SAN-1483-1/3

CONCEPTUAL DESIGN OF ADVANCED CENTRAL RECEIVER POWER SYSTEMS SODIUM-COOLED RECEIVER CONCEPT

Final Report. Volume 2, Book 2. Appe

March 1979

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Rockwell International
Energy Systems Group
Canoga Park, California

U.S. Department of Energy

Solar Energy

NOTICE

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CONCEPTUAL DESIGN OF ADVANCED CENTRAL RECEIVER POWER SYSTEMS SODIUM-COOLED RECEIVER CONCEPT FINAL REPORT

VOLUME II
BOOK 2
APPENDICES

MARCH 1979

PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
AS PART OF
CONTRACT NO. EG-77-C-03-1483

Rockwell International
Energy Systems Group

University of Houston Founded 1927
McDonnell Douglas Corporation
Salt River Project WATER ◆ POWER
Stearns-Roger Engineering Co.

PREFACE

This report is submitted by the Energy Systems Group to the Department of Energy under Contract EG-77-C-03-1483 as final documentation. This Conceptual Design Report summarizes the analyses, design, planning, and cost efforts performed between October 1, 1977, and September 1, 1978. The report is submitted in four volumes, as follows:

Volume I	Executive Summary	
Volume II	Book 1, Commercial Plant Conceptual Design	
	Book 2, Appendices	⇦
Volume III	Development Plan and Pilot Plant Description	
Volume IV	Commercial and Pilot Plant Cost Data	

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DESIGN DATA SHEETS AND P&I DRAWING FOR 100-MWe COMMERCIAL PLANT DESIGN, FOR ALL-SODIUM STORAGE CONCEPT

CONTENTS:

ADVANCED CENTRAL RECEIVER
100 MWe SYSTEM SUMMARY DATA
(Sheet 1 of 2)

Net Electrical Power (MWe)	100
Parasitic Power (MWe)	
Daytime	12
Nighttime	6
Insolation (W/m^2)	950
Maximum Solar Power Absorbed (MWt)	390
Nominal Solar Power Absorbed for Direct Operating (MWt)	260
Plant Net Efficiency (%)	22.9
Collector Field Configuration	Single 360^0, North Biased
Solar Multiple, Equinox Noon	1.5
Number of Heliostats	14,100
Heliostat Shape and Size [m (ft)]	~Square, 7.38 x 7.42 (24.2 x 24.3)
Number of Towers/Receivers	1
Land Area (acre)	780
Receiver Mid-Point Elevation [m (ft)]	174 (571)
Receiver Configuration	External Cylinder
Number of Receiver Panels	24
Receiver Height and Diameter [m (ft)]	16.1 x 16.1 (52.8 x 52.8)
Receiver Maximum Heat Flux (MW/m^2)	1.53
Sodium Temperatures [^{o}C (^{o}F)]	288/593 (550/1100)
Receiver Sodium Flow Rate [kg/hr (lb/hr)]	3.66 x 10^6 (8.07 x 10^6)
Steam Generator Sodium Flow Rate (Direct Operation) [kg/hr (lb/hr)]	2.34 x 10^6 (5.29 x 10^6)

ADVANCED CENTRAL RECEIVER
100 MWe SYSTEM SUMMARY DATA
(Sheet 2 of 2)

Thermal Storage Capacity (MWth)	805
Total Sodium Inventory kg (lb)	7.6×10^6 (16.8×10^6)
Steam Generator and Reheater Type	Modular Steam Generator
Steam Conditions [MN/m^2, °C (psia, °F)]	
Initial	12.51, 538 (1815, 1000)
Reheated	2.72, 538 (394, 1000)
Steam Flow Rate [kg/hr (lb/hr)]	
Daytime	3.32×10^5 (7.32×10^5)
Nighttime	3.15×10^5 (6.95×10^5)
TSS Sodium Flow Rate [kg/hr (lb/hr)]	2.31×10^6 (5.09×10^6)
Feedwater Temperature [°C (°F)]	234 (453)
Turbine Back Pressure [MN/m^2 (in. Hg)]	0.007 (2.0)
Heat Rejection [MW (Btu/hr)]	
Daytime	158 (540×10^6]
Nighttime	150 (511×10^6)

RECEIVER SUBSYSTEM

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DESIGN DATA SHEET

PREPARED BY	
APPROVED BY	
TITLE	Advanced Central Receiver Receiver Subsystem
NUMBER	
PAGE	1 of 14
WBS NO.	
DATE	5/16/78

NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Receiver Subsystem</u>					
		Nominal Thermal Power	MWt	260			
		Maximum Thermal Power	MWt	390			
		Receiver Temperature					
		- In	^oC (^oF)	288 (550)			
		- Out	^oC (^oF)	593 (1100)			
		Flow Rate - Max Receiver	Kg/hr (lb/hr)	3.66 x 10^6 (8.07 x 10^6)			
		- Max Steam Generator	Kg/hr (lb/hr)	2.34 x 10^6 (5.29 x 10^6)			
		Volume of Sodium in Subsystem	m^3 (gals)	341 (90,000)			
		Weight of Sodium in Subsystem	kg (lbs)	291,000 (641,000)			
		Pump Outlet Pressure	MN/m^2 (psia)	2.38 (345)			
		Pump Inlet Pressure	MN/m^2 (psia)	0.10 (15)			
		Total Radiation and Convection Loss	%	9% at Peak Power 12.5% at 50% Power			

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DESIGN DATA SHEET

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TITLE
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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Receiver Subsystem (Cont.)					
		Steam Generator Units Sodium Side					
		Superheat - Temp In	^{o}C (^{o}F)	593 (1100)			Tube and Shell Hockey Stick
		- Temp Out	^{o}C (^{o}F)	462 (864)			
		- Power	MWt	76.1			
		Reheat - Temp In	^{o}C (^{o}F)	593 (1100)			Tube and Shell Hockey Stick
		- Temp Out	^{o}C (^{o}F)	462 (864)			
		- Power	MWt	35.3			
		Evaporator - Temp In	^{o}C (^{o}F)	462 (864)			Tube and Shell Hockey Stick
		- Temp Out	^{o}C (^{o}F)	288 (550)			
		- Power	MWt	148.6			
		Pumps - Number and Type		1			Fixed Speed, Double Suction Centrifugal, Single Stage
		Receiver - Size and Type	m x m (ft x ft)	16.1 x 16.1 (53 x 53)			External 24 Panel
		Large Valves, 61 cm (24") Block		2			CS, Riser and Pump Return
		61 cm (24") Check		1			CS, Riser
		46 cm (18") Block		1			SS, Downcomer
		41 cm (16") Control		1			SS, Superheater Control
		20 cm (8") Control		24			SS, Receiver Panel Control
		15 cm (6") Control		1			SS, Reheater Control

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Receiver Subsystem (Cont.)					
		Large Pipe Length, 61 cm (24")	m (ft)	305 (1000)			CS
		46 cm (18")	m (ft)	366 (1200)			CS and SS
		41 cm (16")	m (ft)	18 (60)			SS
		20 cm (8")	m (ft)	512 (1680)			CS and SS
		15 cm (6")	m (ft)	18 (60)			SS
		Receiver Assembly					
		Diameter	m (ft)	16.1 (53)			
		Height	m (ft)	16.1 (53)			
		Receiver Mid-Point Elevation	m (ft)	211 (692)			
		Receiver Maximum Elevation	m (ft)	219 (720)			
		Number of Absorber Panels		24			
		Receiver Weight, Dry					
		Total	Kg (lb)	275,000 (606,000)			
		Pressure Parts	Kg (lb)	60,200 (132,500)			
		Total Sodium in Receiver	Kg (lb)	66,400 (146,000)			
		Absorber Panel					
		Height	m (ft)	16 (53)			
		Width	m (ft)	2.1 (6.9)			
		Dry Weight, Pressure Parts	Kg (lb)	1,638 (3,600)			
		Number of Tubes		110			
		Tube OD	cm (in.)	1.91 (0.75)			
		Tube ID	cm (in.)	1.65 (0.65)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Absorber Panel (Cont)					
		Tube Material		CRES 304H			
		Solar Surface Coating		Pyromark			
		Panel Insulation	cm (in.)	15.2 (6)			Closed-Pore Fiberglass
		Thermal Expansion	cm (in.)	12.7 (5)			Flexible Tube Bends
		Absorptivity, Minimum		0.95			
		Peak Heat Flux	MW/m^2 (Btu/in^2-sec	1.37 (0.84)			
		Outlet Temperature	^oC (^oF)	593 (1100)			
		Inlet Temperature	^oC (^oF)	288 (550)			
		Maximum Tube Surface Temperature	^oC (^oF)	635 (1175)			
		Tower Assembly					
		Construction					Slip formed concrete
		Concrete Height	m (ft)	157 (516)			
		Diameter - Base	m (ft)	24 (80)			
		- Top	m (ft)	9.1 (30)			
		Wall Thickness - Base	m (ft)	0.46 (1.5)			
		- Top	m (ft)	0.25 (.83)			
		Mat - OD	m (ft)	39.6 (130)			
		- ID	m (ft)	9.1 (30)			
		- Thickness	m (ft)	3.0 (10)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Riser</u>					
		Nominal Pipe OD	cm (in.)	61 (24)			
		Nominal Wall Thickness		TBD			
		Material		CS			
		Design Temperature	°C (°F)	371 (700)			
		Design Pressure ANSI B31.1		2.76 (400)			
		Maximum Flow Rate	kg/hf (lb/hr)	3.66×10^6 (8.07×10^6)			
		Velocity at Maximum Flow Rate	m/sec (ft/sec)	4.99 (16.3)			
		<u>Downcomer</u>					
		Nominal Pipe OD	cm (in.)	45.7 (18)			
		Nominal wall thickness		TBD			
		Material		304H			
		Design Temperature	°C (°F)	593 (1100)			
		Design Pressure ANSI B31.1		2.76 (400)			
		Maximum Flow Rate	kg/hf (lb/hr)	3.66×10^6 (8.07×10^6)			
		Velocity at Maximum Flow Rate	m/sec (ft/sec)	7.45 (24.5)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Receiver Pump					
		<u>Physical Description</u>					
		Quantity		1			
		Number of Stages		2			
		Height, w/motor	m (ft)	7.6 (25)			
		Tank Size	m (ft)	2.3 x 4.2 (7.8 x 14)			
		Inlet Nozzle	m (in.)	0.91 (36)			
		Outlet Nozzle	m (in.)	0.61 (24)			
		Dry Weight Pump	kg (lb)	44,600 (98,300)			
		<u>Motor</u>					
		Size	MW (hp)	3.36 (4,500)			
		Dimensions w/coupling	m (ft)	1.8 x 3.6 (6 x 11)			
		Voltage	v	4160			
		Cooling		TBD			
		Weight	kg (lb)	9,545 (21,000)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Pump Operating Conditions</u>					
		Developed Head	m (ft)	251 (824)			
		Flow Rate	kg/hr (lb/hr)	3.66×10^6 (8.07×10^6)			
		Speed	rpm	700			
		Temperature	^oC (^oF)	288 (550)			
		Sodium Volume	m^3 (gal)	5.9 (1562)			
		NPSH	m (ft)	9.1 (30)			
		Speed Control	%	Fixed Speed			
		Pump Power (η= 78%)	MW (hp)	3.2 (4,321)			
		<u>Design Conditions</u>					
		Developed Head	m (ft)	257 (844)			
		Flow Rate	m^3/s (gpm)	1.3 (20,000)			
		Speed	rpm	700			
		Temperature	^oC (^oF)	300 (600)			
		NPSH (Minimum Required)	m (ft)	9.1 (30)			
		Code					Sect. VIII, Div. 1

