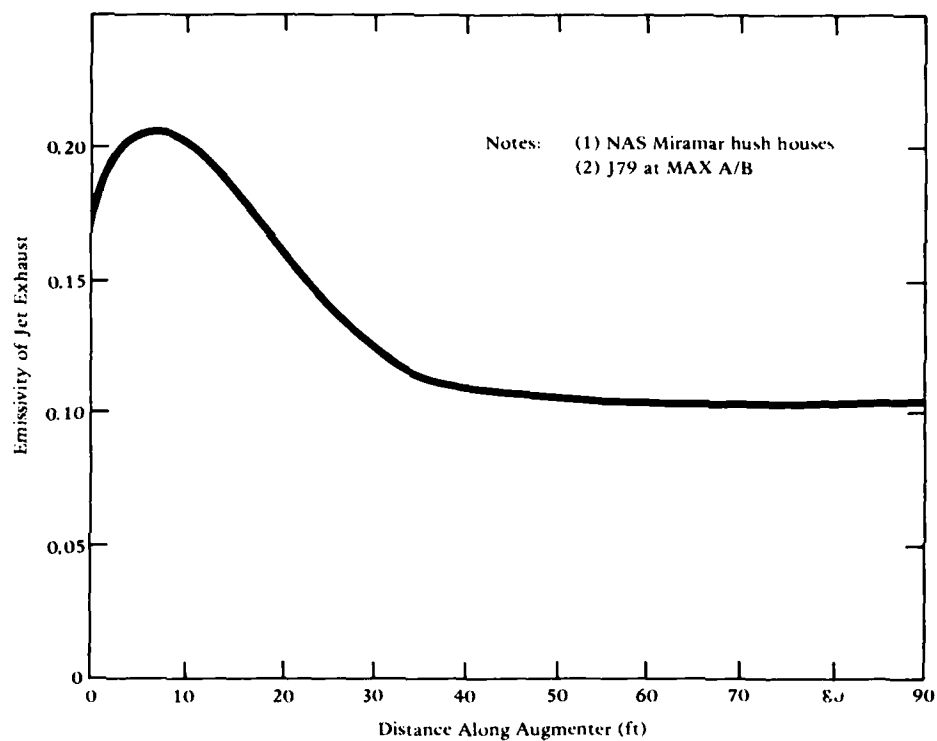


Figure A-5. Typical emissivities of jet exhaust.

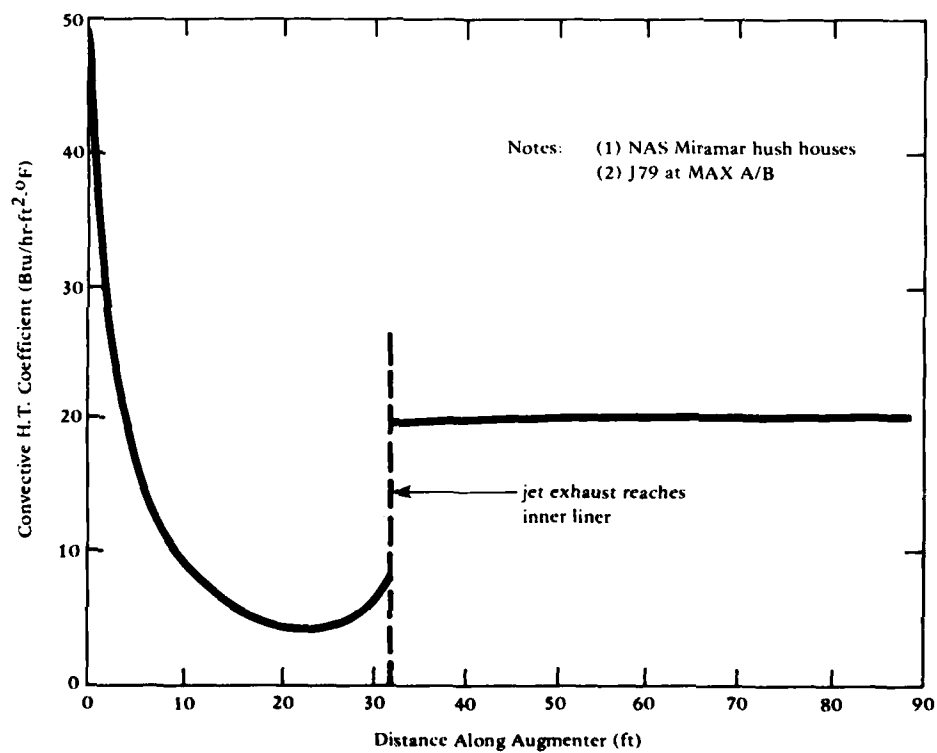


Figure A-6. Typical coefficients of convective heat transfer between inner liner and augmentation airflow.

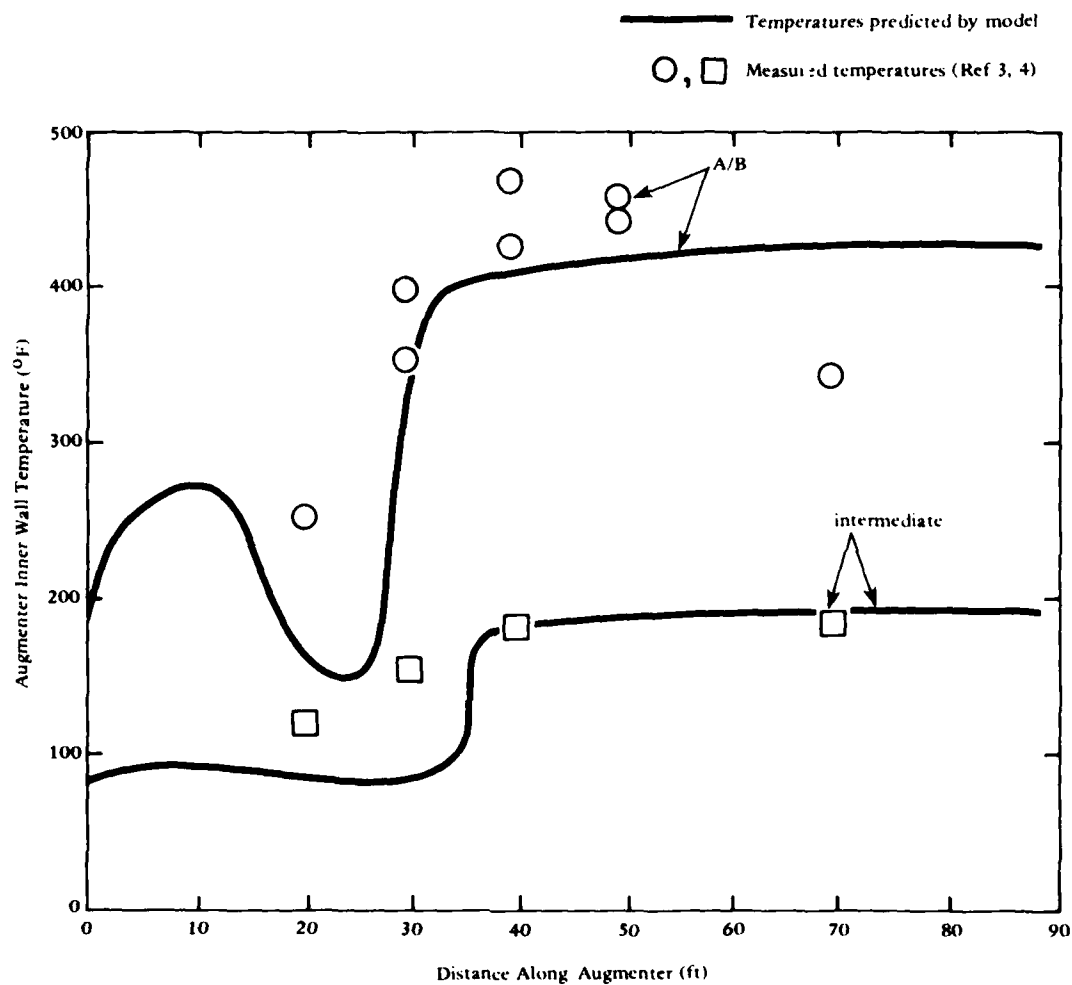


Figure A-7. Evaluation of augmentor model by comparison with temperatures measured during J79 testing in the hush houses at NAS Miramar.

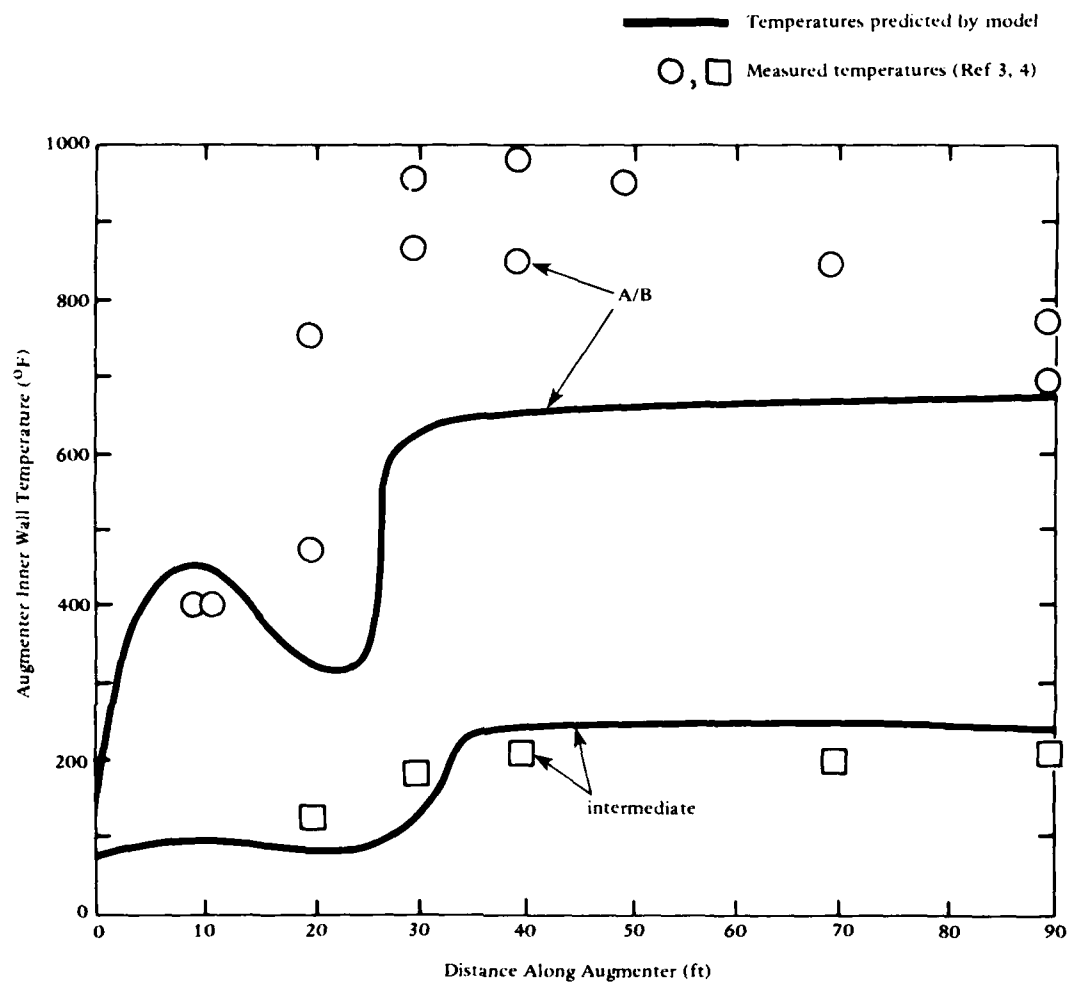


Figure A-8. Evaluation of augmentor model by comparison with temperatures measured during TF30 testing in the hush houses at NAS Miramar.

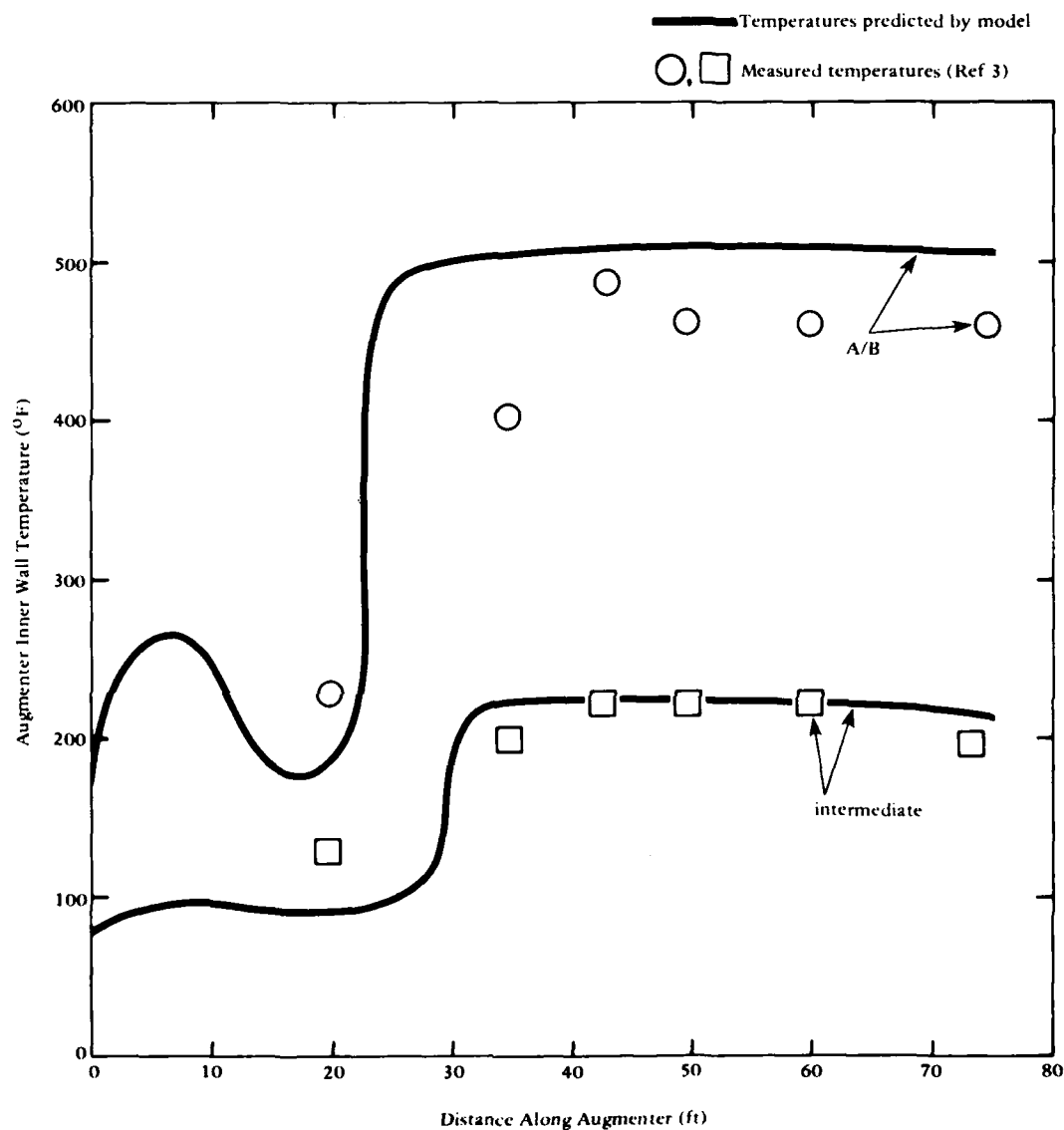


Figure A-9. Evaluation of augmentor model by comparison with temperatures measured during J79 testing in the hush house at MCAS El Toro.