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			UNIT	VALUE			
		Steam Generator - Evaporator					
		Physical Description					
		Quantity		1			
		Type					Tube & Shell Hockey Stick
		Height	m (ft)	29.0 (95)			
		Width	m (ft)	4.87 (16)			
		Shell diameter	m (in.)	1.22 (48)			
		Heat Transfer Area	m^2 (ft^2)	1305 (14039)			
		Number of Tubes		1100			
		Tube Size	cm (in.)	1.59 (5/8)			
		Tube Wall Thickness	cm (in.)	0.19 (0.075)			
		Material		2-1/4 Cr - 1 Mo			
		Sodium Nozzle OD/Thickness	cm (in.)	91/2.5 (36/1.0)			
		Tubesheet Diameter/Thickness	cm (in.)	122/30.5 (48/12)			
		Steam Nozzle OD/Thickness	cm (in.)	201/3.8 (8/1.5)			
		Weight	kg (ton)	58,000 (64)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Operating Conditions					
		Sodium Side:					
		Flow	kg/hr (lb/hr)	2.34 x 10^6 (5.29 x 10^6)			
		Inlet Temperature	°C (°F)	462 (864)			
		Outlet Temperature	°C (°F)	288 (500)			
		Pressure Drop	MN/m^2	0.207 (30)			
		Duty	MWt	148.6			
		Water/Steam:					
		Flow	kg/hr (lb/hr)	3.32 x 10^5 (7.32 x 10^5)			
		Inlet Temperature	°C (°F)	234 (453)			
		Outlet Temperature	°C (°F)	341 (646)			
		Pressure	MN/m^2)	15.06 (2185)			
		Pressure Drop	MN/m^2 (psi)	2.07 (300)			
		Design Conditions:					
		Pressure-Sodium Side	MN/m^2 (psig)	2.07 (300)			
		Pressure-Steam Side	MN/hr^2 (psig)	16.55 (2400)			
		Temperature	°C (°F)	482 (900)			
		Code					ASME Section VIII, Div. 1

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Steam Generator - Superheater					
		Physical Description					
		Quantity		1			
		Type					Tube & Shell Hockey-Stick
		Height	m (ft)	27.7 (91)			
		Width	m (ft)	4.57 (15)			
		Shell Diameter	m (in.)	0.76 (30)			
		Heat Transfer Area	m^2 (ft^2)	402.8 (4334)			
		Number of Tubes		283			
		Tube Size	cm (in.)	1.90 (3/4)			
		Tube Wall Thickness	cm (in.)	0.335 (0.132)			
		Material		SS 316			
		Sodium Nozzle OD/Thickness	cm (in.)	45.7/2.54 (18/1.0)			
		Tubesheet Diameter/Thickness	cm (in.)	76.2/20.3 (30/8)			
		Steam Nozzle OD/Thickness	cm (in.)	20,3/3 (8/1.2)			
		Weight	kg (ton)	20,000 (22)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Operating Conditions</u>					
		Sodium Side					
		Flow	kg/hr (lb/hr)	1.65×10^6 (3.61×10^6)			
		Inlet Temperature	°C (°F)	594 (1100)			
		Outlet Temperature	°C (°F)	462 (864)			
		Pressure Drop	MN/m^2 (psi)	0.207 (30)			
		Duty (MWt)		76.1			
		Water/Steam:					
		Flow	kg/hr (lb/hr)	3.32×10^5 (7.32×10^5)			
		Inlet Temperature	°C (°F)	341 (646)			
		Outlet Temperature	°C (°F)	538 (1000)			
		Pressure	MN/m^2 (psig)	12.96(1880)			
		Pressure Drop	MN/m^2 (psi)	1.77 (256)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Superheater (Cont.)					
		Design Conditions:					
		Pressure-Sodium Side	MN/m^2 (psig)	2.07 (300)			
		Pressure-Steam Side	MN/m^2 (psig)	15.2 (2200)			
		Temperature	^{o}C (^{o}F)	593 (1100)			
		Code					ASME, Section VIII, Division I
		Steam Generator - Reheat					
		<u>Physical Description</u>					
		Quantity		1			
		Type					Tube & Shell Hockey-Stick
		Height	m (ft)	20.1 (66)			
		Width	m (ft)	5.49 (18)			
		Shell Diameter	m (in.)	0.81 (32)			
		Heat Transfer Area	m^2 (ft^2)	309.4 (3329)			
		Number of Tubes		163			
		Tube Size	cm (in.)	3.81 (1-1/2)			
		Tube Wall Thickness	cm (in.)	0.272 (0.107)			
		Material		SS 316			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Reheat (Cont.)					
		Physical Description (Cont.)					
		Sodium Nozzle OD/Thickness	cm (in.)	30.5/1.9 (12/.75)			
		Tubesheet Diameter/Thickness	cm (in.)	81.3/12.7 (32/5)			
		Steam Nozzle OD/Thickness	cm (in.)	16.8/1.5 (6.6/.6)			
		Weight	kg (ton)	22,000 (24)			
		Operating Conditions					
		Sodium Side:					
		Flow	kg/hr (lb/hr)	0.755 x 10^6 (1.68 x 10^6)			
		Inlet Temperature	^oC (^oF)	594 (1100)			
		Outlet Temperature	^oC (^oF)	462 (864)			
		Pressure Drop	MN/m^2 (psi)	0.207 (30)			
		Duty	MWt	35.3			
		Water/Steam:					
		Flow	kg/hr (lb/hr)	2.89 x 10^5 (6.36 x 10^5)			
		Inlet Temperature	^oC (^oF)	342 (647)			
		Outlet Temperature	^oC (^oF)	538 (1000)			
		Pressure	MN/m^2 (psig	2.80 (406)			
		Pressure Drop	MN/m^2 (psi)	0.15 (22)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Reheat (Cont.)					
		Design Conditions:					
		Pressure-Sodium Side	MN/m^2 (psig)	2.07 (300)			
		Pressure-Steam Side	MN/m^2 (psig)	3.65 (530)			
		Temperature	$^\circ$C ($^\circ$F)	593 (1100)			
		Code					ASME, Section VIII, Division I

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THERMAL STORAGE SUBSYSTEM

ALL-SODIUM STORAGE

Atomics International Division
Rockwell International

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Thermal Storage Subsystem

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		<u>Thermal Storage Subsystem</u>					
		Storage Material		Sodium			
		Number of Tanks		2			
		Thermal Storage Capacity	MWth	812.5			Includes 62.5 MWh_t for Startup and Shutdown
		Maximum Charging Rate	MWt	390			
		Maximum Extraction Rate	MWt	250			
		Time at Maximum Extraction Rate	hr	3			
		Weight of Sodium in Subsystem	kg (lb)	7.6×10^6 (16.8×10^6)			
		Temperature - Hot Tank Storage	°C (°F)	593 (1100)			
		- Cold Tank Storage	°C (°F)	288 (550)			
		Pump - Number and Type		1			Variable Speed, Single Stage Centrifugal
		Large Valves - 46 cm (18 in.) Block		2			CS and SS
		- 46 cm (18 in.) Drag		1			SS
		Large Pipe Length - 46 cm (18 in.)	in (ft)	73 (240)			CS, Standard Wall
		- 46 cm (18 in.)	in (ft)	107 (350)			SS, Standard Wall

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		<u>Low Temperature Sodium Tank</u>					
		Number		1			
		Type					Cylindrical API Type
		Diameter	m (ft)	30.5 (100)			
		Height	m (ft)	12.3 (41)			
		Wall Thickness					
		Top	cm (in.)	0.64 (0.25)			
		Bottom	cm (in.)	2.5 (1.0)			
		Volume	m^3 (gal)	8,700 (2.3 x 10^6)			
		Tank Material					Carbon Steel
		Insulation, Roof and Walls	cm (in.)	15.2 (6)			Calcium Silicate with Aluminum Weather Protection
		Base Insulation	m (ft)	1 (3)			Perlitic Concrete
		Electric Preheat-Temperature Maintenance	kw	274			
		Low Sodium Temperature	^oC (^oF)	288 (550)			
		Ullage Maintenance Unit					
		Ullage Pressure	Pa (psi)	0.0069 (1)			
		Pressurization Media		Argon			

FORM 706-A REV 2-74

Atomics International Division
Rockwell International

DESIGN DATA SHEET

PREPARED BY	
APPROVED BY	
TITLE	Advanced Central Receiver Thermal Storage Subsystem
WBS NO.	
NUMBER	
PAGE	3 of 5
DATE	5/16/78

NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TEN-TATIVE	FIRM	REFERENCES AND REMARKS
		High Temperature Sodium Tank					
		Type		Cylindrical API Type			
		Diameter	m (ft)	30.5 (100)			
		Height	m (ft)	13.6 (45)			
		Wall Thickness					
		Top	cm (in.)	0.64 (0.25)			
		Bottom	cm (in.)	5.1 (2.0)			
		Volume	m^3 (gal)	9460 (2.5 x 10^6)			
		Tank Material, Thickness	cm (in.)	0.64 (0.25 - 2.5 (1.0)			Type 304 SS
		Insulation, Roof and Walls	cm (in.	30.5 (12)			Calcium Silicate with Aluminum Weather Protection
		Base Insulation	m (ft)	1 (3) Perlitic Concrete			
		Electric Preheat-Temperature Maintenance	kw	540			
		Number of High Temperature Tanks		1			
		High Sodium Temperature	^{o}C (^{o}F)	593 (1100^{o}F)			
		Ullage Maintenance Unit		Argon			

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Atomics International Division
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TITLE Advanced Central Receiver Thermal Storage Subsystem

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WBS NO.

NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		STEAM GENERATOR PUMP					
		Physical Description					
		Quantity		1			
		Number of Stages		1			
		Height, w/motor	m (ft)	7.3 (24)			
		Tank Size	m (ft)	1.0 x 3.6 (3.5 x 12)			
		Inlet Nozzle	m (in.)	0.61 (24)			
		Outlet Nozzle	m (in.)	0.46 (18)			
		Dry Weight, Pump	kg (lb)	8,600 (19,000)			
		Motor					
		Size	MW (hp)	0.56 (750)			
		Dimensions w/coupling	m (ft)	1.5 x 3.7 (5 x 12)			
		Voltage	v	4160			
		Cooling		TBD			
		Weight	kg (lb)	3860 (8500)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Pump Operating Conditions					
		Developed Head	m (ft)	76.7 (250)			
		Flow Rate	kg/hr (lb/hr)	2.34 x 10^6 (5.29 x 10^6)			
		Speed	rpm	1160			
		Temperature	^{o}C (^{o}F)	593 (1100)			
		Sodium Volume	m^3 (gal)	5.7 (1500)			
		NPSH	m (ft)	9.1 (30)			
		Speed Control	%	10-100			
		Pump Power (η = 80%)	MW (hp)	0.53 (706)			
		Design Conditions					
		Developed Head	m (ft)	76 (250)			
		Flow Rate	m^3/sec (gpm)	0.95 (15,000)			
		Speed	rpm	1160			
		Temperature	^{o}C (^{o}F)	593 (1100)			
		NPSH (Minimum Required)	m (ft)	7.6 (25)			
		Code					Section VIII, Div. I

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		<u>Drag Valve</u>					
		Location					Upstream of High Temperature Sodium Storage Tank
		Type		Stacked Disc			
		Size (nominal)	inches	18			
		Flow Rate	m^3/sec (gpm)	1.26 (20,000)			
		Pressure Drop	mn/m^2 (psi)	1.74 (253)			
		Pressure Rating	mn/m^2 (psi)	2.75 (400)			
		Temperature	^oC (^oF)	649 (1200)			
		Flow Coefficient, C_v	$m^3/sec/\sqrt{mn/m^2}$ $(gpm/\sqrt{psi})$	.955 (1258)			
		Operator					Yes--Type TBD
		Insulation	in.	8			Calcium Silicate
		Material					Stainless Steel; Inconel Velocity Control Elements
		Pressure Class					ANSI 2500 lb

COLLECTOR

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DESIGN DATA SHEET

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TITLE ADVANCED CENTRAL RECEIVER COLLECTOR SUBSYSTEM

NUMBER

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WBS NO.