Appendix B

METHOD OF CALCULATING THE ECONOMICS OF TEST CELL ENERGY RECOVERY

Once test cell steam generation has been determined, its value is estimated,

$$\text{VALUE} = \dot{M}_{\text{STM}} \times \text{COST} \times \text{TIME} \quad (\text{B-1})$$

where: $\dot{M}_{\text{STM}}$ = mass flux of steam generated

COST = assumed value of one unit of steam

TIME = average utilization of the test cell (see Table C-1)

and accumulated over the economic life of the heat exchanger (or life of the test cell, if shorter),

$$\text{PV}_{\text{NN}} = \sum_{i=1}^{\text{NN}} \left[\text{VALUE} \left(\frac{1 + \text{ESC}}{1 + \text{DISC}} \right)^i \right] \quad (\text{B-2})$$

where: PV_{NN} = present value of steam generated over a period of NN

ESC = assumed escalation rate of the cost of steam (Ref 5)

DISC = assumed discount rate (Ref 5)

allowing a savings/investment ratio to be predicted,

$$\text{SIR}_{\text{NN}} = \frac{\text{PV}_{\text{NN}}}{\text{PRICE}} \quad (\text{B-3})$$

where PRICE is the cost of the waterwalls or heat exchanger.

The economics of the Rankine cycle generation of electricity are analogous, substituting the value of electricity for the value of steam.

COST OF ENERGY RECOVERY HARDWARE

A major obstacle is the determination of PRICE. Very few boilers/heat exchangers large enough for this application are manufactured, and these few are all custom jobs.

To acquire an estimate of the cost of a test cell heat exchanger, twenty boiler manufacturers were asked to provide a preliminary design. Table B-1 describes a water tube heat exchanger composited from their responses. It is presented without documentation. For purposes of applying this design to a particular test cell/engine/power setting, a scaling criterion was developed.

The downstream convection heat exchanger (Configuration No. 1 of Figure 1) cost is ratioed linearly from Table B-1 using the total gas flow as the independent variable,

$$\text{PRICE} = \text{PRICE}_{B1} \left(\frac{\dot{M}_{\text{TOTAL}}}{\dot{M}_{\text{TOTAL},B1}} \right) \quad (\text{B-4})$$

where the subscript B1 refers to the values in Table B-1 and TOTAL refers to the sum of the jet and secondary flow. The overall heat transfer coefficient is kept at approximately 9 Btu/hr-ft²°F, equivalent to a flow velocity of about 80 ft/sec over 2-inch tubes.

When convection heat exchangers are inside the augmentor near the engine nozzle (Configuration No. 4 of Figure 1), the heat transfer area is input directly while the overall heat transfer coefficient is allowed to increase, following the high velocities encountered. The price of the heat exchangers is established in a manner analogous to Equation B-4, using heat transfer area in place of total gas flow,

$$\text{PRICE} = \text{PRICE}_{B1} \left(\frac{A_{\text{TUBES}}}{A_{\text{TUBES},B1}} \right) \quad (\text{B-5})$$

This relationship is applied for lack of a better approach. The high gas velocities would be expected to create some serious tube erosion problems, requiring thicker tubes and probably special alloys. In addition, the tubes would have to withstand occasional bursts of A/B. It follows that these heat exchangers would be more expensive than equivalent downstream configurations.

No waterwall designs were submitted in response to the survey of boiler manufacturers. Waterwall areas are input and heat transfer characteristics built into the model, however, neither presents a problem. The use of waterwall prices will be avoided, to the extent possible, in the comparisons. When necessary, Equation B-5 will be employed.*

*Again, for lack of a better approach. This is tantamount to the assumption that the fabrication of the tubes is the major expense in the manufacture of each device.

Table B-1. Composite Heat Exchanger for Energy Recovery
From Gas Turbine Engine Test Cell

Type	Convection, Shell and Tube
Gas flow	$2.3 (10)^6$ lb/hr
Gas temperature in	420°F
Gas temperature out	367°F
Steam flow	30,300 lb/hr
Steam temperature	350°F
Steam pressure	135 psia
Heat transferred	$30 (10)^6$ Btu/hr
Heat exchanger width	50 ft
Heat exchanger height	15 ft
Heat exchanger length	72 ft
Tube diameter	2 inches
Tube thickness	0.12 inch
Fin segment	0.156 inch
Fin length	0.5 inch
Fin thickness	0.035 inch
Number of fins	6/in.
Number of circuits	45
Number of passes	12
Heat transfer surface	118,000 ft ²
Gas ΔP	5.85 inches H ₂ O
Cost	\$2,000,000.

Appendix C

JET ENGINE TEST CELL CHARACTERISTICS

Table C-1 summarizes the geometries and flow characteristics of test cells used in the analyses. With the exception of the hush houses at the MCAS El Toro, all of these facilities are located in the San Diego area. Geometries and cell utilization were acquired from Reference 10. This reference also describes the cells in greater detail. Flow rates and temperatures were acquired from References 3 and 4. The compositions of the engine exhaust gases at the nozzle were determined by back-calculating from stack gas compositions measured on the Miramar "A" test cell and NARF North Island Test Cell 19 (Ref 11, 12 and 13). It was assumed that the chemical composition of the jet exhaust at the nozzle was dependent only on the type of engine and power setting; the same values were used for the other test cells.

Table C-1. Gas Turbine Engine Test Cell Characteristics

Augmenter Description	Engine Tested	Average Utilization (hr/yr)	Jet Exhaust				Augmentation Airflow (lb/sec)	Comments	
			Flow Rate (lb/sec)	Total Temperature (°F)	Composition (% Weight)				
					CO ₂	H ₂ O			CO
NAS Miramar Hush Houses									
Length: 90.5 ft Effective Diameter: 11 ft ^a Liner: Acoustic pads between inner and outer perforated stainless steel sheets	TF30 at intermediate	150 ^b	250	940	2.75	3.0	0.5	1,200	F-14A
	TF30 afterburning	15	250	3,140	16.3	8.15	1.0	1,200	F-14A
	J79 at intermediate	113	180	1,140	4.5	3.75	0.5	1,520	F-4
	J79 afterburning	12	180	3,060	15.9	8.0	1.0	1,520	F-4
	J52 at intermediate	65	140	1,420	--	--	--	--	A-4
MCAS El Toro Hush House									
Length: 67 ft Effective Diameter: 9 ft ^a Liner: Acoustic pads between inner and outer perforated stainless steel sheets	J79 at intermediate	--	180	1,140	4.5	3.75	0.5	1,130	F-4
	J52 at intermediate	--	140	1,420	--	--	--	1,410	A-4
NAS Miramar "A" Test Cell									
Length: 35 ft Effective Diameter: 6 ft Liner: Single perforated steel liner, 6-ft space between liner and noise baffles	TF30 at intermediate	72.9	250	940	2.75	3.0	0.5	410	
	T30 afterburning	62.6	250	3,140	16.3	8.15	1.0	410	
NARF North Island Test Cell 10									
Length: 14 ft ^c Effective Diameter: 2 ft 8 in. ^d Liner: Two stainless steel liners separated by 6 in. of wire rope	T64 at intermediate	66	--	--	--	--	--	--	Helicopter engines

continued

Table C-1. Continued

Augmenter Description	Engine Tested	Average Utilization (hr/yr)	Jet Exhaust				Augmentation Airflow (lb/sec)	Comments
			Flow Rate (lb/sec)	Total Temperature (°F)	Composition (% Weight)			
					CO ₂	H ₂ O	CO	
NARF North Island Test Cell 11								
Length: 43 ft ^e Effective Diameter: 2 ft 6 in. ^f	T58 at intermediate	79	15	1,160	--	--	5	Helicopter engines
NARF North Island Test Cell 14								
Length: 27 ft ^g Effective Diameter: 7 ft ^h Liner: Single steel liner, isolated	J79 at intermediate LM2500 at intermediate	15.7 80	180 --	1,140 --	-- --	-- --	300 --	
NARF North Island Test Cell 19								
Length: 80 ft ^g Effective Diameter: 8 ft ⁱ Liner: Two steel liners surrounded by 14 inches of concrete, water injection rings near inlet	J79 at intermediate J79 afterburning	196.3 17.7	180 180	1,140 3,060	-- --	-- --	470 470	Test cell 19 scheduled for modernization
NARF North Island Test Cell 20								
Length: 74 ft Effective Diameter: 13 ft Liner: Inner and outer stainless steel liners with acoustic pads between them	J79 and F404	unknown	--	--	--	--	--	Test cell 20 currently undergoing modernization

^a Cross section is elliptical.^b Each hush house.^c Augmenter is followed by 20-ft muffler.^d Augmenter expands to 7-ft-diam muffler section.^e Front section of augmenter is curved.^f Sections from 1 ft 11 in. diameter to 3 ft 4 in. diameter.^g Telescoping sections.^h Sections from 5 ft 10 in. to 10 ft 2 in. inner diameter.ⁱ Slightly tapered.

Appendix D

COMPUTER MODELLING OF AUGMENTER TUBE

The relationships in Appendixes A and B were programmed in FORTRAN IV. Figure D-1 is a flow chart of the program. A listing and some typical results follow.

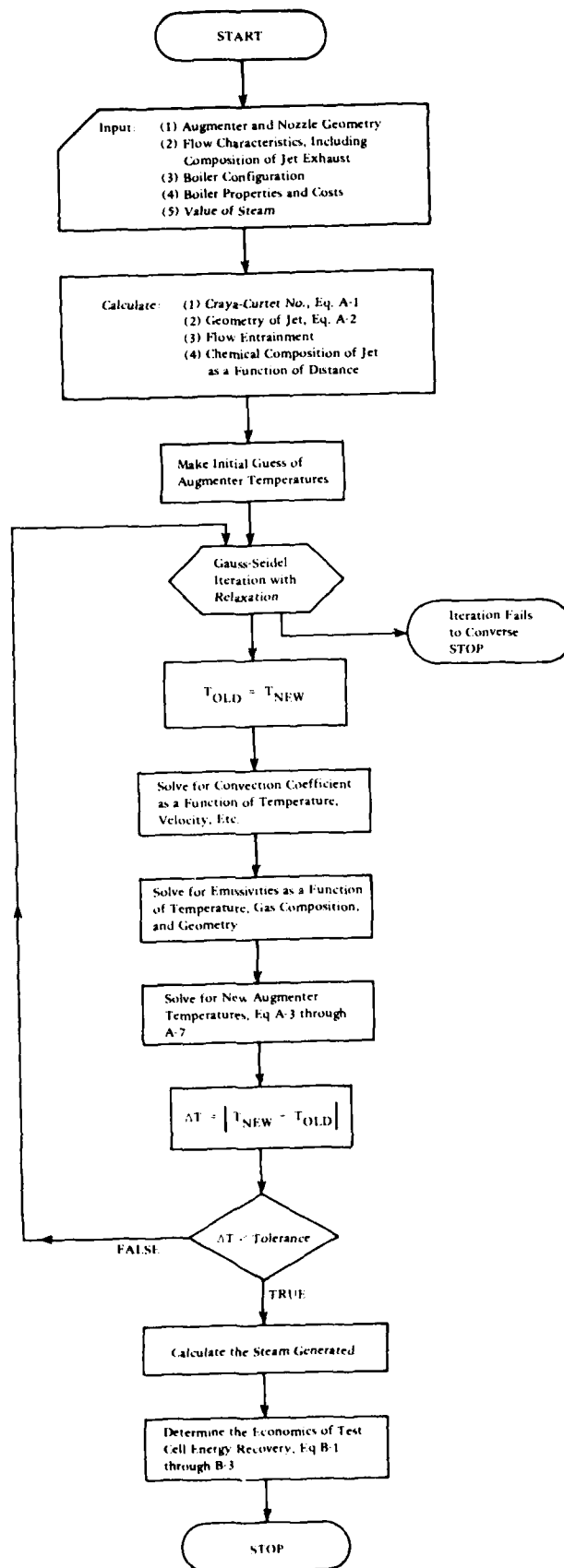


Figure D-1. Flowchart of computer modeling of augmenter tube.

PROGRAM LISTING

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      PROGRAM JETEST (INPUT,OUTPUT,TAPES=INPUT,TAPE6=OUTPUT)
C   PROGRAM TO CALCULATE THE HEAT TRANSFER FROM A JET EXHAUST TO THE
C   TEST CELL AUGMENTER WALLS OR TO BOILERS WRAPPED AROUND THE WALLS
C   OR TO BOILERS PLACED IN THE JET STREAM AT THE AUGMENTER EXIT OR BOTH
C
C   STEADY STATE AXISYMMETRIC FLOW THRU A CYLINDRICAL DUCT IS ASSUMED
C   IN ADDITION, IT IS ASSUMED THAT BOTH THE JET AND SECONDARY FLOW ARE
C   TURBULENT, PERFECTLY MIXED IDEAL GASES
C
      REAL MJET(51),MSEC(51),KDUCT,KAINT,KAEXT,KPAD,N2(50),L(50),KAIR,
      1QUAIR,MSTM1(50),K
      INTEGER TYPE
      COMMON O2,N2,CO2,H2O,CO,H2,LUM
      DIMENSION T(50,4),TEMP(50,4),HCONV(50),ARAD(50),F(50,50),DELM(50)
      1,O2(50),AJET(50),RJET(50),RADST(50),ABOIL(2),TSTM(2),PSTM(2)
      2,HSTM(2),RADIN(50),RADOUT(50),Z(50),CO2(50),H2O(50),CO(50),H2(50)
      3,CONV(50),EMIS(50),F1(50,50),UJET(51)
      DIMENSION PV(25),SIR(25),P18(50),P49(50),P39(50)
      DATA PI,PRESS,RAIR,SIGMA,TDATUM/3.1416,2116.,53.36,0.1714E-8,520./
      DATA ITER,TOL/100,1./
      DATA R/-0.5/
      DATA EMPIR1,EMPIR2/14.,14./
C
C   INPUT THE NUMBER OF AXIAL SEGMENTS THAT THE AUGMENTER TUBE WILL BE
C   DIVIDED INTO, N.LE.50
      READ(5,1) N
C   INPUT THE AUGMENTER GEOMETRY....THE AREA OF THE JET NOZZLE AND THE
C   AREA OF THE AUGMENTER INLET, BOTH IN SQFT....THE LENGTH OF THE
C   AUGMENTER IN FEET....AND THE THICKNESSES OF THE DUCT AND THE ACOUSTIC
C   PILLOWS IN INCHES
      READ(5,2) AJET(1),AAUG,AUGL,DELR,DELPAD
C   INPUT SECONDARY FLOW RATE IN LBS/SEC AND ITS TEMPERATURE IN DEGF
      READ(5,3) MSEC(1),T(1,2)
C   INPUT JET FLOW RATE IN LBS/SEC, TOTAL TEMPERATURE AND TOTAL PRESSURE
C   OF JET IN DEGF AND PSIA, AND RATIO OF JET SPECIFIC HEATS
      READ(5,4) MJET(1),TTJET,PTJET,GAMMA
C   INPUT THE CHEMICAL COMPOSITION OF THE JET....PERCENT WEIGHT OF
C   OXYGEN, NITROGEN, CARBON DIOXIDE, CARBON MONOXIDE, WATER VAPOR, AND
C   HYDROGEN
      READ(5,6) O2(1),N2(1),CO2(1),CO(1),H2O(1),H2(1)
C   INPUT THE LENGTH OF THE LUMINOUS PORTION OF THE JET EXHAUST IN FEET
      READ(5,3) FLAME
C   INPUT THE COEFFICIENT OF THERMAL CONDUCTIVITY OF THE DUCT WALLS AND
C   THE ACOUSTIC PILLOWS IN BTU/HR-FT-DEGF....IF THE PILLOWS ARE NOT
C   USED, INPUT DELPAD=0. AND KPAD=10000.
      READ(5,7) KDUCT,KPAD
C   INPUT BOUNDARY CONDITIONS TO SIMULATE THE HOUSE STRUCTURE ACTING AS
C   A HEAT SINK.....THE EFFECTIVE TEMPS AND THERMAL CONDUCTANCES, IN DEGF
C   AND BTU/HR-DEGF, AT THE AUGMENTER INLET AND EXIT, IN THAT ORDER
      READ(5,4) TINT,KAINT,TEXT,KAEXT
C   INPUT AMBIENT CONDITIONS....THE TEMP IN DEGF AND THE NATURAL
C   CONVECTION HEAT TRANSFER COEFFICIENT IN BTU/HR-SQFT-DEGF
      READ(5,3) TAMB,HAMB
C   INPUT THE HEAT EXCHANGER (BOILER) CONFIGURATION
C       "1" SIGNIFIES NO HEAT EXCHANGERS
C       "2" SIGNIFIES WATERWALLS WRAPPED AROUND THE AUGMENTER TUBES
C       "3" SIGNIFIES CONVECTION BOILER IN THE AUGMENTER GASES AT EXIT

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C      *4* SIGNIFIES BOTH WATERWALLS AND CONVECTION BOILERS
      READ(5,1) TYPE
      IF (TYPE.EQ.1) GO TO 10
C      INPUT THE APPLICABLE BOILER CHARACTERISTICS
C      INPUT THE TOTAL NUMBER OF HRS PER DAY THAT THE TEST CELL IS UTILIZED
C      WITH THIS ENGINE AND AT THIS POWER SETTING AND ALSO INPUT IND2.GE.7,
C      FOR A PARAMETRIC STUDY INPUT TIME=0.25 AND IND2=0....INPUT PURCHASE
C      PRICE OF THE WATER-WALL AND CONVECTION HEAT RECOVERY HEAT EXCHANGERS
C      IN THAT ORDER....IF THERE IS ONLY ONE, INPUT ZERO IN THE SPACE
C      FOR THE OTHER
      READ(5,78) TIME,IND2,PRICE1,PRICE2
C      INPUT THE CURRENT COST OF THE STEAM IN $/MBTU, THE DISCOUNT RATE, AND
C      THE LONG TERM ESCALATION RATE OF THE COST OF STEAM IN PERCENT
C      PER YEAR
      READ(5,4) COST,DISC,ESC
      IF (TYPE.EQ.3) GO TO 5
C      INPUT THE WATERWALL CHARACTERISTICS....STEAM TEMP IN DEGF, STEAM
C      PRESSURE IN PSIA, HEAT OF VAPORIZATION IN BTU/LB, AND THE TOTAL HEAT
C      TRANSFER AREA IN SQFT
      READ(5,4) TSTM(1),PSTM(1),HSTM(1),ABOIL(1)
      TSTM(1)=TSTM(1)+460.
C      INPUT THE LOCATION OF THE WATER-WALLS....FRONT AND BACK IN TERMS OF
C      FEET FROM THE AUGMENTER INLET
      READ(5,3) FRONT,BACK
      IF (TYPE.EQ.2) GO TO 10
C      IF BOTH BOILERS ARE UTILIZED, INPUT WATERWALL CHARACTERISTICS FIRST
C      INPUT THE CONVECTION BOILER CHARACTERISTICS....STEAM TEMP, PRESSURE,
C      AND HEAT OF VAPORIZATION, TOTAL HEAT TRANSFER AREA, AND THE OUTER
C      DIAMETER OF THE TUBES IN INCHES
      5 READ(5,8) TSTM(2),PSTM(2),HSTM(2),ABOIL(2),DTUBE
      TSTM(2)=TSTM(2)+460.
C
C      PRINT ALL DIMENSIONS, PROPERTIES, AND BOUNDARY CONDITIONS
10 WRITE(6,11)
      WRITE(6,12) AJET(1),AAUG,AUGL,DELR,DELPAD
      WRITE(6,13)
      WRITE(6,14) MJET(1),TTJET,PTJET,GAMMA
      WRITE(6,16)
      WRITE(6,17) O2(1),N2(1),CO2(1),CO(1),H2O(1),H2(1),FLAME
      WRITE(6,18)
      WRITE(6,19) MSEC(1),T(1,2)
      WRITE(6,57)
      WRITE(6,68) TAMB,HAMB
      WRITE(6,21)
      WRITE(6,22) KDUCT
      IF (DELPAD.LE.0.) GO TO 15
      WRITE(6,23) KPAD
15 WRITE(6,24)
      WRITE(6,26) TINT,KAINT,TEXT,KAEXT
      IF (TYPE.EQ.1) WRITE(6,27)
C
C      SIMPLIFYING AND PRELIMINARY CALCULATIONS
      DELR=DELR/12.
      DELPAD=DELPAD/12.
      DTUBE=DTUBE/12.
      DELZ=AUGL/(N-1)
      LUM=INT(FLAME/DELZ)

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RAUG=SQRT(AAUG/PI)
RJET(1)=SQRT(AJET(1)/PI)
AREAR=2.*PI*RAUG*DELZ
AREAZ=PI*((RAUG+DELR)**2-RAUG**2)
K=(DELR+DELPAD)/(DELR/KDUCT+DELPAD/KPAD)
PTJET=PTJET*144.
T(1,2)=T(1,2)+460.
TTJET=TTJET+460.
TINT=TINT+460.
TEXT=TEXT+460.
TAMB=TAMB+460.
RATIO=(1.+ESC/100.)/(1.+DISC/100.)
P1=K*AREAR/2./(DELR+DELPAD)
P2=AREAR/2.
P3=KDUCT*AREAZ/DELZ
P4=K/(DELR+DELPAD)
P5=2.*P1
P6=KDUCT/DELZ
P7=SIGMA*AREAR
IF ((TYPE.EQ.1).OR.(TYPE.EQ.3)) GO TO 20
IFRONT=INT(FRONT/DELZ)+1
IBACK=INT(BACK/DELZ)+1
IF (IBACK.GT.N) IBACK=N

C
C CALCULATE BULK VELOCITIES AT AUGMENTER INLET
20 RHOS=PRESS/RAIR/T(1,2)
VSEC=MSEC(1)/RHOS/(AAUG-AJET(1))
POWER=(GAMMA-1.)/GAMMA
T(1,1)=TTJET+(PRESS/PTJET)**POWER
RHOJ=PRESS/RAIR/T(1,1)
VJET=MJET(1)/RHOJ/AJET(1)
UJET(1)=VJET
UJET(2)=UJET(1)

C CALCULATE THE CRAYA-CURTET NUMBER
A=AJET(1)/AAUG
B=1.-A
C=0.5-A
CRAYA=(A*VJET+B*VSEC)/(A*VJET**2+C*VSEC**2-0.5*(A*VJET+B*VSEC)**2)
1**0.5
WRITE(6,34) VJET,VSEC,CRAYA

C
C CALCULATE THE EXPANSION OF THE JET USING THE EMPIRICAL RELATIONSHIPS
C OF BECKER, ET AL, 9TH SYMP.(INT) ON COMB.,1963
C THE CONSTANTS HAVE BEEN ADJUSTED TO FIT TEST CELL DATA
FACTOR=0.
IF (CRAYA.GT.0.7) GO TO 40
XR=4.07*EXP(3.54*CRAYA)
FACTOR=1./XR**1.667
A=SQRT(A)
X=AUGL/RAUG
DEV=X
DO 30 I=1,ITER
DSAVE=DEV
XSAVE=X
FF=0.131*(FACTOR*X**2.667+X)-1.+A
DFFDX=0.348*FACTOR*X**1.667+0.131
X=X-FF/DFFDX

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DEV=ABS(X-XSAVE)
IF (DEV.LE.DSAVE) GO TO 25
WRITE(6,36)
WRITE(6,37)
WRITE(6,38)
GO TO 500
25 CONTINUE
IF (DEV.LE.TOL) GO TO 35
30 CONTINUE
WRITE(6,36)
WRITE(6,39) TOL,ITER
WRITE(6,38)
35 XSEP=X*RAUG
GO TO 45
40 XSEP=7.91*(RAUG-RJET(1))
45 CONTINUE
C DETERMINE IF JET EVER REACHES AUGMENTER WALL
IF (XSEP.GT.AUGL) GO TO 50
VSEP=INT(XSEP/DELZ)+2
IF (NSEP.GT.N) NSEP=N
WRITE(6,41) XSEP
GO TO 55
50 VSEP=10000
WRITE(6,42)
55 CONTINUE
C
C CALCULATE THE PROGRESSIVE RADII OF THE JET EXHAUST....AGAIN USE THE
C EMPIRICAL RELATIONSHIPS OF BECKER...
Z(1)=0.
DELM(1)=0.
DO 60 I=2,N
Z(I)=(I-1)*DELZ
RJET(I)=RJET(1)+0.131*Z(I)*(1.+FACTOR*(Z(I)/RAUG)**1.667)
IF (CRAYA.GT.0.7) RJET(I)=RJET(1)+0.1255*Z(I)
IF (RJET(I).GT.RAUG) RJET(I)=RAUG
C CALCULATE SECONDARY FLOW ENTRAINED BY THE EXPANDING JET
DELM(I)=RHOS*VSEC*PI*(RJET(I)**2-RJET(I-1)**2)
60 CONTINUE
KK=N-1
DO 490 I=1,KK
MJET(I+1)=MJET(I)+DELM(I)
MSEC(I+1)=MSEC(I)-DELM(I+1)
490 CONTINUE
MJET(N+1)=MJET(N)
WRITE(6,9)
II=1
DO 65 I=1,5
LIM=10*I
IPRINT=MIN0(LIM,N)
WRITE(6,43)
WRITE(6,44) (Z(J),J=II,IPRINT)
WRITE(6,45) (RJET(J),J=II,IPRINT)
WRITE(6,47) (MJET(J+1),J=II,IPRINT)
WRITE(6,48) (MSEC(J),J=II,IPRINT)
IF (IPRINT.GE.N) GO TO 70
II=IPRINT+1
65 CONTINUE