DATE May 19, 1978

NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		GENERAL					
		TOTAL FIELD AREA (EXCLUDING CENTRAL EXCLUSION)	$10^6 m^2$ $(10^6 ft^2)$	3.06 (32.9)			
		NUMBER OF HELIOSTATS	--	14,106			
		TOTAL MIRROR AREA	$10^6 m^2$ $(10^6 ft^2)$	.6916 (7.44)			
		PEAK POWER @ 950 w/m^2	MW	390			
		ANNUAL COLLECTABLE ENERGY	MWH_t	0.955×10^6			
		TOWER HEIGHT	m (ft)	159 (522)			
		RECEIVER CENTERLINE ELEVATION	m (ft)	174 (571)			
		HELIOSTAT ARRANGEMENT	--	RADIAL STAGGER			
		AIM STRATEGY	--	1-POINT EQUATOR			
		PEAK RECEIVER HEAT FLUX	MW/m^2	1.37			
		CENTRAL EXCLUSION DIAMETER	m (ft)	364 (1200)			

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TITLE ADVANCED CENTRAL RECEIVER COLLECTOR SUBSYSTEM (100 MWe SYSTEM)

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DATE August 20, 1978

PREPARED BY

APPROVED BY

WBS NO.

NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		HELIOSTAT					
		REFLECTOR SHAPE	--	RECTANGULAR			
		REFLECTOR ENVELOPE	m (ft)	7.38 x 7.42 (24.21 x 24.33)			
		MIRROR TYPE		SECOND SURFACE, SILVERED FUSION/FLOAT LAMINATED GLASS			
		MIRROR AREA	m^2 (ft^2)	49.05 (528)			
		AVERAGE REFLECTIVITY		0.91			
		DRIVE SYSTEM					
		ELEVATION		DUAL SCREW JACKS 3 Ø, 480V ac			
		AZIMUTH		HARMONIC DRIVE 3 Ø, 480V ac			
		REFLECTED BEAM ACCURACY	(mr)	2.83			
		DRIVE RATE					
		ELEVATION	Deg/min	15			
		AZIMUTH	Deg/min	15			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		CANT RANGE	m (ft)	1190 (3900)			
		ELECTRICAL DRAW					
		MOTOR RUNNING (STEADY STATE)	amp	1.5			
		MOTOR START SURGE CURRENT	amp	3.0			
		TIME AVERAGE POWER DRAW (PER HELIOSTAT INCL ELECTRONICS)	WATTS	~39			
		INDIVIDUAL HELIOSTAT AVAILABILITY	--	0.9999			
		FIELD ELECTRONICS					
		PRIMARY FEEDER POWER	VOLTAGE	4160			
		PRIMARY FEEDER CABLE	AWG	#4			
		SECONDARY FEEDER POWER	VOLTAGE	480			
		DATA NETWORK	--	FIBER OPTICS			

FORM 706-A REV 2-74

ELECTRIC POWER GENERATION

Atomics International Division
Rockwell International

DESIGN DATA SHEET	TITLE Advanced Central Receiver Electrical Power Generation Subsystem	NUMBER
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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Turbine					
		Type					Tandum Compound, Double-Flow, Extraction, Condensing Turbine
		Rating (kWe)		112,000			
		Heater Extractions		6			
		Shaft Speed (rpm)		3,600			
		Last Stage Bucket Size [cm (in.)]		58.4 (23)			
		Throttle Flow Control Mode					Steam Generator/Turbine Coordinated Control
		Generator					
		Generator Rating (kVA)		135,000			
		Power Factor		0.9			
		Output Voltage (volts)		13,800			
		Frequency (Hz)		60			
		Cooling					Hydrogen Cooled
		Exciter					Static Excitation System
		Shaft Speed (rpm)		3,600			
		Condenser					
		Type					Shell and Tube, 2-Pass
		Surface [m^2 (ft^2)]		8,365 (90,000)			
		Tube Material		90-10 Copper-Ni			ASTM BIII, Alloy 706
		Tube Diameter OD [mm (in.)]		25.4 (1.00)			
		Tube Wall Thickness, 20 BWG [mm (in.)]		0.89 (0.035)			

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Rockwell International

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Condenser</u> (Continued)					
		Tube Length, Effect [m (ft)]		8.54 (28)			
		Condenser Pressure [kPa (in.-HgA)]		7.0 (2.0)			
		Heat Rejection [MW (Btu/hr)]		1.58 (540 x 10^6)			
		Cooling Water Flow [m^3 (gpm)]		5.9 (93,100)			
		Water Velocity [m/s (fps)]		2.18 (7.16)			
		Cooling Water In [^{o}C (^{o}F)]		28.9 (84.0)			
		Cooling Water Out [^{o}C (^{o}F)]		35.3 (95.6)			
		Condenser Air Removal		-			Mechanical Vacuum Pump (2-full capacity)
		<u>Cooling Tower</u>					
		Quantity		1			
		Type					Mechanical Draft, Cross Flow
		Number of Cells		5			
		Fan Motor Size [kW (hp)]		5-150 (200)			
		Design Wet Bulb Temperature [^{o}C (^{o}F)]		23 (74.0)			
		Cold Water Temperature [^{o}C (^{o}F)]		28.9 (84.0)			
		Hot Water Temperature [^{o}C (^{o}F)]		35.3 (95.6)			
		Circulating Water Flow [m^3/s (gpm)]		6.1 (96,000)			
		Heat Rejection [MW (Btu/hr)]		163 (555 x 10^6)			

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Rockwell International

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Feedwater Heaters</u>					
		Low Pressure Heater Quantity		2			Horizontal, Stainless Steel Tubes, Carbon Steel Shell with Drain Cooler, Maximum Tube Side Pressure: 2.2 kPa (315 psia)
		Deaerator Quantity		1			Stainless Steel Trays and Vent Condenser, Carbon Steel Shell, Horizontal Condensate Storage Section [62.5 m^3 (16,500 gal.)], Pressure Rating; 0.45 MPa (65 psia)
		High Pressure Heaters Quantity		3			Horizontal, Carbon Steel Tubes, Carbon Steel Shell with Drain Cooler, Maximum Tube Side Pressure: 20.68 MPa (3,000 psia)
		<u>Feedwater Treatment</u>					
		Equipment					
		- Inline Polishing Demineralizers					2 Full-Capacity Units
		- Makeup Water Demineralizers					2 Full-Capacity Units
		Chemicals					
		- pH Control					Ammonia
		- Oxygen Scavenger					Hydrazine

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MASTER CONTROL

Atomics International Division
Rockwell International

DESIGN DATA SHEET

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NEW REV	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
N	1	PLANT CENTRAL CONTROL CONSOLE (1)					
		LENGTH	FT.	25	X		
		DEPTH	FT.	2	X		
		HEIGHT	FT.	4	X		
R	2	CONTROL PROCESSORS (5)					
		THROUGHPUT	KOPS/SEC	350	X		
		PRIMARY STORAGE CAPACITY	16BIT WORDS	48,000	X		
R	3	SECONDARY CONTROL PROCESSOR STORAGE (5)					
		CAPACITY	MEGABITS	.25	X		
		ACCESS TIME	MSEC.	35	X		
		LATENCY	MSEC.	15	X		
N	4	HARDCOPY LOGGER (2)					
		CHARACTERS	PER LINE	132	X		
		SPEED	LINES/MIN	300	X		—
N	5	RECORDERS, MAGNETIC (2)					
		DENSITY	BITS/INCH	500/800	X		
		SPEED	IN/SEC	45			—
N	6	SAFING - CONTROL PANEL (1)	TBD	TBD			—
N	7	SERIAL DIGITAL DATA BUS (2)					—
		THROUGHPUT	KBITS/SEC	1500	X		
R	8	COLOR CRT DISPLAYS (5)					—
		RASTER SCAN	NO. LINES	256 x 512	X		
		COLORS	NO.	4			

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Atomics International Division
Rockwell International

DESIGN DATA SHEET

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NEW REV	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
N	9	PID CONTROLLERS (100)					
		MICROPROCESSOR LOOP UPDATE RATE	PER SEC.	3	X		
		SCALING	%	0 - 100	X		
		RESOLUTION	BITS	12			
		OUTPUT	MV	4-20			
N	10	DISCRETE CONTROLLERS (125)					
		RESOLUTION	BITS	12	X		
		OUTPUT	MV	4 - 20			
N	11	ANALOG DATA ACQUISITION (350)			X		
		NORMAL RATE	CHAN/SEC	350			
		EMERGENCY RATE	CHAN/SEC	200,000			
		RESOLUTION	BITS	12			
		MULTIPLEXING	TYPE	SEQUENTIAL			
N	12	ANALOG OUTPUTS (TBD)	TBD	TBD	X		
N	13	CLOSED CIRCUIT TELEVISION (4)			X		
		MONITOR SIZE	IN	19			
		CAMERA	TBD	TBD			
		AUTO PAN/TILT	DEGREES	90			
		ZOOM	TBD	TBD			
N	14	UNINTERRUPTIBLE POWER SOURCE					
		10 INPUT	VAC	115 ± 10%			
		REGULATED 10 OUTPUT	VAC	115 ∓ 2%			
		STORAGE BATTERY CAPACITY	HRS	.5			
		DERATED POWER	KVA	TBD			

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NEW REV	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
N	15	TIME OF DAY REFERENCE					
		INPUT-WWV SYNCH.	HERTZ	1000	X		
		OUTPUT - TIME OF DAY BCD FORMAT	BITS	32	X		
N	16	ANNUNCIATOR PANEL	FUNCTIONS	25	X		
N	17	LOCAL WEATHER STATION WIND	MPH DEGREES	80 360	X		
		BAROMETRIC PRESSURE	IN/HG	26 - 34			
		HUMIDITY	PERCENT/REL	0 - 100			
		SOLAR RADIATION	9M/CM^2/MIN	.36 - 2.0 MICRONS			
		PRECIPITATION	IN	20			
		TEMPERATURE	DEG F	-15, +50			

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Rockwell International

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TITLE BEAM CHARACTERIZATION SUBSYSTEM

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
N	1	VIDEO CAMERA SYSTEM (4)					
		SELF CONTAINED CAMERA INCLUDING ENVIRONMENTAL HOUSING AND SYNC GENERATOR	AMBIENT TEMP °C	-20 TO +60			
			WEIGHT -#	27			
			VOLUME -M^3	.34			
		LENS	SPEED	f 2.8			
			FOCAL LENGTH	32 - 320 MM ZOOM			
N	2	VIDEO SIGNAL PROCESSING SYSTEM. COMPOSITE VIDEO INPUT, SERIAL DIGITAL OUTPUT. (4)					
		A/D CONVERSION	WORD LENGTH-BIT	10			
			CONVERSION TIME-μS	32			
		CONTROLLER	TBD				
		LINE DRIVER	LEVEL - DIFF VOLTS	0.25			
			DISTANCE-M.	1500			
N	3	TARGET PANELS, TOWER MOUNTED 1/4" STEEL, PAINTED (4)	SIZE - M.	APPROX. 12 X 12			

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TITLE BEAM CHARACTERIZATION SUBSYSTEM

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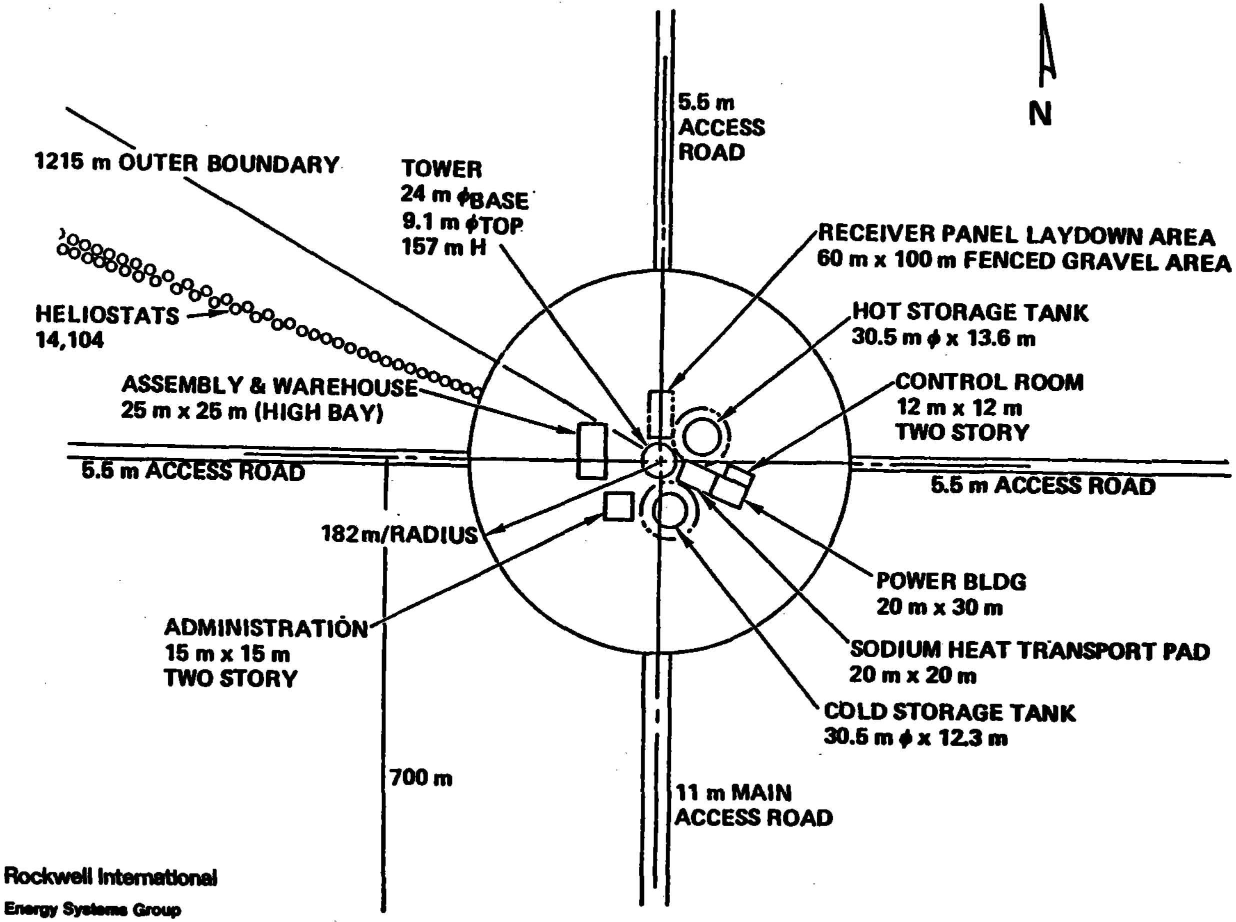
NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
N	5	TARGET INSTRUMENTATION SYSTEM (4)					
		RADIANCE SENSORS	TBD				
		SHUTTER CONTROLLER	TBD				
		MUX - A/D	TBD				
N	6	DATA LINE - RG-11/U (5)	AVG. LENGTH M.	1000			

FORM 706-A REV 2-74

ADVANCED CENTRAL RECEIVER BUILDING LAYOUT, 100 MWe COMMERCIAL CONCEPTUAL DESIGN



Rockwell International
Energy Systems Group

APPENDIX B

DESIGN DATA SHEETS AND P&I DRAWING FOR 100-MWe COMMERCIAL PLANT DESIGN, FOR AIR-ROCK BED STORAGE CONCEPT

CONTENTS:

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Atomics International Division
Rockwell International

DESIGN DATA SHEET

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	VALUE	TEN-TATIVE	FIRM	REFERENCES AND REMARKS
		<u>GENERAL</u>					
		Thermal Storage Capacity	(MWh_t)	812.5* to 3,250			
		Maximum Charging Rate	(MW_t)	390			
		Maximum Extraction Rate	(MW_t)	250			
		Time at Maximum Extraction Rate	(hr)	3.0 to 12.0			
		<u>STORAGE TYPE</u>		Air/Hot Rocks Sensible Heat			
		Input Heat Exchanger		Sodium-to-Air			
		Extraction Heat Exchanger		Air-to-Sodium			
		Bed Storage Temperature	^oC (^oF)	613 (1135)			
		Temperature ΔT for Bed Sizing	^oC (^oF)	256 (460)			
		Reduced Power Operation		0% to 100%			
		Transient Operation					
		Time to 10% to 100% or 100% to 10%		TBD			
		Time to 30% charge to 100% extraction or 100% extraction to 30% charge		TBD			

---

*Includes 62.5 MWh_t for startup and shutdown

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>SUBSYSTEM COMPONENTS</u>					
		Storage Device					
		Number		1			
		Type		Square, Rock Bed			
		Active length = width	[m(ft)]	85, 280			
		Height, overall	[m(ft)]	11 (36)			
		Volume, Container	[m^3, gals, ft^3] x 10^{-6}	0.080, 21.1 2.82			
		Volume, Rock Bed	[m^3, gals, ft^3 x 10^{-6}]	.043, 12.7 1.50			
		Mass, Rock Bed	[Kg(tons)]	6.8×10^7 (75,000)			
		Container - Top		Sand and CS			
		- Bottom		Rock			
		- Wall		Earth and rock			

NOTICE
CONFIDENTIAL PROPRIETARY INFORMATION
OF ROCKWELL INTERNATIONAL CORPORATION

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TABLE 5-4

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TEN-TATIVE	FIRM	REFERENCES AND REMARKS
		Insulation - Top		Sand or soil			
		- Thickness	[m(ft)]	3 (10)			
		- Walls and Bottom		Rock			
		- Thickness	[m(ft)]	1 (3)			
		Temperature - Top of Bed	^oC (^oF)	613 (1135)			
		- Bottom	^oC (^oF)	357 (675)			
		HEAT EXCHANGER					
		Type		Finned tube; counter flow sodium-to-air/ air-to-sodium			
		Number of Modules		54			
		Size	[m(ft)]	Parallelepiped 2.4 x 2.4 x 0.85 (8 x 8 x 2.8)			
		Effective Surface Area	[m^2(ft)]	52800 (568000)			
		Tube OD	cm(in.)	2.60 (1.02)			

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TABLE 5-4

Atomics International Division
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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Wall Thickness	mm(in.)	1.24 (0.049)			
		Material		9% Cr 1% Mo Ferritic Steel			
		Fin Height	mm(in.)	9.1 (0.36)			
		Material		9% Cr 1% Mo Ferritic Steel			
		Fin Thickness	mm(in.)	0.61 (0.024)			
		Fan					
		Number		54			
		Type		Vane-axial, 2 stage, Joy Fan Co.			
		Size - Diameter	cm(in.)	152 (60)			
		Max Air Flow (390 MWt)	KG/S (lbs)	1580 (3470)			
		Nominal Air Flow (250 MWt)	KG/S (lbs)	1010 (2220)			
		Maximum Fan ΔP (390 MWt)	KPa (psi)	1.31 (0.19)			
		Operating Temperature	^{o}C (^{o}F)	> 371 (700)			
		Maximum for Power (390 MWt)	MWe	5.32			

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TABLE 5-4

Atomics International Division
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Advanced Central Receiver Thermal Storage Subsystem Design Data (Air/Rocks Alternative)

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WBS NO.

NEW REV.	NO.	ITEM	DESIGN POINT UNIT	 VALUE	TEN-TATIVE	FIRM	REFERENCES AND REMARKS
		Fan Motor					
		Number		54			
		Type		Variable speed			
		Power (max)	kW (hp)	100 (123)			
		Voltage/Phase		460 V/3Ø			
		Cooling		Air cooled, ducted motor			
		Coupling		TBD			(Either fixed motor speed plus coupling; or variable speed motor without coupling.)
		Mixing Tee 1					See Design Data Sheet
		Mixing Tee 2					See Design Data Sheet

FORM 706-A REV 2-74

Atomics International Division
Rockwell International

DESIGN DATA SHEET

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TITLE
Mixing Tee -1
Air/Rock Thermal
Storage System

WBS NO.

NUMBER

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DATE

NEW REV	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Mixing Tee -1 (Na)					
		Location		See Remarks			Upstream of Steam Generators - function with thermal storage
		Type		Mixing			
		Size (Run/Branch)	in./in.	18/10			
		Wall Thickness	in./cm	0.400 (1.02)			
		Max Flow Velocity	ft/sec	18			
		Run Flow/Branch Flow	lb/sec/ lb/sec	1345/410			
		Operating Pressure					
		Normal	psi (mn/m^2)	230 (1.6)			
		Maximum	psi (mn/m^2)	253 (1.7)			
		Design Pressure	psi (mn/m^2)	400 (2.7)			

FORM 706-A REV 2-74

Atomics International Division
Rockwell International

DESIGN DATA SHEET

TITLE
Mixing Tee -1
Air/Rock Thermal
Storage System

NUMBER

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DATE

NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TEN-TATIVE	FIRM	REFERENCES AND REMARKS
		Operating Temperature					
		Normal Hot Leg/Cold Leg	°F (°C)	1165/715 (629/379)			
		Preheat	°F (°C)	400 (204)			
		Maximum	°F (°C)	1165 (629)			
		Design Temperature	°F (°C)	1200 (649)			
		Material (Body/Liner)		Type 304H/304H			
		Code Classification		Section VIII			Division 1
		Insulation	in.	8			Calcium Silicate
		Size OD x Length	in. x ft	18 x 15			

glb:511

FORM 706-A REV 2-74

Atomics International Division
Rockwell International

DESIGN DATA SHEET

PREPARED BY	
APPROVED BY	
TITLE	Mixing Tee -2 Air/Rock Thermal Storage System
NUMBER	
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WBS NO.	
DATE	

NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Mixing Tee -2 (Na)					
		Location		See Remarks			Downstream of Steam Generators - function with thermal storage
		Type		Mixing			
		Size (Run/Branch)	in./in.	18/10			
		Wall Thickness	in./cm	0.125/0.317			
		Max Flow Velocity	ft/sec				
		Run Flow/Branch Flow	lb/sec/ lb/sec	1755/492			
		Operating Pressure					
		Normal	psi (mn/m^2)	100 (0.68)			
		Maximum	psi (mn/m^2)	125 (0.84)			
		Design Pressure	psi (mn/m^2)	125 (0.84)			

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TITLE
Mixing Tee -2
Air/Rock Thermal
Storage System

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APPROVED BY

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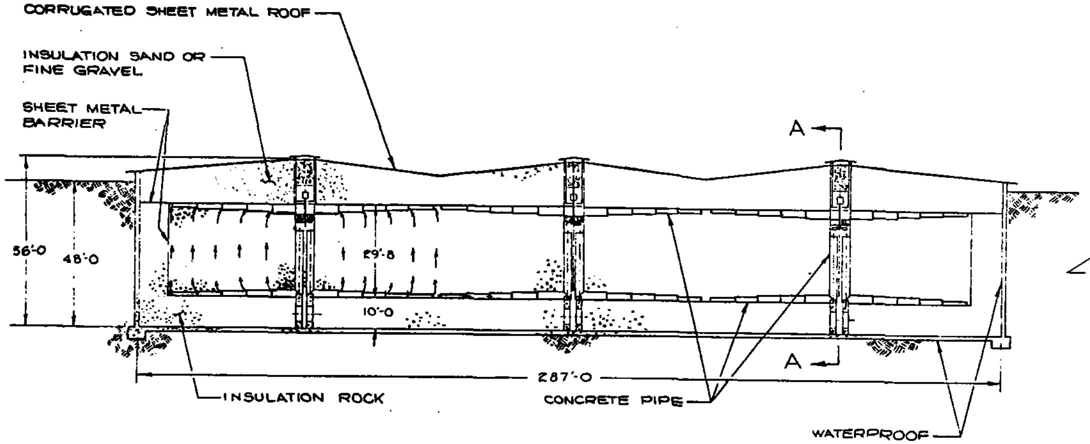
WBS NO.

DATE

NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Operating Temperature					
		Normal Hot Leg/Cold Leg	°F (°C)	715/600 (379/316)			
		Preheat	°F (°C)	400 (204)			
		Maximum	°F (°C)	725 (385)			
		Design Temperature	°F (°C)	750 (399)			
		Material (Body/Liner)					
		Code Classification		Section VIII			Division 1
		Insulation	in.	5			Calcium Silicate
		Size OD x Length	in. x ft	18 x 15			

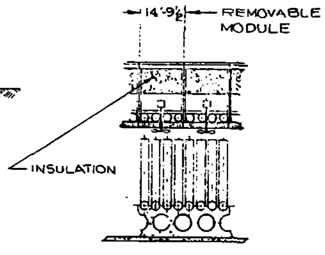
glb:511

FORM 706-A REV 2-74



SECTIONAL ELEVATION

SCALE: $\frac{1}{20}$" = 1'-0



SECT. A-A

HEAT STORAGE CONCEPT

T. E. COWELL 5-30-78

Rockwell International
Atomics International Division

APPENDIX C

ELECTRIC POWER GENERATING WATER-STEAM SYSTEM P&I DRAWING AND EQUIPMENT LIST, 100-MWe COMMERCIAL PLANT DESIGN

CONTENTS:

APPENDIX C

SUPERSEDES CALC. DATED 2-28-78

FORM 62.114
REV. 4.75

PAGE 1 OF 1

JOB NO. C20325 DATE 5/10/78 BY AWM CH'K.