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70 CONTINUE
C
C CALCULATE RADIATION CONSTANTS....AREAS, MEAN BEAM LENGTHS, AND
C SHAPE FACTORS
  DO 75 I=1,N
    ARAD(I)=2.*PI*RJET(I)*DELZ
    L(I)=1.9*RJET(I)
  75 CONTINUE
    ARAD(1)=ARAD(1)/2.
    ARAD(N)=ARAD(N)/2.
    CALL SHAPE(RJET,RAUG,DELZ,F,N)
    CALL SHAPE1(RAUG,DELZ,F1,N)
C
C CALCULATE THE COMPOSITION OF THE JET EXHAUST IN MOLES/LB OF EXHAUST
  O2(1)=O2(1)/3200.
  V2(1)=N2(1)/2800.
  CO2(1)=CO2(1)/4400.
  H2O(1)=H2O(1)/1800.
  CO(1)=CO(1)/2800.
  H2(1)=H2(1)/200.
  DO 80 I=2,N
    O2(I)=O2(I-1)+0.0072*DELM(I)/MJET(I)
    V2(I)=N2(I-1)+0.0272*DELM(I)/MJET(I)
    CO2(I)=CO2(I-1)*MJET(I-1)/MJET(I)
    H2O(I)=H2O(I-1)*MJET(I-1)/MJET(I)
    CO(I)=CO(I-1)*MJET(I-1)/MJET(I)
    H2(I)=H2(I-1)*MJET(I-1)/MJET(I)
  80 CONTINUE
C
C USE GAUSS-SEIDEL ITERATION, WITH RELAXATION, TO SIMULTANEOUSLY SOLVE
C FOR JET AND SECONDARY FLOW TEMPERATURES AS WELL AS TEMPERATURES ON
C THE INSIDE AND OUTSIDE OF THE AUGMENTER WALL
C
C FIRST, INITIALIZE TEMPS FOR THE ITERATION
  TGUSS=(MJET(1)*T(1,1)+MSEC(1)*T(1,2))/(MJET(1)+MSEC(1))
  T(1,3)=TGUSS
  T(1,4)=TAMB
  DO 85 I=2,N
    T(I,1)=T(1,1)-(T(1,1)-TGUSS)*Z(I)/AUGL
    T(I,2)=T(1,2)
    T(I,3)=TGUSS
    T(I,4)=TAMB
  85 CONTINUE
C AND MAKE SOME ADDITIONAL PREPATORY CALCULATIONS
  DO 86 I=1,N
    MJET(I)=3600.*MJET(I)
    MSEC(I)=3600.*MSEC(I)
    DELM(I)=3600.*DELM(I)
    P1B(I)=P1
    P4B(I)=P4
    P5B(I)=P5
    IF ((TYPE.EQ.1).OR.(TYPE.EQ.3)) GO TO 86
    IF ((I.LT.IFRONT).OR.(I.GT.IBACK)) GO TO 85
    P1B(I)=KDUCT*AREAR/2./DELR
    P4B(I)=KDUCT/DELR
    P5B(I)=2.*P1B(I)
  86 CONTINUE

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      MJET(N+1)=MJET(N)
      MSEC(N+1)=MSEC(N)
      IND1=MIN0(N,NSEP)
      IND3=MIN0(N-1,NSEP-1)
      JK=NSEP-1
      DEVMAX=T(1,1)
C
C BEGIN THE ITERATION
      DO 400 I=1,ITER
      JSAVE=DEVMAX
      DEVMAX=0.
C
C CALCULATE THE CONVECTIVE HEAT TRANSFER FILM COEFFICIENTS
C USE THE RELATIONSHIPS OF MCADAMS FOR TURBULENT FLOW THRU A DUCT,
C HOWEVER, USE BOTH VELOCITIES AND THE EQUIVALENT DIAMETER OF THE
C SECONDARY FLOW "DUCT" TO CALCULATE REYNOLDS NO....THE CONSTANT IS
C EMPIRICALLY ADJUSTED TO FIT TEST CELL TEMP DATA
      DO 90 II=1,IND3
      FACTOR=T(II,2)**1.5/(225.+T(II,2))
      KAIR=9.26E-4*FACTOR
      MUAIR=2.694E-3*FACTOR
      RHOAIR=PRESS/RAIR/T(II,2)
      VCONV1=VSEC*T(II,2)/T(1,2)
      RHOJ=PRESS/RAIR/T(II,1)
      VCONV2=MJET(II)/RHOJ/PI/RJET(II)**2/3600.
      VCONV=A*VCONV2+B*VCONV1
      DEQV=2.+(RAUG-RJET(II))
      HCONV(II)=EMPIR1*KAIR/DEQV**0.2*(VCONV*RHOAIR/MUAIR)**0.8
      HCONV(II)=HCONV(II)/II
90 CONTINUE
      IF (NSEP.GT.N) GO TO 100
C ONCE THE JET REACHES THE WALL, THE PROBLEM SIMPLY BECOMES THAT
C OF TURBULENT FLOW THRU A CIRCULAR DUCT
      DO 95 II=IND1,N
      FACTOR=T(II,1)**1.5/(225.+T(II,1))
      KAIR=9.26E-4*FACTOR
      MUAIR=2.694E-3*FACTOR
      RHOAIR=PRESS/RAIR/T(II,1)
      VCONV=(MSEC(1)+MJET(1))/AAUG/RHOAIR/3600.
      HCONV(II)=EMPIR2*KAIR*(VCONV*RHOAIR/MUAIR)**0.8/RAUG**0.2
95 CONTINUE
100 CONTINUE
C
C CALCULATE BULK VELOCITIES OF THE JET
      DO 102 II=2,N
      RHOJ=PRESS/RAIR/T(II,1)
      AJET(II)=PI*RJET(II)**2
      JJET(II+1)=MJET(II+1)/RHOJ/AJET(II)/3600.
102 CONTINUE
C
      SAVE=T(1,3)
      RADIN(1)=0.
      DO 105 II=1,N
      EMSS=EMISS(T(II,1),L(II),II)
      ALFA=EMSS*SQRT(T(II,1)/T(1,3))
C RADIATION REACHING THE AUGMENTER WALLS HAS TWO SOURCES...FROM THE
C EXHAUST GAS OR FROM OTHER PARTS OF THE WALL

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C   NEGLECT THE FACT THAT SOME RADIATION BETWEEN WALL SEGMENTS DOES NOT
C   PASS THROUGH THE JET
      RADIN(1)=RADIN(1)+SIGMA*ARAD(II)*F(II,1)*(EMSS*T(II,1)**4-ALFA
      1*T(1,3)**4)+P7*F1(II,1)*(1.-EMSS)*(T(II,3)**4-T(1,3)**4)
105  CONTINUE
      T(1,3)=(P1B(1)*T(1,4)+P2*HCONV(1)*T(1,2)+KAINT*TINT+P3*T(2,3)
      1+RADIN(1))/(P1B(1)+P2*HCONV(1)+P3+KAINT)
      T(1,3)=T(1,3)+R*(T(1,3)-SAVE)
      DEV=ABS(T(1,3)-SAVE)
      IF (DEV-DEVMAX) 115,115,110
110  DEVMAX=DEV
115  CONTINUE
      DO 125 J=1,N
      SAVE=T(J,4)
      IF ((TYPE.EQ.2).OR.(TYPE.EQ.4)) GO TO 116
      T(J,4)=(HAMB*TAMB+P4*T(J,3))/(HAMB+P4)
      GO TO 117
116  IF ((J.GE.IFRONT).AND.(J.LE.IBACK)) T(J,4)=(1000.*TSTM(1)+P6*
      1T(J,3))/(1000.+P6)
117  T(J,4)=T(J,4)+R*(T(J,4)-SAVE)
      DEV=ABS(T(J,4)-SAVE)
      IF (DEV-DEVMAX) 125,125,120
120  DEVMAX=DEV
125  CONTINUE
      DO 140 J=2,IND3
      SAVE=T(J,1)
      RADOUT(J)=0.
      EMSS=EMISS(T(J,1),L(J),J)
      DO 130 II=1,N
      ALFA=EMSS*SQRT(T(J,1)/T(II,3))
C   IT IS ASSUMED THAT THERE IS NO RADIATION BETWEEN DIFFERENT LOCATIONS
C   ALONG THE JET EXHAUST STREAM
      RADOUT(J)=RADOUT(J)+SIGMA*ARAD(J)*F(J,II)*(EMSS*T(J,1)**4-ALFA
      1*T(II,3)**4)
130  CONTINUE
      CPIN=SPHT(T(J-1,1),J-1)
      CPOUT=SPHT(T(J,1),J)
      T(J,1)=(MJET(J+1)*CPOUT+TDATUM+MJET(J)*CPIN*(T(J-1,1)-TDATUM)+
      10.24*DELM(J)*(T(J-1,2)-TDATUM)-RADOUT(J)+2.E-5*(MJET(J)*
      2JJET(J)**2-MJET(J+1)*UJET(J+1)**2))/MJET(J+1)/CPOUT
      T(J,1)=T(J,1)+R*(T(J,1)-SAVE)
      DEV=ABS(T(J,1)-SAVE)
      IF (DEV-DEVMAX) 140,140,135
135  DEVMAX=DEV
140  CONTINUE
      DO 150 J=2,IND3
      SAVE=T(J,2)
      T(J,2)=(0.24*((DELM(J+1)+MSEC(J+1))*TDATUM+MSEC(J)*(T(J-1,2)
      1-TDATUM))+AREAR*HCONV(J)*T(J,3))/(0.24*(DELM(J+1)+MSEC(J+1))
      2+AREAR*HCONV(J))
      T(J,2)=T(J,2)+R*(T(J,2)-SAVE)
      DEV=ABS(T(J,2)-SAVE)
      IF (DEV-DEVMAX) 150,150,145
145  DEVMAX=DEV
150  CONTINUE
      DO 165 J=2,IND3
      SAVE=T(J,3)

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RADIN(J)=0.
DO 155 II=1,N
  EMSS=EMISS(T(II,1),L(II),II)
  ALFA=EMSS*SQR(T(II,1)/T(J,3))
  RADIN(J)=RADIN(J)+SIGMA*ARAD(II)*F(II,J)*(EMSS*T(II,1)**4-ALFA
1+T(J,3)**4)+P7*F1(II,J)*(1.-EMSS)*(T(II,3)**4-T(J,3)**4)
155 CONTINUE
  T(J,3)=(P5B(J)+T(J,4)+P3*(T(J+1,3)+T(J-1,3))+AREAR*HCONV(J)*T(J,2)
1+RADIN(J))/(P5B(J)+2.*P3+AREAR*HCONV(J))
  T(J,3)=T(J,3)+R*(T(J,3)-SAVE)
  DEV=ABS(T(J,3)-SAVE)
  IF (DEV-DEVMAX) 165,165,160
160 DEVMAX=DEV
165 CONTINUE
C THE DOWNSTREAM CALCULATIONS DEPEND UPON WHETHER THE JET EVER REACHES
C AUGMENTER WALL
  IF (NSEP-N) 170,230,260
C THE CASE WHERE THE JET REACHES THE WALL UPSTREAM FROM AUGMENTER EXIT
170 DO 185 J=NSEP,KK
  RADOUT(J)=SIGMA*ARAD(J)*EMISS(T(J,1),L(J),J)*(T(J,1)**4
1-SQRT(T(J,1)/T(J,3))*T(J,3)**4)
  CPIN=SPHT(T(J-1,1),J-1)
  CPOUT=SPHT(T(J,1),J)
  SAVE=T(J,1)
  T(J,1)=(MJET(J+1)*CPOUT+TDATUM+AREAR*HCONV(J)*T(J,3)+MJET(J)
1*CPIN*(T(J-1,1)-TDATUM)+0.24*DELM(J)*(T(J-1,2)-TDATUM)-RADOUT(J)
2+2.E-5*(MJET(J)*UJET(J)**2-MJET(J+1)*UJET(J+1)**2))/(MJET(J+1)*
3CPOUT+AREAR*HCONV(J))
  T(J,1)=T(J,1)+R*(T(J,1)-SAVE)
  DEV=ABS(T(J,1)-SAVE)
  IF (DEV-DEVMAX) 185,185,180
180 DEVMAX=DEV
185 CONTINUE
  DO 200 J=NSEP,KK
  RADIN(J)=0.
  DO 190 II=1,N
    EMSS=EMISS(T(II,1),L(II),II)
    ALFA=EMSS*SQR(T(II,1)/T(J,3))
    RADIN(J)=RADIN(J)+SIGMA*ARAD(II)*F(II,J)*(EMSS*T(II,1)**4
1-ALFA*T(J,3)**4)+P7*F1(II,J)*(1.-EMSS)*(T(II,3)**4-T(J,3)**4)
190 CONTINUE
    SAVE=T(J,3)
    T(J,3)=(P5B(J)+T(J,4)+P3*(T(J+1,3)+T(J-1,3))+AREAR*HCONV(J)*T(J,1)
1+RADIN(J))/(P5B(J)+2.*P3+AREAR*HCONV(J))
    T(J,3)=T(J,3)+R*(T(J,3)-SAVE)
    DEV=ABS(T(J,3)-SAVE)
    IF (DEV-DEVMAX) 200,200,195
195 DEVMAX=DEV
200 CONTINUE
    SAVE=T(N,3)
    RADIN(N)=0.
    DO 205 II=1,N
      EMSS=EMISS(T(II,1),L(II),II)
      ALFA=EMSS*SQR(T(II,1)/T(N,3))
      RADIN(N)=RADIN(N)+SIGMA*ARAD(II)*F(II,N)*(EMSS*T(II,1)**4-ALFA
1*T(N,3)**4)+P7*F1(II,N)*(1.-EMSS)*(T(II,3)**4-T(N,3)**4)
205 CONTINUE