CUSTOMER ATOMICS INT'L PROJECT ADVANCED CENTRAL RECEIVER

SUBJECT AUXILIARY POWER REQUIREMENTS

REFERENCE : S-R HEAT BALANCE DAC-01D 4/10/78
MAX. GUAR. LOAD (TURBINE RATING) 112,000 KW @ 2"HgA
1800 PSIG - 1000°/1000°F THROTTLE FLOW 731,800 LB/HR

1. BOILER FEED PUMP	2100 KW	INPUT TO MOTOR
2. COND. HOTWELL PUMP	150	
3. CIRCULATING WATER PUMPS	1870	
4. COOLING TOWER FANS	850	
5. CONDENSER VACUUM. PUMP	35	
6. GLAND STEAM CONDENSER EXHAUSTER	5	
7. GENERATOR VAPOR EXTRACTOR	5	
8. EQUIPMENT COOLING WATER PUMP	20	
9. BEARING COOLING WATER PUMP	40	
10. INSTRUMENT AIR COMPRESSOR	30	
11. SERVICE AIR COMPRESSOR	40	
12. RAW WATER PUMP	60	
13. COOLING TOWER MAKEUP PUMP	35	
14. WATER TREATING SYSTEMS (LOT)	25	
15. PLANT HVAC	175	
16 MISC. A.C.	100	
TOTAL AUX. POWER (EPGS)	5540 KW	

4.94% OF GROSS GENERATION

EQUIPMENT LIST

(ELECTRICAL POWER GENERATION SUBSYSTEM)

PROJECT 100 MW Advanced Central Receiver

CUSTOMER AI/DOE

PHASE I - CONCEPTUAL DESIGN

JOB NO. C-20325

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EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
Turbine - Generator	1		112,000 kW Tandum Compound Double Flow (TC2F), re-	
			heat, condensing turbine with 58.4 cm (28 in) last	
			stage blades, 3600 RPM. Inlet Pressure 12.51 MPa	
			(1815 psia), Inlet Temperature 538°C (1000°F), re-	
			heat temperature 538°C (1000°F). Turbine exhaust	
			pressure 6.77 kPa (2.0 in. Hg. A). Turbine rating	
			(max. guar.) 112,000 kW. Max. Expected Output	
			116,471 kW at Rated Pressure, Valves Wide Open.	
			Generator: 135,000 kVA, 0.90 P.F., 13,800 V.,	
			Hydrogen Cooled, Static Exciter, 3600 RPM.	
			Accessories:	
			Turbine Gland Steam Condenser w/Exhauster	
			Generator Vapor Extractor	
			A.C. Lube Oil Pump	
			D.C. Lube Oil Pump	
			Lube Oil Reservoir w/Exhauster	
			Lube Oil Coolers	
			Generator Hydrogen Coolers	
			Electro-Hydraulic Control System	

EQUIPMENT LIST

(ELECTRICAL POWER GENERATION SUBSYSTEM)

PROJECT 100 MW Advanced Central Receiver

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EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
Condenser	1		8365 m^2 (90,000 $ft.^2$) surface condenser,	H.E.I. Std.
			2-pass, 25.4 mm (1 in.) O.D. x 20 BWG, 90-10 Cu-Ni	
			Tubes x 8.54m (28 ft.) Effective Length, 158 MWt	
			(540 x 10^6 Btu/hr)	
			Heat Rejection, 6.77 kPa (2.0 in. Hg A)	
			Design Pressure, 28.9°C (84.0 F) inlet	
			Water Temperature, 5.9 m^3/s (93,100 GPM)	
			Circulating Water Flow, 2.18 m/s (7.16 fps)	
			velocity.	
Condenser Vacuum Pumps	2		0.35 m^3/min. (12.5 SCFM) @ 25.4 mm (1 in. HgA)	H.E.I. Std.
			Nash Mechanical Vacuum Pump, 700 RPM, 37 kW (50HP).	Ea. Full Size
			460 V. - 3 Ph. - 60 Hz. motor	
Cooling Tower	1		5-Cell, Mechanical Draft, Cross Flow, 150 kW	C.T.I. Std.
			(200 H.P.) Fans, per cell, 163 MWt (555 x 10^6	
			Btu/hr Heat Rejection, 23°C (74°F) Wet Bulb, 5.6°C	(10°F) Approach,
			6.1 m^3/s (96,000 GPM) Circ. Water Flow	
Circulating Water Pumps	2		Horizontal, centrifugal, double suction, single	Ea. Half Size
			stage, Cast Iron Case, Bronze Impeller, 3.05 m^3/s	

EQUIPMENT LIST

(ELECTRICAL POWER GENERATION SUBSYSTEM)

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EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
Circulating Water Pumps (Cont'd)	2		(48,000 GPM) @ 23.2m (76.0 ft.) Head, 930 kW	
			(1250 HP), 4160 v., 514 RPM Motor	
Condensate Hotwell Pumps	2		Vertical Turbine Can Type, Steel can,	Ea. Full Size
			cast iron bowls, bronze impellers, stainless steel	
			shaft, 5 stages, 0.10 m^3/s (1540 GPM), @ 136m	
			(446 ft.) Head, 186 kw (250 H.P.), 460 V., 1800	
			RPM Motor	
Boiler Feed Pumps	2		Horizontal centrifugal, double case barrel	Ea. Full Size
			type, carbon steel outer case, alloy steel inner	
			case and impellers, stainless steel shaft, 9	
			stages, 3440 RPM, 0.115m^3/s (1825 GPM)	
			@ 1681m (5515 ft.) head, 80.5% Efficiency, Hydraulic coupling . Variable speed drive, 2250 kW	
			(3000 HP) 4160 V., 3600 RPM Motor	
Equipment Cooling Water Pumps	2		Horizontal, centrifugal, double suction, single	Ea. Full Size
			stage, cast iron case, bronze impeller, 0.015 m^3/s	
			(2365 GPM) @ 9.2m(30 ft.) head, 22.5kW (30 H.P.),	

EQUIPMENT LIST

(ELECTRICAL POWER GENERATION SUBSYSTEM)

PROJECT 100 MW Advanced Central Receiver

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EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
Equipment Cooling Water Pumps				
Cont'd			460 V., 1800 RPM motor	
Condensate Transfer Pumps	2		Horizontal End Suction, Centrifugal, Cast Iron	
			case, bronze impeller, single stage, 0.019 m^3/s	
			(300 GPM) @ 67m (220 ft.) head, 25 kW (30 H.P.),	
			460V., 3500 RPM motor.	
Low Pressure Heater No. 1	1		Horizontal, Shell & Tube, Carbon Steel shell,	ASME Code
			Stainless Steel Tubes, with drain cooler, 185m^2	Sect. VIII
			(1990 ft.^{2}) surface, 2.2 MPa (315 PSIA) Tube Design	
			Pressure, (Located in Condenser neck).	
Low Pressure Heater No. 2	1		Horizontal Shell & Tube, Carbon Steel Shell,	ASME Code
			Stainless Steel Tubes, with drain cooler, 197m^2	Sect. VIII
			(2120 ft.^{2}) surface. 2.2 MPa (315 PSIA) Tube	
			Design Pressure	
Deaerator Heater No. 3	1		Horizontal, Spray-Tray Type with internal stainless steel vent condenser and trays, 363,000 kg/hr	ASME Code
				Sect. VIII
			capacity, 0.005 cc/liter O_2 in Effluent,	

EQUIPMENT LIST
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EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
Deaerator Heater No. 3, Cont'd			Horizontal Storage Tank $62.5 m^3$ (16,500 gal.) capacity, 0.45 MPa (65 PSIA) Design Pressure.	
High Pressure Heater No. 4	1		Horizontal, shell & tube, carbon steel shell and tubes, with desuperheat section and drain cooler section, $266 m.^2$ ($2865 ft.^2$) surface, 20.7 MPa (3015 PSIA) Tube Design Pressure.	ASME Code Sect. VIII
High Pressure Heater No. 5	1		Horizontal, shell & tube, carbon steel shell and tubes, with desuperheat section and drain cooler section, $212 m^2$ ($2280 ft.^2$) surface, 20.7 MPa (3015 PSIA) Tube Design Pressure.	ASME Code Sect. VIII
High Pressure Heater No. 6	1		Horizontal, shell & tube, carbon steel shell and tubes, with desuperheat section and drain cooler section, $293 m^2$ ($3150 ft.^2$) surface, 20.7 MPa (3015 PSIA) Tube Design Pressure	ASME Code Sect. VIII
Condensate Storage Tank	2		$378 m^3$ (100,000 Gal.), Carbon Steel w/Plasite Lining 8.5m (28'-0") Dia. x 6.7m x (22'-0") Hi., Wt. 24,000 kg (53,000 lb.)	

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EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
Turbine Lube Oil Filter Set	1		Cartridge Type, Dual Filter Pump Set 0.057 m^3/min.	
			(15GPM). Gear Pump 0.5kW (3/4HP), 460V.-3Ph-60Hz.	
			Motor	
Turbine Lube Oil Purifier	1		Centrifuge Separator,0.057 m^3/min.(15 GPM), 0.75	
			kW (1HP), 460V.-3Ph-60Hz. Motor	
Turbine Lube Oil Storage Tank	1		22.7 m^3 (6000 Gal.), 2 Compartment, Carbon Steel	
			4.3m(14'-0") x 2.4m(8'-0")x 2.4m(8'-0"), Wt. 4,550	
			kg (10,000 lb).	
Turbine Lube Oil Transfer Pump	1		0.19 m^3/min. (50GPM) Gear Pump 0.75 kW (1HP) Motor	
Makeup Demineralizer System	2		0.38 m^3/min. (100 GPM) Capacity	Ea. Full Size
Inline Demineralizer System	2		0.076 m^3/s (1200 GPM) Capacity	Ea. Full Size
Cooling Tower Acid Tank	1		22.7 m^3 (6000 Gal), Horizontal 2.4m.(8'0") Dia x	
			(16'1") Str. Shell 0.95 cm. (3/8") PL, Wt. 3950 kg	
			(8700 lb)	
Cooling Tower Chlorinator	1		2,720 kg/day (6000 lb/day) V-Notch Chlorinator w/	
			Evaporator	
Cooling Tower Chem Feed Tank	1		0.19m^3 (50 Gal.), Type 304 Stainless Steel	
Bearing Water Heat Exch	2		Horiz Shell and Tube, Carbon Steel Shell, Cu-Ni	Ea. Full Size
			Tubes, 0.038 m^3/s (600 GPM)	
Cooling Tower Chem. Feed Pump	2		0.0075 m^3/hr (2 GPH), Posit. Displ. w/0.19kW (1/4	
			HP). D.C. Motor	Ea. Full Size

EQUIPMENT LIST

(ELECTRICAL POWER GENERATION SUBSYSTEM)