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      T(N,3)=(P1B(N)*T(N,4)+P3*T(N-1,3)+KAEXT*TEXT+P2*HCONV(N)*T(N,1)
1+RADIN(N))/(P1B(N)+P3+KAEXT+P2*HCONV(N))
      T(N,3)=T(N,3)+R*(T(N,3)-SAVE)
      DEV=ABS(T(N,3)-SAVE)
      IF (DEV-DEVMAX) 215,215,210
210 DEVMAX=DEV
215 CONTINUE
      SAVE=T(N,1)
      CPOUT=SPHT(T(N,1),N)
      CPIN=SPHT(T(N-1,1),N-1)
      EMSS=EMISS(T(N,1),L(N),N)
      RADOUT(N)=SIGMA*ARAD(N)*EMSS*(T(N,1)**4-SQRT(T(N,1)/T(N,3))
1*T(N,3)**4)
      T(N,1)=(MJET(N+1)*CPOUT+TDATUM-RADOUT(N)+MJET(N)*CPIN*(T(N-1,1)
1-TDATUM)+P2*HCONV(N)*T(N,3)+2.E-5*(MJET(N)*UJET(N)**2-MJET(N+1)
2*UJET(N+1)**2))/(MJET(N+1)*CPOUT+P2*HCONV(N))
      T(N,1)=T(N,1)+R*(T(N,1)-SAVE)
      DEV=ABS(T(N,1)-SAVE)
      IF (DEV-DEVMAX) 225,225,220
220 DEVMAX=DEV
225 CONTINUE
      DO 226 J=NSEP,N
      T(J,2)=T(J,1)
226 CONTINUE
      GO TO 305
C THE CASE WHERE THE JET REACHES THE WALL AT THE AUGMENTER EXIT
230 SAVE=T(N,3)
      RADIN(N)=0.
      DO 235 II=1,N
      EMSS=EMISS(T(II,1),L(II),II)
      ALFA=EMSS*SQRT(T(II,1)/T(N,3))
      RADIN(N)=RADIN(N)+SIGMA*ARAD(II)*F(II,N)*(EMSS*T(II,1)**4-ALFA
1*T(N,3)**4)+P7*F1(II,N)*(1.-EMSS)*(T(II,3)**4-T(N,3)**4)
235 CONTINUE
      T(N,3)=(P1B(N)*T(N,4)+P3*T(N-1,3)+KAEXT*TEXT+P2*HCONV(N)*T(N,1)
1+RADIN(N))/(P1B(N)+P3+KAEXT+P2*HCONV(N))
      T(N,3)=T(N,3)+R*(T(N,3)-SAVE)
      DEV=ABS(T(N,3)-SAVE)
      IF (DEV-DEVMAX) 245,245,240
240 DEVMAX=DEV
245 CONTINUE
      SAVE=T(N,1)
      CPOUT=SPHT(T(N,1),N)
      CPIN=SPHT(T(N-1,1),N-1)
      EMSS=EMISS(T(N,1),L(N),N)
      RADOUT(N)=SIGMA*ARAD(N)*EMSS*(T(N,1)**4-SQRT(T(N,1)/T(N,3))
1*T(N,3)**4)
      T(N,1)=(MJET(N+1)*CPOUT+TDATUM+MJET(N)*CPIN*(T(N-1,1)-TDATUM)+P2
1*HCONV(N)*T(N,3)+0.24*DELM(N)*(T(N-1,2)-TDATUM)-RADOUT(N)
2+2.E-5*(MJET(N)*UJET(N)**2-MJET(N+1)*UJET(N+1)**2))/(MJET(N+1)
3*CPOUT+P2*HCONV(N))
      T(N,1)=T(N,1)+R*(T(N,1)-SAVE)
      DEV=ABS(T(N,1)-SAVE)
      IF (DEV-DEVMAX) 255,255,250
250 DEVMAX=DEV
255 CONTINUE
      T(N,2)=T(N,1)

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      GO TO 305
C   THE CASE WHERE THE JET NEVER REACHES THE AUGMENTER WALL
260  SAVE=T(N,3)
      RADIN(N)=0.
      DO 265 II=1,N
        EMSS=EMISS(T(II,1),L(II),II)
        ALFA=EMSS*SQRT(T(II,1)/T(N,3))
        RADIN(N)=RADIN(N)+SIGMA*ARAD(II)*F(II,N)*(EMSS*T(II,1)**4-ALFA
1*T(N,3)**4)+P7*F1(II,N)*(1.-EMSS)*(T(II,3)**4-T(N,3)**4)
265  CONTINUE
      T(N,3)=(P1B(N)*T(N,4)+P3*T(N-1,3)+KAEXT*TEXT+P2*HCONV(N)*T(N,2)
1+RADIN(N))/(P1B(N)+P3+KAEXT+P2*HCONV(N))
      T(N,3)=T(N,3)+R*(T(N,3)-SAVE)
      DEV=ABS(T(N,3)-SAVE)
      IF (DEV-DEVMAX) 275,275,270
270  DEVMAX=DEV
275  CONTINUE
      SAVE=T(N,1)
      RADOUT(N)=0.
      EMSS=EMISS(T(N,1),L(N),N)
      DO 280 II=1,N
        ALFA=EMSS*SQRT(T(N,1)/T(II,3))
        RADOUT(N)=RADOUT(N)+SIGMA*ARAD(N)*F(N,II)*(EMSS*T(N,1)**4-ALFA
1*T(II,3)**4)
280  CONTINUE
      CPIN=SPHT(T(N-1,1),N-1)
      CPOUT=SPHT(T(N,1),N)
      T(N,1)=(MJET(N+1)*CPOUT*TDATUM+MJET(N)*CPIN*(T(I-1,1)-TDATUM)+
10.24*DELM(N)*(T(N-1,2)-TDATUM)-RADOUT(N)+2.E-5*(MJET(N)*
2UJET(N)**2-MJET(N+1)*UJET(N+1)**2))/MJET(N+1)/CPOUT
      T(N,1)=T(N,1)+R*(T(N,1)-SAVE)
      DEV=ABS(T(N,1)-SAVE)
      IF (DEV-DEVMAX) 290,290,285
285  DEVMAX=DEV
290  CONTINUE
      SAVE=T(N,2)
      T(N,2)=(0.24*MSEC(N+1)*TDATUM+MSEC(N)*(T(N-1,2)-TDATUM)+P2
1*HCONV(N)*T(N,3))/(0.24*MSEC(N+1)+P2*HCONV(N))
      T(N,2)=T(N,2)+R*(T(N,2)-SAVE)
      DEV=ABS(T(N,2)-SAVE)
      IF (DEV-DEVMAX) 300,300,295
295  DEVMAX=DEV
300  CONTINUE
305  CONTINUE

C
C   CHECK TO SEE IF ITERATION IS CONVERGING
      IF (DEVMAX.LE.DSAVE) GO TO 310
      WRITE(6,36)
      WRITE(6,49)
      WRITE(6,38)
      GO TO 500
C   CHECK TO SEE IF ITERATION HAS CONVERGED TO WITHIN TOLERANCE
310  IF (DEVMAX.LE.TOL) GO TO 405
C
400  CONTINUE
C
      WRITE(6,36)

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      WRITE(6,51) TOL,ITER
      WRITE(6,38)
405 CONTINUE
      WRITE(6,39) I,DEVMAX
C   CONVERT TEMPS FROM RANKINE TO FAHRENHEIT AND PRINT RESULTS
      DO 410 M=1,N
      DO 410 J=1,4
      TEMP(M,J)=T(M,J)-460.
410 CONTINUE
      II=1
      ISEC=0
      DO 415 M=1,5
      LIM=10*M
      IPRINT=MIN0(LIM,N)
      IPRNT=MIN0(LIM,NSEP-1)
      WRITE(6,52)
      WRITE(6,44) (Z(J),J=II,IPRINT)
      WRITE(6,53) (TEMP(J,1),J=II,IPRINT)
      IF (ISEC.GT.0) GO TO 412
      WRITE(6,54) (TEMP(J,2),J=II,IPRNT)
412 WRITE(6,56) (TEMP(J,3),J=II,IPRINT)
      WRITE(6,57) (TEMP(J,4),J=II,IPRINT)
      IF (IPRINT.GE.N) GO TO 420
      II=IPRINT+1
      IF (IPRNT.GE.JK) ISEC=1
415 CONTINUE
420 CONTINUE
C   PRINT JET VELOCITY AT AUGMENTER EXIT
      WRITE(6,69) UJET(N)
C   PRINT THE HEAT TRANSFER CHARACTERISTICS OF THE JET EXHAUST
      DO 421 M=1,N
      EMIS(M)=EMISS(T(M,1),L(M),M)
421 CONTINUE
      II=1
      DO 422 M=1,5
      LIM=10*M
      IPRINT=MIN0(LIM,N)
      WRITE(6,72)
      WRITE(6,44) (Z(J),J=II,IPRINT)
      WRITE(6,73) (HCONV(J),J=II,IPRINT)
      WRITE(6,74) (EMIS(J),J=II,IPRINT)
      IF (IPRINT.GE.N) GO TO 423
      II=IPRINT+1
422 CONTINUE
423 CONTINUE
C
C   CALCULATE THE STEAM GENERATION.....ASSUME FEED WATER ENTERS THE BOILER
C   IN A SATURATED CONDITION
      IF (TYPE.EQ.1) GO TO 500
      IF (TYPE.EQ.2) WRITE(6,28)
      IF (TYPE.EQ.3) WRITE(6,29)
      IF (TYPE.EQ.4) WRITE(6,31)
      IF (TYPE.EQ.3) GO TO 455
C   STEAM GENERATION IN WATER WALL BOILER
      DO 424 I=1,N
      QCONV(I)=0.
      MSTM1(I)=0.

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RADST(I)=0.
424 CONTINUE
ABOIL(1)=ABOIL(1)/(IBACK-IFRONT)
MSTM1(IFRONT)=ABOIL(1)/2.*P43(IFRONT)*(T(IFRONT,3)-T(IFRONT,4))
1/HSTM(1)
MSTM1(IBACK)=ABOIL(1)/2.*P43(IBACK)*(T(IBACK,3)-T(IBACK,4))
1/HSTM(1)
STEAM1=MSTM1(IFRONT)+MSTM1(IBACK)
JFRONT=IFRONT+1
JBACK=IBACK-1
DO 425 I=JFRONT,JBACK
MSTM1(I)=ABOIL(1)*P43(I)*(T(I,3)-T(I,4))/HSTM(1)
STEAM1=STEAM1+MSTM1(I)
425 CONTINUE
TSTM(1)=TSTM(1)-460.
ABOIL(1)=ABOIL(1)*(IBACK-IFRONT)
QTOT=STEAM1+HSTM(1)
WRITE(6,32) TSTM(1),PSTM(1),HSTM(1),ABOIL(1)
WRITE(6,77) FRONT,BACK
WRITE(6,58) STEAM1
WRITE(6,76) QTOT
WRITE(6,59)
II=1
DO 430 I=1,5
LIM=10*I
IPRINT=MIN0(LIM,N)
WRITE(6,44)(Z(J),J=II,IPRINT)
WRITE(6,61)(MSTM(J),J=II,IPRINT)
IF (IPRINT.GE.N) GO TO 435
II=IPRINT+1
430 CONTINUE
435 CONTINUE
C CALCULATE AND PRINT FRACTION OF STEAM GENERATION DUE TO CONVECTION
C AND TO RADIATION
QCONV(IFRONT)=HCONV(IFRONT)*P2*(T(IFRONT,2)-T(IFRONT,3))
RADST(IFRONT)=RADIN(IFRONT)/2.
QTOT=ABS(QCONV(IFRONT))+ABS(RADST(IFRONT))
QCONV(IFRONT)=QCONV(IFRONT)/QTOT
RADST(IFRONT)=RADST(IFRONT)/QTOT
QCONV(IBACK)=HCONV(IBACK)*P2*(T(IBACK,2)-T(IBACK,3))
RADST(IBACK)=RADIN(IBACK)/2.
QTOT=ABS(QCONV(IBACK))+ABS(RADST(IBACK))
QCONV(IBACK)=QCONV(IBACK)/QTOT
RADST(IBACK)=RADST(IBACK)/QTOT
DO 440 I=JFRONT,JBACK
QCONV(I)=HCONV(I)*AREAR*(T(I,2)-T(I,3))
RADST(I)=RADIN(I)
QTOT=ABS(QCONV(I))+ABS(RADST(I))
RADST(I)=RADST(I)/QTOT
QCONV(I)=QCONV(I)/QTOT
RADIN(I)=RADIN(I)/QTOT
440 CONTINUE
II=1
DO 445 I=1,5
LIM=10*I
IPRINT=MIN0(LIM,N)
WRITE(6,62)

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      WRITE(6,44) (Z(J),J=II,IPRINT)
      WRITE(6,63) (QCONV(J),J=II,IPRINT)
      WRITE(6,64) (RADST(J),J=II,IPRINT)
      IF (IPRINT.GE.N) GO TO 450
      II=IPRINT+1
445 CONTINUE
450 CONTINUE
      IF (TYPE.EQ.2) GO TO 460
C   STEAM GENERATION IN CONVECTION BOILER....ASSUME FLOW OVER STAGGERED
C   WATER TUBES....PROPERTIES WILL BE BASED UPON FILM CONDITIONS
455 CPAVG=(0.24*MSEC(N)+CPOUT*MJET(N))/(MSEC(N)+MJET(N))
      TAVG=TDATUM+(0.24*MSEC(N)*(T(N,2)-TDATUM)+CPOUT*MJET(N)*(T(N,1)
1-TDATUM))/(CPAVG*(MSEC(N)+MJET(N)))
      TGAS=TAVG
      TAVG=0.5*(TAVG+TSTM(2))
C   USE THE EUCKEN EQUATIONS TO ESTIMATE CONDUCTIVITY AND VISCOSITY
      FACTOR=TAVG**1.5/(225.+TAVG)
      KAIR=9.26E-4*FACTOR
      MUAIR=2.694E-3*FACTOR
      RHOAIR=PRESS/RAIR/TAVG
      VCONV=(MSEC(N)+MJET(N))/AAUG/RHOAIR
      HTUBES=0.237*KAIR/DTUBE*(RHOAIR*VCONV*DTUBE/MUAIR)**0.6
C   IT HAS BEEN ASSUMED THAT THE JET AND SECONDARY FLOW ARE COMPLETELY
C   MIXED BY THE TIME THEY REACH THE CONVECTION BOILER
      QSTM2=HTUBES*ABOIL(2)*(TGAS-TSTM(2))
      STEAM2=QSTM2/HSTM(2)
      TSTM(2)=TSTM(2)+460.
      TGAS=TGAS+460.
      DTUBE=12.*DTUBE
      WRITE(6,33) TSTM(2),PSTM(2),HSTM(2),ABOIL(2),DTUBE
      WRITE(6,66) STEAM2
      WRITE(6,71) TGAS,HTUBES,QSTM2
460 CONTINUE
C
C   DETERMINE THE ECONOMICS OF GAS TURBINE TEST CELL HEAT RECOVERY
      IF (TYPE.EQ.4) WRITE(6,9)
      WRITE(6,79)
461 IF (TYPE.EQ.3) GO TO 475
C   FIRST FOR THE WATER-WALL HEAT EXCHANGER
      IF ((IND2.EQ.1).AND.(TYPE.NE.4)) WRITE(6,9)
      IF ((IND2.EQ.2).AND.(TYPE.EQ.4)) WRITE(6,9)
      IF ((IND2.EQ.0).OR.(IND2.GE.7)) WRITE(6,81) PRICE1
      IF ((IND2.GT.0).AND.(IND2.LT.7).AND.(TYPE.EQ.4)) WRITE(6,91)
C   CALCULATE THE VALUE OF THE STEAM GENERATED
      VALUE1=0.365E-3*STEAM1*HSTM(1)*TIME+COST
C   CALCULATE THE PRESENT VALUE OF THE SAVINGS ACCUMULATED OVER THE
C   ECONOMIC LIFE OF THE HEAT RECOVERY HEAT EXCHANGER
      PV(1)=VALUE1*RATIO
      IF (PV(1).LT.0.) PV(1)=0.
      SIR(1)=PV(1)/PRICE1
      DO 465 I=2,25
      PV(I)=PV(I-1)+VALUE1*RATIO**I
      IF (PV(I).LT.0.) PV(I)=0.
      SIR(I)=PV(I)/PRICE1
465 CONTINUE