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EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
Bearing Cooling Water Pumps	2		Horizontal, End Suction Centrigufal, Single Stage,	Ea. Full Size
			22kW(30HP), 460V.-3Ph.-60Hz. Motor 0.038 m^3/s	
			(600 GPM) @ 39.6m (130Ft.) TDH	
Bearing Cooling Water Head Tank	1		Vertical Tank, 0.6m (2'-0") O.D. x 1.2m (4'-0") Hi	
Potable Water Pump	2		Horizontal, End Suction, Centrifugal, 0.19m^3/min.	
			(50GPM) @ 18.3m (60 Ft.) TDH, 1.1kW (1.5HP) Motor	
Potable Water Heater	1		0.57 m^3 (150 Gal.) Electric 440V.-3Ph.-60Hz.	
Potable Water Storage Tank	1		37.8 m^3 (10,000 Gal.) Vertical 3.65m (12'-0") Dia.	
			x 3.65m (12'-0") Hi (Lined) 0.95cm (3/8") PL Wt.	
			6800 kg (15,000 lb)	
Sewage Treatment Plant	1		4000 GPD, Aeration Unit	
Service Air Compressor	2		9.9 m^3/s (350SCFM) @ 0.79 MPa (115 PSIA), Recipro-	Ea. Full Size
			cating, Double Acting, Two Stage, 56kW(75HP)Motor	
Service Air Aftercooler	2		Shell and Tube Type with Moist. Separator	Ea. Full Size
Service Air Receiver	1		4.2m^3 (150 CU.Ft.) Carbon Steel ASME Code, Wt.	
			1720 kg (3800 lb)	
Instrument Air Compressor	2		8.5 m^3/s (300SCFM) @ 0.79MPa (115 PSIA), Recipro-	Ea. Full Size
			cating, Double Acting Single Stage, Oil-Free Air,	
			38kW(50HP) Motor, 460V.-3Ph.-60Hz.	
Instrument Air Aftercooler	2		Shell and Tube Type with Moist. Separator	Ea. Full Size

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(ELECTRICAL POWER GENERATION SUBSYSTEM)

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EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
Instrument Air Receiver	1		$4.2m^3$ (150 Cu.Ft.) Carbon Steel, ASME Code, Wt	
			1720 kg (3800 lb)	
Instrument Air Dryer	2		8.5 m^3/s (300SCFM) Desiccant Type, Dual Column,	Ea. Full Size
			Electric Regeneration, -40°C (-40°F) Dew Point,	
			ASME Code	
Instrument Air Prefilter	2		8.5 m^3/s (300SCFM) Cartridge Filter, ASME Code	
Instrument Air Afterfilter	2		8.5 m^3/s (300SCFM), Cartridge Filter, ASME Code	
Raw Water Clarifier (Lime Soft.)	1		0.11 m^3/s (1800 GPM), 15.2m(50'-0") Dia.	
Make-up Demineralizer Sand Filter	2		0.38 $m^3/min.$ (100 GPM), 2.0m (6'-6") Dia.	
Demineralizer Caustic Storage Tank	1		$22.7m^3$ (6000 Gal.) Carbon Steel, Horiz. 2.4m	
			(8'-0") Dia x 4.9m (16'-1"), Shell 0.95 cm. (3/8")	
			PL, Wt. 3950 kg (8700 lb)	
Demineralizer Caustic Pump	4		0.45 m^3/hr (120 GPH), Posit. w/0.56kW (3/4 H.P.),	
			460V-3Ph-60Hz Motor	
Demineralizer Acid Storage Tank	1		27.7 m^3(6000 Gal) Carbon Steel, Horiz. 2.4m (8'-0")	
			Dia. x 4.9m (16'-1") Shell 0.95 cm. (3/8") PL, Wt	
			3950 kg (8700 lb)	
Demineralizer Acid Pump	2		0.38 m^3/hr (100 GPH) Posit Displ w/0.56kW (3/4 HP),	In-line Demin.
			460V-3Ph-60 Hz Motor	
Feedwater Chem. Feed Tank	2		$0.19m^3$ (50 Gal.), Type 304 S.S., Hydrazine and Ammonia	

EQUIPMENT LIST

(ELECTRICAL POWER GENERATION SUBSYSTEM)

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EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
Feedwater Chem. Feed Pump	3		0.0075 m3/hr (2 GPH), Posit. Displ. W/0.19 kW (1/4 H.P.), 460V-3Ph-60 Hz Motor.	1 Spare
Fire Pump (Motor Driven)	1		0.095 m^3/s (1500 GPM) @ 97.5m (320Ft) TDH, Horiz. Centrifugal 150 kW(200HP), 460V-3Ph.-60Hz. Elect. Motor	NFPA Code
Fire Pump (Engine Driven)	1		0.095 m^3/s (1500 GPM) @ 97.5m (320 Ft.) TDH, Horiz. Centrifugal 150kW (200HP) Diesel Engine	NFPA Code
Jockey Pump (Fire Maint.)	1		0.19 m^3/min. (50 GPM) @ 97.5m (320 Ft) TDH, Horiz. Centrifugal 7.5 kW (10 HP) 460V.-3Ph.-60Hz. Motor	
Diesel Generator	2		500 kW Diesel Engine Generator Unit, 4160V.	Emerg. Shutdown
Station Battery	1		125 V.D.C., 400 Amp. - Hr.	
Battery Charger	1		75 Amp 125V.D.C./460V A.C. 3-Ph-60Hz.	
Evaporative Cooler	4		$33m^3$/s (70,000 CFM) EA. Unit	
Demineralizer Acid Pump	2		0.76 m /hr (200 GPH) Posit, Displ., 0.75kW(1 HP), 460V-3Ph-60Hz Motor	Makeup Demin.
Raw Water Pump	2		Vertical Turbine, 0.13 m^3/s (2000 GPM) @ 30.5m (100 Ft.), 56kW(175 HP) Motor	Ea. Full Size
Clarified Water Pump	2		Vertical Turbine, $0.12m^3$/s (1800 GPM) @ 24.4m (80 Ft.), 37 kW (50 HP) Motor	Ea. Full Size
Demineralizer Feedwater Pump	2		Horiz. End Suct., 0.016 m^3/s (250 GPM) @ 33.5m (110 Ft) 11.2kW (15 H.P.) Motor	

EQUIPMENT LIST

(ELECTRICAL POWER GENERATION SUBSYSTEM)

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PHASE I - CONCEPTUAL DESIGN

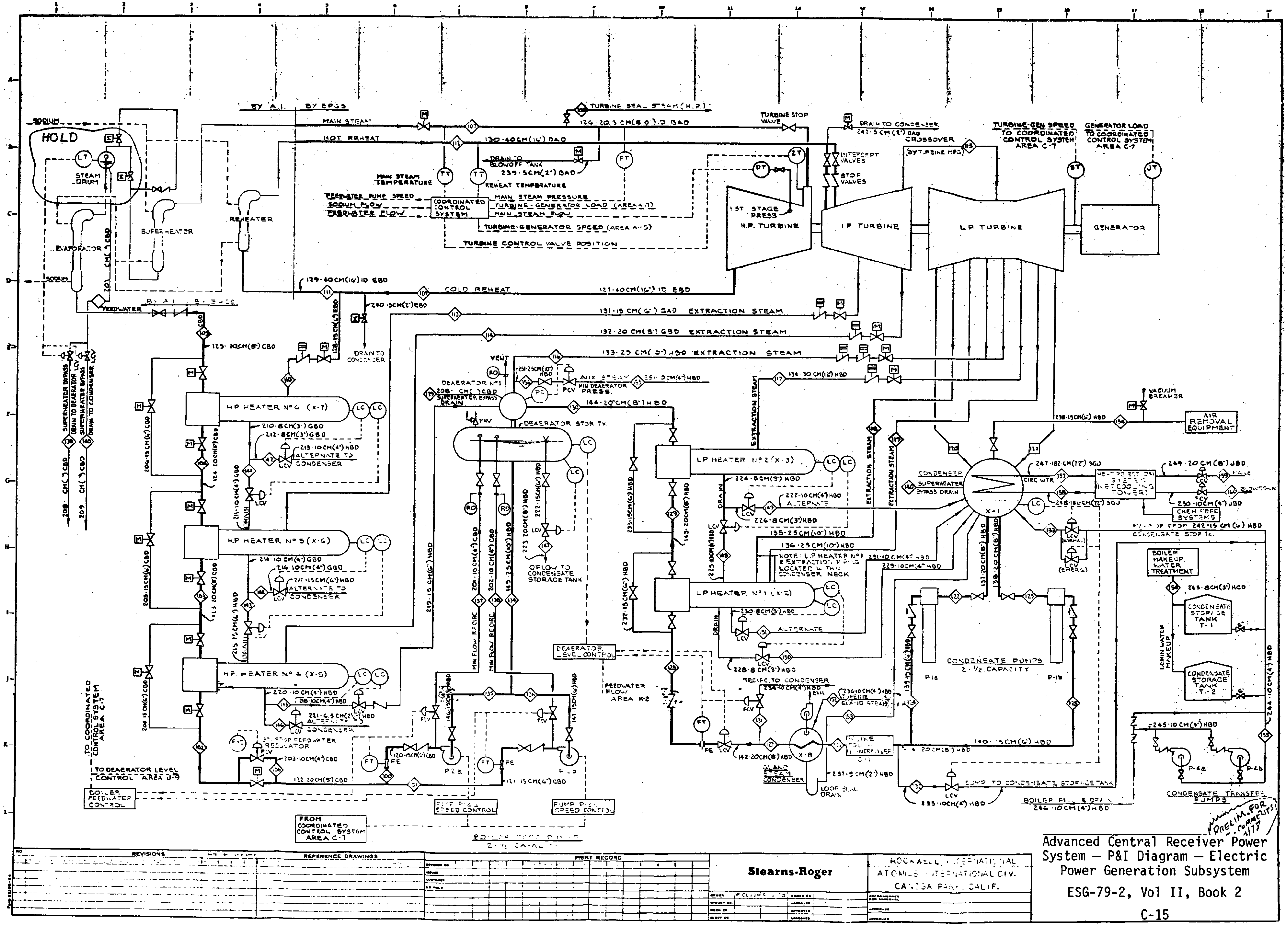
EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
Boiler Water Sample Panel	1		Boiler Water Sampling & Monitoring Panel	
Control Room Air Conditioner	1		40 Ton Chiller Unit	
Cooling Tower Acid Feed Pumps	2		0.01 m^3/hr (3 GPH), Posit. Displ., 0.56 kW (3/4	1 Spare
			HP), D.C. Motor	
Lime Silo	1		113 m^3 (4000 Cu. Ft.), 5.5m (18'-0") Dia. x 10.6m	
			(35'-0") Hi, carbon steel	
Lime Unloading/Conveying System	1 Lot		Railcar and/or Truck Lime Unloading System	
Lime Feeder	2		453 kg/hr (1000 lb/hr	1 Spare
Lime Slaker	2		453 kg/hr (1000 lb/hr	1 Spare
Clarifier Chem Feed Equipment	Lot		Polymer/Coagulant/Alum. Feed Equipment	
Turbine Room Crane	1		36,288 kg (40 Ton) Bridge Crane 15.2m (50'-0")	
			Span, 9,070 kg (10 Ton) Aux. Hook	
Aux. Steam Boiler	1		22,680 kg/hr (50,000 lb/hr), 310 kPa(45 PSIA),	
			Oil-Fired, ASME Code.	
Fuel Oil Storage Tank	1		Vertical Above Ground Tank, 7.6m (25'-0") Dia x	API Std 650
			5.5m (18'-0") Hi, 250 m^3 (65,940 Gal.) No. 2 Fuel	
			Oil	
Main Power Transformer	1		130 MVA, FOA, 115-13.2 kV, Wye Grounded-Delta	
Aux. Power Transformer	1		10.0/13.3/16.6 MVA, OA/FA/FA, 13.2-4.16 kV, Delta-Wye Resistance	
			Grounded.	
Start-Up Transformer	1		10.0/13.3/16.6 MVA, OA/FA/FA, 115-4.16 kV, Wye Grounded, Wye	
			Resistance ~~Grounded~~	

EQUIPMENT LIST
(ELECTRICAL POWER GENERATION SUBSYSTEM)

PROJECT 100 MW Advanced Central Receiver
CUSTOMER AI/DOE
PHASE I - CONCEPTUAL DESIGN

JOB NO. C-20325
REV./DATE 0 / 8-1-78
PAGE 11 **OF** 11

EQUIPMENT	QUANTITY	I.D. NUMBER	DESCRIPTION	REMARKS
4160 Volt Switchgear	1		Metal Clad Switchgear with 22-5kV, 1200A.,	
			250 MVA Circuit Breakers	
480 Volt Load Center	2		Load Center, Double-Ended, 2-1250 kVA,4160-480V. Transformers	
480 Volt Load Center	2		Load Center, Double-Ended, 2-1250 kVA,4160-480V. Transformers	
Outdoor Oil Circuit Breaker	1		121kV,1200 Amp., 20,000 Amp. short circuit current.	
Disconnect Switches	2		121kV,1200 Amp., 3 Pole Gang Operation	
Steel Structure	1		For 2-121kV, 1200 Amp. Disconnect Switches & Circuit Switcher	
Circuit Switcher	1		115kV, 1200 Ampere	
480 Volt Motor Control Center	2		Circuit Breaker & Circuit Breaker Combination Starters.	
480/120/208 V. Transformer	6		30kVA, Dry Type, 3 Phase	
120/208V. Distribution Panel	9			
D.C./A.C. Inverter	2		15kVA, 480 V., A.C., 3 Phase, 125 V.D.C.	
Isolated Phase Bus	1		15kV, 6000 Amp., with Surge Protection & V.T. Cubicle.	



PRELIM. FOR COMMENTS 1/17

Advanced Central Receiver Power System — P&I Diagram — Electric Power Generation Subsystem

ESG-79-2, Vol II, Book 2

APPENDIX D

DESIGN DATA SHEETS AND P&I DRAWING FOR 281-MWe COMMERCIAL PLANT DESIGN

CONTENTS:

281 MWe COMMERCIAL PLANT

RECEIVER SUBSYSTEM

ADVANCED CENTRAL RECEIVER SYSTEM
281 MWe COMMERCIAL PLANT
SUMMARY DATA
(Sheet 1 of 2)

Net Electrical Power MWe)	281
Parasitic Power (MWe)	
Daytime	31
Nighttime	16
Insolation (W/m^2)	950
Maximum Solar Power Absorbed (MWt)	1084
Nominal Solar Power Absorbed for Direct Operating (MWt)	723
Plant Net Efficiency (%)	25
Collector Field Configuration	Single 360°, North Biased
Solar Multiple, Equinox Noon	1.5
Number of Heliostats	40,591
Heliostat Shape and Size [m (ft)]	Square, 7.38 x 7.42 (24.2 x 24.3)
Number of Towers/Receivers	1
Land Area (acre)	2220
Receiver Mid-Point Elevation [m (ft)]	268 (879)
Receiver Configuration	External Cylinder
Number of Receiver Panels	24
Receiver Height and Diameter [m (ft)]	22.8 x 22.8 (74.8 x 74.8)
Receiver Maximum Heat Flux (MW/m^2)	1.94
Sodium Temperatures [°C (°F)]	288/593 (550/1100)
Receiver Sodium Flow Rate [kg/hr (lb/hr)]	10.2×10^6 (22.6×10^6)
Steam Generator Sodium Flow Rate (Direct Operation) [kg/hr (lb/hr)]	6.82×10^6 (15.0×10^6)

ADVANCED CENTRAL RECEIVER SYSTEM
281 MWe COMMERCIAL PLANT

SUMMARY DATA
(Sheet 2 of 2)

Thermal Storage Capacity (MWth)	2350*
Total Sodium Inventory [kg (lb)]	23 x 10^6 (50.4 x 10^6)
Steam Generator and Reheater Type	Modular Steam Generator
Steam Conditions [MN/m^2, °C (psia, °F)]	
Initial	16.6, 538 (2400, 1000)
Reheated	538 (1000)
Steam Flow Rate [kg/hr (lb/hr)]	
Daytime	9.3 x 10^5 (20.5 x 10^5)
Nighttime	8.80 x 10^5 (19.5 x 10^5)
TSS Sodium Flow Rate [kg/hr (lb/hr)]	6.82 x 10^6 (15.0 x 10^6)
Feedwater Temperature [°C (°F)]	242 (468)
Turbine Back Pressure [MN/m^2 (in. Hg)]	0.007 (2.0)
Heat Rejection [MW (Btu/hr)]	
Daytime	442 (1500 x 10^6)
Nighttime	420 (1430x 10^6)

*Includes 180 MWt for startup/shutdown

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DESIGN DATA SHEET

TITLE
281 MWe Commercial
Advanced Central Receiver
Receiver Subsystem

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		Receiver Subsystem					
		Nominal Thermal Power	MWt	723			
		Maximum Thermal Power	MWt	1084			
		Receiver Temperature					
		- In	^oC (^oF)	288 (550)			
		- Out	^oC (^oF)	593 (1100)			
		Flow Rate - Max Receiver	Kg/hr (lb/hr)	10.2×10^6 (22.6×10^6)			
		- Max Steam Generator	Kg/hr (lb/hr)	7×10^6 (15×10^6)			
		Volume of Sodium in Subsystem	m^3 (gals)	459 (121,400)			
		Weight of Sodium in Subsystem	kg (lb)	$.37 \times 10^6$ $(.823 \times 10^6)$			
		Pump Outlet Pressure	MN/m^2 (psia)	2.69 (390)			
		Pump Inlet Pressure	MN/m^2 (psia)	0.10 (15)			
		Total Radiation and Convection Loss	%	9% @ Peak Power 12.5% @ 50% Power			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Receiver Subsystem (Cont.)					
		Steam Generator Units Sodium Side					
		Superheat - Temp In	°C (°F)	593 (1100)			Tube and Shell Hockey Stick
		- Temp Out	°C (°F)	462 (864)			
		- Power	MWt	212			
		Reheat - Temp In	°C (°F)	593 (1100)			Tube and Shell Hockey Stick
		- Temp Out	°C (°F)	462 (864)			
		- Power	MWt	98			
		Evaporator - Temp In	°C (°F)	462 (864)			Tube and Shell Hockey Stick
		- Temp Out	°C (°F)	288 (550)			
		- Power Each Unit	MWt	206.5			Two Units
		Pumps - Number and Type		1			Fixed Speed, Double Suction Centrifugal, Single Stage
		Receiver - Size and Type	m x m (ft x ft)	22.8 x 22.8 (74.8 x 74.8)			External 24 Panel
		Large Valves, 97 cm (38) Block		2			CS, Riser and Pump Return
		97 cm (38) Check		1			CS, Riser
		71 cm (28) Block		1			SS, Downcomer
		61 cm (24) Control		1			SS, Superheater Control
		31 cm (12) Control		24			SS, Receiver Panel Control
		25 cm (10) Control		1			SS, Reheater Control

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TITLE 281 MWe Commercial Advanced Central Receiver Receiver Subsystem

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		<u>Receiver Subsystem</u> (Cont.)					
		Large Pipe Length, 97 cm (38)	m (ft)	488 (1600)			CS
		52 cm (22)	m (ft)	549 (1800)			CS and SS
		30 cm (12)	m (ft)	249 (500)			SS
		<u>Receiver Assembly</u>					
		Diameter	m (ft)	22.8 (74.8)			
		Height	m (ft)	22.8 (74.8)			
		Receiver Mid-Point Elevation	m (ft)	268 (879)			
		Receiver Maximum Elevation	m (ft)	280 (918)			
		Number of Absorber Panels		24			
		Receiver Weight					
		Total	Kg (lb)	611×10^3 (1.345×10^6)			
		Pressure Parts	Kg (lb)				
		<u>Absorber Panel</u>					
		Height	m (ft)	22.8 (748)			
		Width	m (ft)	3.0 (9.8)			
		Dry Weight, Pressure Parts	kg (lb)				
		Number of Tubes					
		Tube OD	cm (in.)				3.2 (1.25)
		Tube ID	cm (in.)				2.9 (1.15)

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Absorber Panel (Cont.)					
		Tube Material		CRES 304H			
		Solar Surface Coating		Pyromark			
		Panel Insulation	cm (in.)	15.2 (6)			Closed-Pore Fiberglass
		Thermal Expansion	cm (in.)	18.3 (7.2)			Flexible Tube Bends
		Absorptivity, Minimum		0.95			
		Peak Heat Flux$_2$ (Btu/in^2-sec)	MW/m^2	1.60			
		Outlet Temperature	^{o}C (^{o}F)	593 (1100)			
		Inlet Temperature	^{o}C (^{o}F)	288 (550)			
		Maximum Tube Surface Temperature	^{o}C (^{o}F)	635 (1175)			
		Tower Assembly					
		Construction					Slip Formed Concrete
		Concrete Height	m (ft)	248 (813)			
		Diameter - Base	m (ft)	(130)			
		- Top	m (ft)	(50)			
		Wall Thickness - Base	m (ft)	0.5 (1.7)			
		- Top	m (ft)	0.3 (.9)			
		Mat - OD	m (ft)	61 (200)			
		- ID	m (ft)	23 (75)			
		- Thickness	m (ft)	4 (13)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Riser</u>					
		Nominal Pipe ID	cm (in.)	97 (38)			
		Nominal Wall Thickness		TBD			
		Material		CS			
		Design Temperature	^{o}C (^{o}F)	371 (700)			
		Design Pressure ANSI B31.1		2.76 (400)			
		Maximum Flow Rate	kg/hf (lb/hr)	10.2×10^6 (22.6×10^6)			
		Velocity at Maximum Flow Rate	m/sec (ft/sec)	4.42 (14.5)			
		<u>Downcomer</u>					
		Nominal Pipe ID	cm (in.)	52 (22)			
		Nominal Wall Thickness		TBD			
		Material		304H			
		Design Temperature	^{o}C (^{o}F)	593 (1100)			
		Design Pressure ANSI B31.1		2.76 (400)			
		Maximum Flow Rate	kg/hf (lb/hr)	10.2×10^6 (22.6×10^6)			
		Velocity at Maximum Flow Rate	m/sec (ft/sec)	14.3 (46.9)			
		<u>Surge Tank</u>					
		Diameter	m (ft)	7.6 (25)			
		Height	m (ft)	4.5 (15)			
		Wall	cm (in.)	1 (.5)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Receiver Pump					
		<u>Physical Description</u>					
		Quantity		1			
		Number of Stages		1			Double Suction
		Height, w/motor	m (ft)	10.6 (35)			
		Tank Size	m (ft)	4 (13.7)			
		Inlet Nozzle	m (in.)	97 (38)			
		Outlet Nozzle	m (in.)	97 (38)			
		Dry Weight Pump	kg (lb)	117,132 (258,000)			
		<u>Motor</u>					
		Size	MW (hp)	13 (18,000)			
		Dimensions w/coupling	m (ft)	2.6/3.3 (8.6/11)			
		Voltage	v	4160			
		Cooling		TBD			
		Weight	kg (lb)	16 (30,000)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Pump Operating Conditions</u>					
		Developed Head	m (ft)	310 (1016)			
		Flow Rate	kg/hr (lb/hr)	10.2×10^6 22.5×10^6			
		Speed	rpm	1130			
		Temperature	^oC (^oF)	288 (550)			
		Sodium Volume	m^3 (gal)	10.3 (366)			
		NPSH	m (ft)	9.1 (30)			
		Speed Control	%	Fixed Speed			
		Pump Power (η = 78%)	kW (hp)	12.6 (17,000)			
		<u>Design Conditions</u>					
		Developed Head	m (ft)	325 (1066)			
		Flow Rate	m^3/s (gpm)	3.8 (60,000)			
		Speed	rpm	1130			
		Temperature	^oC (^oF)	300 (600)			
		NPSH (Minimum Required)	m (ft)	9.1 (30)			
		Code					Sect. VIII, Div. 1

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		Steam Generator-Evaporator					
		<u>Physical Description</u>					
		Quantity		2			
		Type					Tube & Shell Hockey Stick
		Height	m (ft)	29 (95)			
		Width	m (ft)	4.9 (16)			
		Shell diameter	m (in.)	1.6 (62)			
		Heat Transfer Area	m^2 (ft^2)	1812 (19500)			For each unit
		Number of Tubes		1530			For each unit
		Tube Size	cm (in.)	1.6 (5/8)			
		Tube Wall Thickness	cm (in.)	.21 (0.082)			
		Material		2-1/4 Cr - 1 Mo			
		Tubesheet Diameter/Thickness	cm (in.)	157/36 (62/14)			
		Weight	kg (ton)	82,000 (90)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Operating Conditions (Evaporator)</u>					
		Sodium Side:					
		Flow	kg/hr (lb/hr)	6.8×10^6 (15×10^6)			
		Inlet Temperature	^oC (^oF)	462 (864)			
		Outlet Temperature	^oC (^oF)	288 (550)			
		Pressure Drop	MN/m^2	0.207 (30)			
		Duty Each Unit	MWt	206			2 Units
		Water/Steam:					
		Flow	kg/hr (lb/hr)	0.92×10^6 (2.02×10^6)			
		Inlet Temperature	^oC (^oF)	242 (468)			
		Outlet Temperature	^oC (^oF)	364 (687)			
		Pressure	MN/m^2	19.50 (2830)			
		Pressure Drop	MN/m^2 (psi)	2.07 (300)			
		Design Conditions:					
		Pressure-Sodium Side	MN/m^2 (psi)	2.07 (300)			
		Pressure-Steam Side	MN/hr^2 (psig)	20 (2900)			
		Temperature	^oC (^oF)	482 (900)			
		Code					ASME Section VIII, Div. 1