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      IF ((IND2.EQ.0).OR.(IND2.GE.7)) WRITE(5,82) DISC,COST,ESC
      WRITE(5,83)
      DO 470 I=1,5
      J=5*I
      WRITE(5,84) J,TIME,PV(J),SIR(J)
470 CONTINUE
475 IF (TYPE.EQ.2) GO TO 495
C THEN FOR THE CONVECTION HEAT EXCHANGER
      IF ((IND2.EQ.3).AND.(TYPE.NE.4)) WRITE(5,9)
      IF ((IND2.EQ.4).AND.(TYPE.EQ.4)) WRITE(5,9)
      IF ((IND2.EQ.0).OR.(IND2.GE.7)) WRITE(5,88) PRICE2
      IF ((IND2.GT.0).AND.(IND2.LT.7).AND.(TYPE.EQ.4)) WRITE(5,92)
C AS ABOVE, CALCULATE THE VALUE OF THE STEAM GENERATED
      VALUE1=0.365E-3*STEAM2*HSTM(2)*TIME*COST
      PV(1)=VALUE1*RATIO
      IF (PV(1).LT.0.) PV(1)=0.
      STR(1)=PV(1)/PRICE2
      DO 480 I=2,25
      PV(I)=PV(I-1)+VALUE1*RATIO**I
      IF (PV(I).LT.0.) PV(I)=0.
      SIR(I)=PV(I)/PRICE2
480 CONTINUE
      IF ((IND2.EQ.0).OR.(IND2.GE.7)) WRITE(5,87) DISC,COST,ESC
      WRITE(5,83)
      DO 485 I=1,5
      J=5*I
      WRITE(5,84) J,TIME,PV(J),SIR(J)
485 CONTINUE
495 TIME=2.*TIME
      IF (IND2.EQ.3) TIME=3.
      IF (IND2.EQ.4) TIME=5.
      IF (IND2.EQ.5) TIME=8.
      IND2=IND2+1
      IF (IND2.LT.7) GO TO 461
500 STOP
1 FORMAT(I5)
2 FORMAT(3F10.0,2F10.3)
3 FORMAT(2F10.1)
4 FORMAT(4F10.1)
6 FORMAT(6F10.2)
7 FORMAT(2F10.3)
8 FORMAT(4F10.1,F10.3)
9 FORMAT(1H1)
11 FORMAT(1H1,5X,"AUGMENTER GEOMETRY")
12 FORMAT(1H0,10X,"INITIAL AREA OF JET = ",F5.2," SQFT",/11X,"CROSS S
1 ECTIONAL AREA OF AUGMENTER = ",F5.1," SQFT",/11X,"LENGTH OF AUGMEN
2 TER = ",F5.1," FT",/11X,"THICKNESS OF AUGMENTER WALLS = ",F5.3," I
3 N",/11X,"THICKNESS OF ACOUSTIC PILLOWS = ",F5.2," IN"//)
13 FORMAT(1H ,5X,"PHYSICAL CHARACTERISTICS OF JET EXHAUST")
14 FORMAT(1H0,10X,"MASS FLOW RATE OF JET = ",F4.0," LB/SEC",/11X,"TOT
14 L TEMPERATURE = ",F5.0," DEGF",/11X,"TOTAL PRESSURE = ",F4.1," PS
21A",/11X,"RATIO OF SPECIFIC HEATS = ",F4.2)
15 FORMAT(1H ,10X,"COMPOSITION OF EXHAUST (PERCENT WEIGHT)")
17 FORMAT(1H ,15X,"OXYGEN.....",F5.2,/15X,"NITROGEN.....
1... ",F5.2,/15X,"CARBON DIOXIDE.....",F5.2,/15X,"CARBON MONOXIDE..
2... ",F5.2,/15X,"WATER VAPOR.....",F5.2,/15X,"HYDROGEN.....
3... ",F5.2,/11X,"LENGTH OF LUMINOUS JET = ",F5.1," FT"//)

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13 FORMAT(1H,5X,"PHYSICAL CHARACTERISTICS OF SECONDARY FLOW")
19 FORMAT(1H0,10X,"SECONDARY FLOW RATE = ",F3.0," LB/SEC",/11X,"STATI
10 TEMPERATURE = ",F4.0," DEGF"/)
21 FORMAT(1H,5X,"HEAT TRANSFER PROPERTIES")
22 FORMAT(1H0,10X,"THERMAL CONDUCTIVITY OF AUGMENTER WALLS = ",F4.1,"
1 BTU/HR-FT-DEGF")
23 FORMAT(1H,10X,"THERMAL CONDUCTIVITY OF ACOUSTIC PILLOWS = ",F5.3,
1" BTU/HR-FT-DEGF")
24 FORMAT(1H,10X,"EFFECTIVE HUSH HOUSE CHARACTERISTICS")
26 FORMAT(1H,15X,"TEMPERATURE AT AUGMENTER INLET = ",F4.0," DEGF",/1
15X,"CONDUCTANCE AT AUGMENTER INLET = ",E9.3," BTU/HR-DEGF",/16X,"T
2 TEMPERATURE AT AUGMENTER EXIT = ",F4.0," DEGF",/15X,"CONDUCTANCE AT
3 AUGMENTER EXIT = ",E9.3," BTU/HR-DEGF"/)
27 FORMAT(1H,5X,"THE FACILITY HAS NO BOILERS"/)
28 FORMAT(1H1,5X,"THE FACILITY HAS A WATER-WALL BOILER WRAPPED AROUND
1 THE AUGMENTER"/)
29 FORMAT(1H1,5X,"THE FACILITY HAS A STAGGERED WATER-TUBE BOILER IN T
1 HE GAS PATH AT THE AUGMENTER EXIT")
31 FORMAT(1H1,5X,"THE FACILITY HAS BOTH A WATER-WALL BOILER WRAPPED A
1 ROUND THE AUGMENTER AND",/6X,"A STAGGERED WATER-TUBE BOILER IN THE
2 GAS PATH AT THE AUGMENTER EXIT"/)
32 FORMAT(1H,1/6X,"WATER-WALL BOILER CHARACTERISTICS",/16X,"STEAM TEM
1 PERATURE = ",F4.0," DEGF",/16X,"STEAM PRESSURE = ",F5.1," PSIA",/1
25X,"HEAT OF VAPORIZATION = ",F6.1," BTU/LB",/16X,"TOTAL HEAT TRANS
3 FER AREA = ",F5.0," SQFT"/)
33 FORMAT(1H0,1/6X,"CONVECTION WATER-TUBE BOILER CHARACTERISTICS",/16
1 X,"STEAM TEMPERATURE = ",F4.0," DEGF",/16X,"STEAM PRESSURE = ",F5.
21," PSIA",/16X,"HEAT OF VAPORIZATION = ",F6.1," BTU/LB",/16X,"TOTA
3 L HEAT TRANSFER AREA = ",F5.0," SQFT",/16X,"OUTER DIAMETER OF TUBE
4 S = ",F4.2," IN"/)
34 FORMAT(1H0,5X,"BULK VELOCITIES AT AUGMENTER INLET",/11X,"JET VELOC
1 ITY = ",F5.0," FT/SEC",/11X,"SECONDARY FLOW VELOCITY = ",F4.0," FT
2 /SEC",/6X,"CRAYA-CURTET NUMBER = ",F4.2/)
36 FORMAT(1H0,1/6X,"*****")
37 FORMAT(1H,5X,"ITERATION FOR JET SEPARATION POINT IS DIVERGING, AN
1 ALYSIS IS TERMINATED"/)
38 FORMAT(1H,5X,"*****")
39 FORMAT(1H,5X,"ITERATION FOR JET SEPARATION POINT DID NOT CONVERGE
1 TO WITHIN ",F3.1," FEET AFTER ",I3," ITERATIONS"/)
41 FORMAT(1H0,5X,"JET EXHAUST REACHES THE AUGMENTER WALL AT AN AXIAL
1 DISTANCE OF ",F4.0," FEET FROM THE INLET"/)
42 FORMAT(1H0,5X,"JET EXHAUST NEVER REACHES THE AUGMENTER WALLS"/)
43 FORMAT(1H0,1/6X,"MASS FLOW RATES (LB/SEC) VARIATION WITH AXIAL LOCA
1 TION (FT) AND JET RADIUS (FT)"/)
44 FORMAT(1H,5X,"DIST FM INLET",1X,10F10.2)
46 FORMAT(1H,5X,"RADIUS OF JET",1X,10F10.2)
47 FORMAT(1H,5X,"JET FLOW",6X,10F10.2)
48 FORMAT(1H,5X,"SECONDARY FLOW",10F10.2)
49 FORMAT(1H,5X,"ITERATION FOR TEMPERATURES IS DIVERGING, ANALYSIS I
1 S TERMINATED"/)
51 FORMAT(1H,5X,"ITERATION FOR TEMPERATURES DID NOT CONVERGE TO WITH
1 IN ",F3.1," DEGF AFTER ",I3," ITERATIONS"/)
52 FORMAT(1H0,1/6X,"TEMPERATURE (DEGF) VARIATION WITH AXIAL LOCATION (
1 FT). THE WALL OD INCLUDES ACOUSTIC PILLOWS, IF ANY.)/)
53 FORMAT(1H,5X,"JET TEMP",6X,10F10.1)

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54 FORMAT(1H,5X,"SEC FLOW TEMP",1X,10F10.1)
56 FORMAT(1H,5X,"AUG WALL ID",3X,10F10.1)
57 FORMAT(1H,5X,"AUG WALL OD",3X,10F10.1)
58 FORMAT(1H,76X,"TOTAL STEAM GENERATION IN WATER-WALL BOILER = ",E1
10.4," LB/HR"/)
59 FORMAT(1H,5X,"WATER-WALL STEAM GENERATION (LB/HR) VARIATION WITH
1AXIAL LOCATION (FT FROM AUGMENTER INLET)"/)
61 FORMAT(1H,5X,"STEAM GEN",5X,10F10.1)
62 FORMAT(1H,76X,"FRACTION OF WATER-WALL STEAM GENERATION BY CONVECT
1ION AND BY RADIATION"/)
63 FORMAT(1H,5X,"CONVECTION",4X,10F10.3)
64 FORMAT(1H,5X,"RADIATION",5X,10F10.3)
66 FORMAT(1H,76X,"TOTAL STEAM GENERATION IN CONVECTION WATER-TUBE B
1OILER = ",E10.4," LB/HR")
67 FORMAT(1H,5X,"AMBIENT CONDITIONS")
68 FORMAT(1H,10X,"TEMPERATURE = ",F4.0," DEG F",/11X,"CONVECTIVE FILM
1 COEFFICIENT = ",F5.1," BTU/HR-SQFT-DEG F"/)
69 FORMAT(1H,76X,"BULK VELOCITY OF JET AT AUGMENTER EXIT = ",F5.0,"
1 FT/SEC"/)
71 FORMAT(1H,5X,"AVERAGE GAS TEMPERATURE AT BOILER INLET = ",F5.0,"
1 DEG F",/6X,"BOILER OVERALL HEAT TRANSFER COEFFICIENT = ",F5.1," BTU
2/HR-SQFT-DEG F",/6X,"TOTAL HEAT TRANSFERRED = ",E10.4," BTU/HR")
72 FORMAT(1H,76X,"EXHAUST GAS EMISSIVITY AND CONVECTIVE FILM COEFFIC
1IENT (BTU/HR-SQFT-DEG F) BY LOCATION"/)
73 FORMAT(1H,5X,"FILM COEFF",4X,10F10.2)
74 FORMAT(1H,5X,"EMISSIVITY",4X,10F10.4)
76 FORMAT(1H,5X,"TOTAL HEAT TRANSFERRED = ",E10.4," BTU/HR"/)
77 FORMAT(1H,5X,"THE WATER-WALLS ARE LOCATED ALONG THE SECTION BEGIN
1VING ",F5.1," FEET FROM THE AUGMENTER INLET",/6X,"AND ENDING AT A
2)DISTANCE OF ",F5.1," FEET FROM THE AUGMENTER INLET"/)
78 FORMAT(1H,10.1,I10,2F15.2)
79 FORMAT(1H,76X,"THE ECONOMICS OF GAS TURBINE TEST CELL ENERGY REC
1OVERY")
81 FORMAT(1H,76X,"THE PURCHASE PRICE OF THE WATER-WALL HEAT EXCHANG
1ER IS $",F10.2," PAYABLE WHEN INSTALLATION IS COMPLETE"/)
82 FORMAT(1H,5X,"THE ACCUMULATED PRESENT VALUE OF SAVINGS RESULTING
1 FROM THE ADDITION OF THE WATER-WALL BOILER",/6X,"ASSUMING A DISCOU
2NT RATE OF ",F4.1," PERCENT, A CURRENT STEAM PRICE OF $",F5.2,"/MB
3TU, AND A",/6X,"STEAM ESCALATION RATE OF ",F4.1," PERCENT")
83 FORMAT(1H,6X,"ECONOMIC",6X,"OPERATION",11X,"ACCU PV OF",12X,"SIR
1",/6X,"LIFE (YRS)",5X,"(HRS/DAY)",10X,"STEAM GEN ($)")
84 FORMAT(1H,8X,I2,12X,F4.2,10X,F14.0,10X,F5.2)
87 FORMAT(1H,5X,"THE ACCUMULATED PRESENT VALUE OF SAVINGS RESULTING
1 FROM THE ADDITION OF THE CONVECTION BOILER",/6X,"ASSUMING A DISCOU
2NT RATE OF ",F4.1," PERCENT, A CURRENT STEAM PRICE OF $",F5.2,"/MB
3TU, AND A",/6X,"STEAM ESCALATION RATE OF ",F4.1," PERCENT")
88 FORMAT(1H,76X,"THE PURCHASE PRICE OF THE CONVECTION HEAT EXCHANG
1ER IS $",F10.2," PAYABLE WHEN INSTALLATION IS COMPLETE"/)
89 FORMAT(1H,2X," SOLUTION CONVERGED AFTER ",I3," ITERATIONS TO WITH
1IN ",F4.2," DEGREES"/)
91 FORMAT(1H,76X,"WATER-WALL HEAT EXCHANGER")
92 FORMAT(1H,76X,"CONVECTION (WATER TUBE) HEAT EXCHANGER")
END

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      FUNCTION SPHT(T,I)
C   PROGRAM TO CALCULATE THE MEAN SPECIFIC HEAT BETWEEN T AND 60 DEGF
C   OF A MIXTURE OF GASES....THE GASES CONSIDERED ARE OXYGEN, NITROGEN
C   CARBON MONOXIDE, HYDROGEN, WATER VAPOR, AND CARBON DIOXIDE
C   SPECIFIC HEAT CALCULATED IN BTU/LB-DEGF
      REAL MW,MOLES,N2,NIT(50),MONOX(50)
      COMMON OXY,NIT,DIOX,WATER,MONOX,HYD,LUM
      DIMENSION OXY(50),DIOX(50),WATER(50),HYD(50)
      DIMENSION CP(6)
      DATA TDATUM/520./
      SPHT=0.
      DELTA=T-TDATUM
      O2=OXY(I)
      N2=NIT(I)
      CO=MONOX(I)
      H2=HYD(I)
      H2O=WATER(I)
      CO2=DIOX(I)
C   FIRST CALCULATE THE MEAN SPECIFIC HEAT OF INDIVIDUAL COMPONENTS
C   USING THE RELATIONSHIPS OF SWEIGERT AND BEARDSLEY, REF. GEORGIA
C   INST. OF TECH. BULLETIN 2 (1938)
      CP(1)=(11.515*DELTA-344.+(SQRT(T)-SQRT(TDATUM)))+1530.
      1*(ALOG(T)-ALOG(TDATUM)))/DELTA*O2
      CP(2)=(9.47*DELTA-3.47E3*(ALOG(T)-ALOG(TDATUM)))-1.16E6
      1*(1./T-1./TDATUM))/DELTA*N2
      CP(3)=(9.46*DELTA-3.29E3*(ALOG(T)-ALOG(TDATUM)))-1.07E6
      1*(1./T-1./TDATUM))/DELTA*CO
      CP(4)=(5.76*DELTA+2.89E-4*(T**2-TDATUM**2)+40.+(SQRT(T)
      1-SQRT(TDATUM)))/DELTA*H2
      CP(5)=(19.86*DELTA-1194.+(SQRT(T)-SQRT(TDATUM)))+7500.
      1*(ALOG(T)-ALOG(TDATUM)))/DELTA*H2O
      CP(6)=(16.2*DELTA-6.53E3*(ALOG(T)-ALOG(TDATUM)))-1.41E6
      1*(1./T-1./TDATUM))/DELTA*CO2
C   THE TOTAL NUMBER OF MOLES IN THE MIXTURE
      MOLES=O2+N2+CO+H2+H2O+CO2
C   THE MOLECULAR WEIGHT OF THE MIXTURE
      MW=(O2*32.+N2*28.+CO*28.+H2*2.+H2O*18.+CO2*44.)/MOLES
C   ALLOWING THE MEAN SPECIFIC HEAT TO BE DETERMINED
      DO 5 J=1,6
      SPHT=SPHT+CP(J)/MOLES/MW
      5 CONTINUE
      RETURN
      END

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      FUNCTION EMISS(T,L,I)
C   PROGRAM TO CALCULATE THE EMISSIVITY OF A MIXTURE OF COMBUSTION GASES.
C   CARBON DIOXIDE, WATER VAPOR, AND CARBON MONOXIDE ALL CONTRIBUTE AND
C   THEIR INDIVIDUAL EMISSIVITIES ARE OBTAINED FROM CURVE FITS OF THE
C   TABLES OF MCADAMS, "HEAT TRANSMISSION", MCGRAW-HILL, (1954)
      REAL L,MOLES,N2,NIT(50),MONOX(50)
      COMMON OXY,NIT,DIOX,WATER,MONOX,HYD,LUM
      DIMENSION OXY(50),DIOX(50),WATER(50),HYD(50)
      DATA DELTA/0./

C
C   IF SEGMENT "I" OF THE JET EXHAUST IS LUMINOUS, SET THE EMISSIVITY
C   EQUAL TO ONE
      IF (I.GT.LUM) GO TO 5
      EMISS=1.
      GO TO 50

C
      5 O2=OXY(I)
      N2=NIT(I)
      CO=MONOX(I)
      H2=HYD(I)
      H2O=WATER(I)
      CO2=DIOX(I)

C   CALCULATE THE PARTIAL PRESSURE OF INDIVIDUAL GASES IN ATMOSPHERES
C   ASSJMING A TOTAL PRESSURE OF ONE ATMOSPHERE
      MOLES=CO2+H2O+CO+O2+N2+H2
      PCO2=CO2/MOLES
      PH2O=H2O/MOLES
      PCO=CO/MOLES

C   THE INDEPENDENT VARIABLE IS PARTIAL PRESSURE TIMES MEAN BEAM LENGTH
      PCO2L=PCO2*L
      PH2OL=PH2O*L
      PCOL=PCO*L

C
C   CALCULATE EMISSIVITY OF CARBON DIOXIDE
      IF (PCO2L.LE.0.) GO TO 10
      POWER=-0.721+0.215*ALOG10(PCO2L)
      EMAX=-0.04+10.**POWER
      TMAX=2600.+800.*ALOG10(EMAX)
      POWER=((T-TMAX)/2800.):**2
      POWER=EXP(-POWER)-1.
      ECO2=EMAX*10.**POWER

C   CORRECT FOR OVERLAP WITH WATER VAPOR
      ECO2=ECO2-DELTA
      GO TO 15

10 ECO2=0.

C   CALCULATE EMISSIVITY OF WATER VAPOR
15 IF (PH2OL.LE.0.) GO TO 20
      EMAX=2.*ALOG10(PH2OL)
      EMAX=-2.097+0.821*EMAX-0.1115*EMAX*(EMAX-1.)-0.00567*EMAX
      1*(EMAX-1.)*(EMAX-2.)
      POWER=(EMAX-0.59)*(T+5000.)/7000.+0.59
      EH2O=10.**POWER

C   CORRECT FOR PARTIAL PRESSURE OTHER THAN ZERO
      EH2O=EH2O*(1.+(0.62-0.1*ALOG(PH2OL))*PH2O)
      GO TO 25

20 EH2O=0.

C   CALCULATE EMISSIVITY OF CARRON MONOXIDE

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25 IF (PCOL.LE.0.) GO TO 30
   POWER=-0.8477+0.1809*ALOG10(PCOL)
   EMAX=-0.0403+10.**POWER
   TMAX=1600.+3280.*(0.122-EMAX)
   POWER=((T-TMAX)/1800.)**2
   POWER=-1.+EXP(-POWER)
   ECO=EMAX*10.**POWER
C  CORRECT EMISSIVITY OF CO FOR OVERLAP WITH CO2
   ECO=0.7*ECO
   GO TO 35
30 ECO=0.
C
C  CALCULATE THE TOTAL EMISSIVITY OF THE COMBUSTION GASES
35 EMISS=ECO2+EH2O+ECO
   IF (EMISS.LE.1.) GO TO 50
   WRITE(6,1)
   WRITE(6,2)
   WRITE(6,3)
50 RETURN
1  FORMAT(1H0,///5X,"*****")
1 *****")
2  FORMAT(1H ,//6X,"EMISSIVITY GREATER THAN ONE.....THE GAS COMPOSITI
1ON IS PROBABLY INCORRECT")
3  FORMAT(1H ,//6X,"*****")
1 *****"//)
END

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      SUBROUTINE SHAPE(RI,RO,L,F,N)
C   PROGRAM TO CALCULATE THE SHAPE FACTORS FOR RADIANT HEAT TRANSFER
C   BETWEEN CONCENTRIC CYLINDERS OF VARIOUS LENGTHS AND ASPECTS
C   THE EXPRESSIONS USED HERE WERE DEVELOPED FROM EXPRESSIONS FOR SHAPE
C   FACTORS DERIVED BY LEUENBERGER AND PERSON, "COMPILATION OF RADIATION
C   SHAPE FACTORS FOR CYLINDRICAL ASSEMBLIES", ASME PAPER 56-A-144 (1956)
      REAL L,L1
      DIMENSION F(50,50),RI(50),F1(2)
      DATA PI/3.1416/

C
C   FIRST CALCULATE SHAPE FACTORS OF DIRECTLY OPPOSED SEGMENTS
      DO 5 I=1,N
        IF (RI(I).LT.RO) GO TO 2
        F(I,I)=1.00
        GO TO 5
      2 Z=L
        IF ((I.EQ.1).OR.(I.EQ.N)) Z=0.5*L
        A=Z**2-RO**2+RI(I)**2
        B=Z**2+RO**2-RI(I)**2
        C=A/B
        D=Z**2+RO**2+RI(I)**2
        F(I,I)=1.-1./PI*(ACOS(C)-0.5/RI(I)/Z*(SQRT(D**2-(2.*RI(I)*RO)**2)
          1*ACOS(C*RI(I)/RO)+A*ASIN(RI(I)/RO)-0.5*PI*B))
      5 CONTINUE
C   AND THEN ALL OTHERS
      DO 40 I=1,N
        DO 35 J=1,N
          IF (I.EQ.J) GO TO 35
          IF (RI(I).LT.RO) GO TO 10
          F(I,J)=0.
          GO TO 35
        10 CONTINUE
          IF (J.GT.I) GO TO 20
C
C   FIRST, SEGMENTS RADIATING "UPSTREAM"
          JJ=J+1
          II=I-1
          L1=(I-J+1)*L
          IF (I.EQ.N) L1=L1-0.5*L
          DO 15 K=1,2
            A=L1**2-RO**2+RI(I)**2
            B=L1**2+RO**2-RI(I)**2
            C=A/B
            D=L1**2+RO**2+RI(I)**2
            F1(K)=RI(I)*L1/PI/(RO**2-RI(I)**2)*(ACOS(C)-0.5/RI(I)/L1*(SQRT
              1(D**2-(2.*RI(I)*RO)**2)*ACOS(C*RI(I)/RO)+A*ASIN(RI(I)/RO)
              2-0.5*PI*B))
            L1=L1-L
          15 CONTINUE
          Z=L
          IF (I.EQ.N) Z=0.5*L
          F(I,J)=0.5*(1.-F(I,I)-(RO**2-RI(I)**2)/RI(I)/Z*(F1(1)-F1(2)))
C   NOTE THAT THESE ARE COMBINED SHAPE FACTORS AND NEED TO BE SEPARATED
          GO TO 35
C
      20 CONTINUE
C   AND THEN SEGMENTS RADIATING "DOWNSTREAM"

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AD-A139 457

THERMAL ENERGY RECOVERY IN GAS TURBINE ENGINE TEST
CELLS(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA
C A KODRES NOV 83 NCEL-TN-1679

22

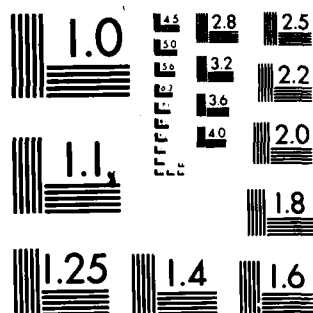
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

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      II=I+1
      JJ=J-1
      L1=(J-I+1)*L
      IF (I.EQ.1) L1=L1-0.5*L
      DO 25 K=1,2
      A=L1**2-R0**2+RI(I)**2
      B=L1**2+R0**2-RI(I)**2
      C=A/B
      D=L1**2+R0**2+RI(I)**2
      F1(K)=RI(I)*L1/PI/(R0**2-RI(I)**2)*(ACOS(C)-0.5/RI(I)/L1*(SQRT
1(D**2-(2.*RI(I)*R0)**2)*ACOS(C*RI(I)/R0)+A*ASIN(RI(I)/R0)
2-0.5*PI*B))
      L1=(J-I)*L
25  CONTINUE
      Z=L
      IF (I.EQ.1) Z=0.5*L
      F(I,J)=0.5*(1.-F(I,I)-(R0**2-RI(I)**2)/RI(I)/Z*(F1(1)-F1(2)))
      IF (J.LE.II) GO TO 35
      DO 30 K=II,JJ
      F(I,J)=F(I,J)-F(I,K)
30  CONTINUE
35  CONTINUE
40  CONTINUE
C
C  SEPARATE THE "UPSTREAM" SHAPE FACTORS
      DO 55 I=3,N
      JJ=I-2
      LL=I-1
      DO 50 M=1,JJ
      J=JJ-M+1
      KK=J+1
      DO 45 K=KK,LL
      F(I,J)=F(I,J)-F(I,K)
45  CONTINUE
50  CONTINUE
55  CONTINUE
      RETURN
      END

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      SUBROUTINE SHAPE1(R,Z,F,N)
C   PROGRAM TO CALCULATE THE SHAPE FACTOR FOR RADIANT HEAT TRANSFER
C   BETWEEN FINITE RING AREAS ON INTERIOR OF RIGHT CIRCULAR CYLINDER
C   REF...HOTTEL AND SAROFIM, "RADIATIVE TRANSFER", MCGRAW-HILL, (1957)
      DIMENSION F(50,50)
      DATA PI/3.1416/
C
      DO 10 I=1,N
      DO 10 J=1,N
      IF (I.EQ.J) GO TO 5
      A=IABS(I-J)*Z
      B=(IABS(I-J)-1.)*Z
      C=(IABS(I-J)+1.)*Z
      F(I,J)=PI/2.*(B**2-B*SQRT(4.*R**2+B**2))-2.*(A**2-A*SQRT(4.*R**2
1+A**2))+C**2-C*SQRT(4.*R**2+C**2))
      GO TO 8
5    F(I,J)=PI*(2.*R*Z+Z**2-Z*SQRT(4.*R**2+Z**2))
8    AREA=2.*PI*R*Z
      F(I,J)=F(I,J)/AREA
10  CONTINUE
      RETURN
      END

```

TYPICAL RESULTS

This particular summary is for the J79 at A/B being tested in the hush house at the Marine Corps Air Station, El Toro, Calif. Waterwalls and a water tube boiler are examined together in order to illustrate the capabilities of the model.

AUGMENTER GEOMETRY

INITIAL AREA OF JET = 4.20 SQFT
CROSS SECTIONAL AREA OF AUGMENTER = 63.0 SQFT
LENGTH OF AUGMENTER = 67.0 FT
THICKNESS OF AUGMENTER WALLS = .111 IN
THICKNESS OF ACOUSTIC PILLOWS = 6.00 IN

PHYSICAL CHARACTERISTICS OF JET EXHAUST

MASS FLOW RATE OF JET = 180. LB/SEC
TOTAL TEMPERATURE = 3060. DEGF
TOTAL PRESSURE = 36.8 PSIA
RATIO OF SPECIFIC HEATS = 1.40
COMPOSITION OF EXHAUST (PERCENT WEIGHT)
OXYGEN..... 0.00
NITROGEN.....75.00
CARBON DIOXIDE.....16.00
CARBON MONOXIDE..... 1.00
WATER VAPOR..... 8.00
HYDROGEN..... 0.00
LENGTH OF LUMINOUS JET = 0.0 FT

PHYSICAL CHARACTERISTICS OF SECONDARY FLOW

SECONDARY FLOW RATE = 1130. LB/SEC
STATIC TEMPERATURE = 75. DEGF

AMBIENT CONDITIONS

TEMPERATURE = 75. DEGF
CONVECTIVE FILM COEFFICIENT = 5.0 BTU/HR-SQFT-DEGF

HEAT TRANSFER PROPERTIES

THERMAL CONDUCTIVITY OF AUGMENTER WALLS = 30.0 BTU/HR-FT-DEGF
THERMAL CONDUCTIVITY OF ACOUSTIC PILLOWS = .050 BTU/HR-FT-DEGF
EFFECTIVE HUSH HOUSE CHARACTERISTICS
TEMPERATURE AT AUGMENTER INLET = 70. DEGF
CONDUCTANCE AT AUGMENTER INLET = .500E+03 BTU/HR-DEGF
TEMPERATURE AT AUGMENTER EXIT = 150. DEGF
CONDUCTANCE AT AUGMENTER EXIT = .500E+03 BTU/HR-DEGF

BULK VELOCITIES AT AUGMENTER INLET

JET VELOCITY = 2928. FT/SEC
SECONDARY FLOW VELOCITY = 259. FT/SEC

CRAYA-CURTET NUMBER = .62

JET EXHAUST REACHES THE AUGMENTER WALL AT AN AXIAL DISTANCE OF 24. FEET FROM THE INLET

MASS FLOW RATES (LB/SEC) VARIATION WITH AXIAL LOCATION (FT) AND JET RADIUS (FT)

DIST FM INLET	0.00	3.72	7.44	11.17	14.89	18.61	22.33	26.06	29.78	33.50
RADIUS OF JET	1.16	1.64	2.14	2.64	3.14	3.66	4.19	4.48	4.48	4.48
JET FLOW	140.00	262.61	375.07	518.86	695.92	908.57	1159.60	1310.00	1310.00	1310.00
SECONDARY FLOW	1130.00	1047.39	934.93	791.14	614.08	401.43	150.40	.00	.00	.00

MASS FLOW RATES (LB/SEC) VARIATION WITH AXIAL LOCATION (FT) AND JET RADIUS (FT)

DIST FM INLET	37.22	40.94	44.67	48.39	52.11	55.83	59.56	63.28	67.00	
RADIUS OF JET	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	
JET FLOW	1310.00	1310.00	1310.00	1310.00	1310.00	1310.00	1310.00	1310.00	1310.00	
SECONDARY FLOW	.00	.00	.00	.00	.00	.00	.00	.00	.00	

SOLUTION CONVERGED AFTER 32 ITERATIONS TO WITHIN .84 DEGREES

TEMPERATURE (DEGF) VARIATION WITH AXIAL LOCATION (FT). THE WALL OD INCLUDES ACOUSTIC PILLOWS, IF ANY.

DIST FM INLET	0.00	3.72	7.44	11.17	14.89	18.61	22.33	26.06	29.78	33.50
JET TEMP	2248.9	1830.4	1417.1	1096.2	861.3	690.0	563.4	509.5	509.7	509.7
SEC FLOW TEMP	75.0	75.3	75.6	75.8	75.9	76.1	76.5			
AUG WALL ID	117.4	235.2	264.7	227.7	190.6	169.6	173.9	493.5	498.9	497.3
AUG WALL OD	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0

TEMPERATURE (DEGF) VARIATION WITH AXIAL LOCATION (FT). THE WALL OD INCLUDES ACOUSTIC PILLOWS, IF ANY.

DIST FM INLET	37.22	40.94	44.67	48.39	52.11	55.83	59.56	63.28	67.00	
JET TEMP	507.4	509.1	508.8	508.5	508.3	508.1	508.0	508.2	508.8	
AUG WALL ID	353.2	353.2	353.2	353.2	353.2	353.2	353.2	353.2	352.6	
AUG WALL OD	352.0	352.0	352.0	352.0	352.0	352.0	352.0	352.0	352.0	

BULK VELOCITY OF JET AT AUGMENTER EXIT = 508. FT/SEC

EXHAUST GAS EMISSIVITY AND CONVECTIVE FILM COEFFICIENT (BTU/HR-SQFT-DEGF) BY LOCATION

DIST FM INLET	0.00	3.72	7.44	11.17	14.89	18.61	22.33	26.06	29.78	33.50
FILM COEFF	55.15	17.87	10.71	7.70	5.19	5.45	5.58	23.61	23.61	23.61
EMISSIVITY	.1711	.2048	.1997	.1840	.1646	.1510	.1376	.1241	.1164	.1164

EXHAUST GAS EMISSIVITY AND CONVECTIVE FILM COEFFICIENT (BTU/HR-SQFT-DEGF) BY LOCATION

DIST FM INLET	37.22	40.94	44.67	48.39	52.11	55.83	59.56	63.28	67.00	
FILM COEFF	23.61	23.61	23.61	23.61	23.60	23.60	23.60	23.61	23.61	
EMISSIVITY	.1164	.1164	.1164	.1164	.1164	.1164	.1164	.1164	.1164	

THE FACILITY HAS BOTH A WATER-WALL BOILER WRAPPED AROUND THE AUGMENTER AND A STAGGERED WATER-TUBE BOILER IN THE GAS PATH AT THE AUGMENTER EXIT

WATER-WALL BOILER CHARACTERISTICS
 STEAM TEMPERATURE = 352. DEGF
 STEAM PRESSURE = 138.2 PSIA
 HEAT OF VAPORIZATION = 869.1 BTU/LB
 TOTAL HEAT TRANSFER AREA = 950. SQFT

THE WATER-WALLS ARE LOCATED ALONG THE SECTION BEGINNING 40.0 FEET FROM THE AUGMENTER INLET AND ENDING AT A DISTANCE OF 67.0 FEET FROM THE AUGMENTER INLET

TOTAL STEAM GENERATION IN WATER-WALL BOILER = .4005E+04 LB/HR

TOTAL HEAT TRANSFERRED = .3481E+07 BTU/HR

WATER-WALL STEAM GENERATION (LB/HR) VARIATION WITH AXIAL LOCATION (FT FROM AUGMENTER INLET)

DIST FM INLET	0.00	3.72	7.44	11.17	14.89	18.61	22.33	26.05	29.78	33.50
STEAM GEN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DIST FM INLET	37.22	40.94	44.67	48.39	52.11	55.83	59.56	63.28	67.00	
STEAM GEN	259.7	523.3	516.8	514.0	512.6	512.2	512.6	514.2	130.3	

FRACTION OF WATER-WALL STEAM GENERATION BY CONVECTION AND BY RADIATION

DIST FM INLET	0.00	3.72	7.44	11.17	14.89	18.61	22.33	26.05	29.78	33.50
CONVECTION	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
RADIATION	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

FRACTION OF WATER-WALL STEAM GENERATION BY CONVECTION AND BY RADIATION

DIST FM INLET	37.22	40.94	44.67	48.39	52.11	55.83	59.56	63.28	67.00
CONVECTION	.935	.961	.972	.975	.977	.978	.978	.979	.989
RADIATION	.065	.039	.028	.025	.023	.022	.022	.022	.011

CONVECTION WATER-TUBE BOILER CHARACTERISTICS
 STEAM TEMPERATURE = 352. DEGF
 STEAM PRESSURE = 138.2 PSIA
 HEAT OF VAPORIZATION = 869.1 BTU/LB
 TOTAL HEAT TRANSFER AREA = 1520. SQFT
 OUTER DIAMETER OF TUBES = 3.00 IN

TOTAL STEAM GENERATION IN CONVECTION WATER-TUBE BOILER = .1320E+05 LB/HR

AVERAGE GAS TEMPERATURE AT BOILER INLET = 509. DEGF
 BOILER OVERALL HEAT TRANSFER COEFFICIENT = 48.1 BTU/HR-SQFT-DEGF
 TOTAL HEAT TRANSFERRED = .1147E+08 BTU/HR

THE ECONOMICS OF GAS TURBINE TEST CELL ENERGY RECOVERY

THE PURCHASE PRICE OF THE WATER-WALL HEAT EXCHANGER IS \$1000000.00, PAYABLE WHEN INSTALLATION IS COMPLETE

THE ACCUMULATED PRESENT VALUE OF SAVINGS RESULTING FROM THE ADDITION OF THE WATER-WALL BOILER ASSUMING A DISCOUNT RATE OF 10.0 PERCENT, A CURRENT STEAM PRICE OF \$ 9.73/MBTU, AND A STEAM ESCALATION RATE OF 8.0 PERCENT

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	.25	14632.	.01
10	.25	27981.	.03
15	.25	40159.	.04
20	.25	51271.	.05
25	.25	61409.	.06

THE PURCHASE PRICE OF THE CONVECTION HEAT EXCHANGER IS \$2000000.00, PAYABLE WHEN INSTALLATION IS COMPLETE

THE ACCUMULATED PRESENT VALUE OF SAVINGS RESULTING FROM THE ADDITION OF THE CONVECTION BOILER ASSUMING A DISCOUNT RATE OF 10.0 PERCENT, A CURRENT STEAM PRICE OF \$ 9.73/MBTU, AND A STEAM ESCALATION RATE OF 8.0 PERCENT

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	.25	48203.	.02
10	.25	92180.	.05
15	.25	132301.	.07
20	.25	168906.	.08
25	.25	202302.	.10

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	.50	29263.	.03
10	.50	55961.	.06
15	.50	80319.	.08
20	.50	102541.	.10
25	.50	122816.	.12

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	.50	96405.	.05
10	.50	184359.	.09
15	.50	264603.	.13
20	.50	337812.	.17
25	.50	404404.	.20

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	1.00	58527.	.06
10	1.00	111923.	.11
15	1.00	160638.	.16
20	1.00	205083.	.21
25	1.00	245631.	.25

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	1.00	192810.	.10
10	1.00	368718.	.18
15	1.00	529206.	.26
20	1.00	675625.	.34
25	1.00	809208.	.40

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	2.00	117053.	.12
10	2.00	223845.	.22
15	2.00	321276.	.32
20	2.00	410165.	.41
25	2.00	491262.	.49

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	2.00	385621.	.19
10	2.00	737437.	.37
15	2.00	1058412.	.53
20	2.00	1351249.	.68
25	2.00	1618416.	.81

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	3.00	175580.	.18
10	3.00	335768.	.34
15	3.00	491914.	.48
20	3.00	615248.	.62
25	3.00	736893.	.74

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	3.00	578431.	.29
10	3.00	1106155.	.55
15	3.00	1587618.	.79
20	3.00	2026874.	1.01
25	3.00	2427623.	1.21

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	5.00	292633.	.29
10	5.00	559613.	.56
15	5.00	803187.	.80
20	5.00	1025413.	1.03
25	5.00	1228155.	1.23

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	5.00	964052.	.48
10	5.00	1843592.	.92
15	5.00	2645030.	1.32
20	5.00	3378123.	1.69
25	5.00	4046039.	2.02

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	8.00	468213.	.47
10	8.00	895381.	.90
15	8.00	1285103.	1.29
20	8.00	1640660.	1.64
25	8.00	1965044.	1.97

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN (\$)	SIR
5	8.00	1542483.	.77
10	8.00	2949744.	1.47
15	8.00	4233644.	2.12
20	8.00	5404957.	2.70
25	8.00	6473663.	3.24

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- 6 Construction equipment and machinery
- 7 Fire prevention and control
- 8 Antenna technology
- 9 Structural analysis and design (including numerical and computer techniques)
- 10 Protective construction (including hardened shelters, shock and vibration studies)
- 11 Soil/rock mechanics
- 13 BEQ
- 14 Airfields and pavements
- 15 ADVANCED BASE AND AMPHIBIOUS FACILITIES
- 16 Base facilities (including shelters, power generation, water supplies)
- 17 Expedient roads/airfields/bridges
- 18 Amphibious operations (including breakwaters, wave forces)
- 19 Over-the-Beach operations (including containerization, materiel transfer, lighterage and cranes)
- 20 POL storage, transfer and distribution
- 24 POLAR ENGINEERING
- 24 Same as Advanced Base and Amphibious Facilities, except limited to cold-region environments

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- 46 Seafloor construction systems and operations (including diver and manipulator tools)
- 47 Undersea structures and materials
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