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Steam Generator - Superheater					
		Physical Description					
		Quantity		1			
		Type					Tube & Shell Hockey-Stick
		Height	m (ft)	27.7 (91)			
		Width	m (ft)	4.57 (15)			
		Shell Diameter	m (ft)	1.02 (40)			
		Heat Transfer Area	m^2 (ft^2)	735 (7920)			
		Number of Tubes		620			
		Tube Size	cm (in.)	1.6 (5/8)			
		Tube Wall Thickness	cm (in.)	0.3 (0.135)			
		Material		SS 316			
		Tubesheet Diameter/Thickness	cm (in.)	1.01 x 28 (40	x 11		
		Weight	kg (ton)	38,000 (36)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Operating Conditions - Superheater					
		Sodium Side:					
		Flow	kg/hr (lb/hr)	4.6×10^6 (10.25×10^6)			
		Inlet Temperature	^oC (^oF)	594 (1100)			
		Outlet Temperature	^oC (^oF)	462 (864)			
		Pressure Drop	MN/m^2 (psi)	0.207 (30)			
		Duty (MWt)		210			
		Water/Steam:					
		Flow	kg/hr (lb/hr)	9.2×10^5 (2.02×10^6)			
		Inlet Temperature	^oC (^oF)	353 (668)			
		Outlet Temperature	^oC (^oF)	538 (1000)			
		Pressure	MN/m^2 (psig)	17 (2500)			
		Pressure Drop	MN/m^2 (psi)	1.77 (256)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Superheater</u>: (Continued)					
		Design Conditions:					
		Pressure-Sodium Side	MN/m^2 (psig)	2.07 (300)			
		Pressure-Steam Side	MN/m^2 (psig)	19.3 (2800)			
		Temperature	^{o}C (^{o}F)	593 (1100)			
		Code					ASME, Section VIII, Division 1
		Steam Generator - Reheat					
		<u>Physical Description</u>					
		Quantity		1			
		Type					Tube & Shell Hockey-Stick
		Height	m (ft)	21.9 (72)			
		Width	m (ft)	4.27 (14)			
		Shell Diameter	m (ft)	1.02 (40)			
		Heat Transfer Area	m^2 (ft^2)	521 (5610)			
		Number of Tubes		264			
		Tube Size	cm (in.)	3.49 (1-3/8)			
		Tube Wall Thickness	cm (in.)	0.28 (0.11)			
		Material		SS 316			

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Reheat (Continued)					
		Physical Description (Continued)					
		Tubesheet Diameter/Thickness	cm (in.)	101x15 (40x6)			
		Weight	kg (ton)	36,000 (40)			
		Operating Conditions					
		Sodium Side:					
		Flow	kg/hr (lb/hr)	2.15×10^6 4.74×10^6			
		Inlet Temperature	^oC (^oF)	594 (1100)			
		Outlet Temperature	^oC (^oF)	462 (864)			
		Pressure Drop	MN/m^2 (psi)	0.207 (30)			
		Duty	MWt	98			
		Water/Steam:					
		Flow	kg/hr (lb/hr)	8×10^5 (17.6×10^5)			
		Inlet Temperature	^oC (^oF)	342 (647)			
		Outlet Temperature	^oC (^oF)	538 (1000)			
		Pressure	MN/m^2 (psig)	3.36 (487)			
		Pressure Drop	MN/m^2 (psi)	.18 (26)			

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			UNIT	VALUE			
		Reheat (Continued)					
		Design Conditions:					
		Pressure-Sodium Side	MN/m^2 (psig)	2.07 (300)			
		Pressure-Steam Side	MN/m^2 (psig)	3.65 (530)			
		Temperature	^oC (^oF)	593 (1100)			
		Code					ASME, Section VIII, Division 1

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281 MWe COMMERCIAL PLANT
THERMAL STORAGE SUBSYSTEM
ALL-SODIUM STORAGE

Atomics International Division
Rockwell International

DESIGN DATA SHEET

TITLE 281 MWe Commercial
Advanced Central Receiver
Thermal Storage Subsystem

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TEN-TATIVE	FIRM	REFERENCES AND REMARKS
		Thermal Storage Subsystem					
		Storage Material		Sodium			
		Number of Tanks		2			
		Thermal Storage Capacity	MWt hr	2350			Includes 180 MW$_{th}$ for Startup and Shutdown (15 min. @ 723 MWt)
		Maximum Charging Rate	MWt	1084			
		Maximum Extraction Rate	MWt	723			
		Time at Maximum Extraction Rate	hr	3			
		Weight of Sodium in Subsystem	kg (lb)	22.16 x 10^6 (48.75 x 10^6)			
		Temperature - Hot Tank Storage	°C (°F)	593 (1100)			
		- Cold Tank Storage	°C (°F)	288 (550)			
		Pump - Number and Type		1			Variable Speed, Single Stage Centrifugal
		Large Valves - 97 cm (38) Block		2			CS and SS
		- 52 cm (22) Drag		1			SS
		Large Pipe Length - 97 cm (38)	m (ft)	91 (300)			CS, Standard Wall
		- 52 cm (22)	m (ft)	122 (400)			SS, Standard Wall

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Low Temperature Sodium Tank</u>					
		Number		1			
		Type					Cylindrical API Type
		Diameter	m (ft)	42.7 (140)			
		Height	m (ft)	213 (70)			
		Wall Thickness					
		Top	cm (in.)	0.64 (0.25)			
		Bottom	cm (in.)	4.4 (1.75)			
		Volume	m^3 (gal)	3.05×10^4 (8.05×10^6)			
		Tank Material					Carbon Steel
		Insulation, Roof and Walls	cm (in.)	15.2 (6)			Calcium Silicate with Aluminum Weather Protection
		Base Insulation	m (ft)	1 (3)			Perlitic Concrete
		Electric Preheat-Temperature Maintenance	kw	274			
		Low Sodium Temperature	^oC (^oF)	288 (550)			
		Ullage Maintenance Unit					
		Ullage Pressure	Pa (psi)	0.0069 (1)			
		Pressurization Media		Argon			

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Rockwell International

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TITLE 281 MWe Commercial
Advanced Central Receiver
Thermal Storage Subsystem

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>High Temperature Sodium Tank</u>					
		Type		Cylindrical API Type			
		Diameter	m (ft)	42.7 (140)			
		Height	m (ft)	21.3 (70)			
		Wall Thickness					
		Top	cm (in.)	0.64 (0.25)			
		Bottom	cm (in.)	4.4 (1.75)			
		Volume	m^3 (gal)	3.05×10^4 (8.05×10^6)			Includes capacity for receiver subsystem plus 10% ullage
		Tank Material					Type 304 SS
		Insulation, Roof and Walls	cm (in.)	30.5 (12)			Calcium Silicate with Aluminum Weather Protection
		Base Insulation	m (ft)	1 (3) Perlitic Concrete			
		Electric Preheat-Temperature Maintenance	kw	540			
		Number of High Temperature Tanks		1			
		High Sodium Temperature	^oC (^oF)	593 (1100^{o}F)			
		Ullage Maintenance Unit		Argon			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		STEAM GENERATOR PUMP					
		<u>Physical Description</u>					
		Quantity		1			
		Number of Stages		1			
		Height, w/motor	m (ft)	10 (34)			
		Tank Size	m (ft)	1.6 (5.4)			
		Inlet Nozzle	m (in.)	97 (38)			
		Outlet Nozzle	m (in.)	71 (28)			
		Dry Weight, Pump	kg (lb)	14,000 (31,000)			
		<u>Motor</u>					
		Size	MW (hp)	2.2 (3000)			
		Dimensions w/coupling	m (ft)	2.2 x 5 (7.2 x 17)			
		Voltage	v	4160			
		Cooling		TBD			
		Weight	kg (lb)	5556 (12,240)			

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			UNIT	VALUE			
		Pump Operating Conditions					
		Developed Head	m (ft)	65 (215)			
		Flow Rate	kg/hr (lb/hr)	7 x 10^6 (15 x 10^6)			
		Speed	rpm	1160			
		Temperature	^{o}C (^{o}F)	593 (1100)			
		Sodium Volume	m^3 (gal)	8 (2000)			
		NPSH	m (ft)	9.1 (30)			
		Speed Control	%	10-100			
		Pump Power (η = 85%)	MW (hp)	2.64 (2510)			
		Design Conditions					
		Developed Head	m (ft)	76 (250)			
		Flow Rate	m^3/sec (gpm)	2.63 (42,000)			
		Speed	rpm	1160			
		Temperature	^{o}C (^{o}F)	593 (1100)			
		NPSH (Minimum Required)	m (ft)	7.6 (25)			
		Code					Section VIII, Div. I

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Drag Valve</u>					
		Location					Upstream of High Temperature Sodium Storage Tank
		Type					Babcock-Wilcox Drag Valve with Velocity Control Elements Type SL 11
		Size (nominal)	inches	22			
		Flow Rate	$m^3/5$ (gpm)	3.79 (60,000)			
		Pressure Rate	mn/m^2 (psi)	2.24 (326)			
		Pressure Rating	mn/m^2 (psi)	3.44 (500)			
		Temperature	^oC (^oF)	649 (1200)			
		Flow Coefficient, C_v	$m^3/sec/\sqrt{mn/m^2}$ $(gpm/\sqrt{psi})$	2.52 (3323)			
		Operator					Yes--Type TBD
		Insulation	inches	8			Calcium Silicate
		Material					Stainless Steel; Inconel Velocity Control Elements
		Pressure Class					ANSI 2500 lb

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281 MW COMMERCIAL PLANT

COLLECTOR

Atomics International Division
Rockwell International

DESIGN DATA SHEET

TITLE ADVANCED CENTRAL RECEIVER COLLECTOR SUBSYSTEM (281 MWe SYSTEM)

NUMBER

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DATE August 20, 1978

NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		GENERAL					
		TOTAL FIELD AREA (EXCLUDING CENTRAL EXCLUSION)	$10^6 m^2$ $(10^6 ft^2)$	8.86 (95.3)			
		NUMBER OF HELIOSTATS	--	40,591			
		TOTAL MIRROR AREA	$10^6 m^2$ $(10^6 ft^2)$	1.989 (21.4)			
		PEAK POWER @ 950 w/m^2	MW	1,087			
		ANNUAL COLLECTABLE ENERGY	MWH_t	2.685×10^6			
		TOWER HEIGHT	m (ft)	249.5 (818)			
		RECEIVER CENTERLINE ELEVATION	m (ft)	268 (879)			
		HELIOSTAT ARRANGEMENT	--	RADIAL STAGGER			
		AIM STRATEGY	--	MULTI POINT VERTICAL AIM			
		PEAK RECEIVER HEAT FLUX	MW/m^2	1.60			

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COLLECTOR SUBSYSTEM
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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		HELIOSTAT					
		REFLECTOR SHAPE	--	RECTANGULAR			
		REFLECTOR ENVELOPE	m (ft)	7.38 x 7.42 (24.21 x 24.33)			
		MIRROR TYPE		SECOND SURFACE, SILVERED FUSION/FLOAT LAMINATED GLASS			
		MIRROR AREA	m^2 (ft^2)	49.05 (528)			
		AVERAGE REFLECTIVITY		0.91			
		DRIVE SYSTEM					
		ELEVATION		DUAL SCREW JACKS 3 ∅, 480V ac			
		AZIMUTH		HARMONIC DRIVE 3 ∅, 480V ac			
		REFLECTED BEAM ACCURACY	(mr)	2.83			
		DRIVE RATE					
		ELEVATION	Deg/min	15			
		AZIMUTH	Deg/min	15			

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		CANT RANGE	m (ft)	∞			
		ELECTRICAL DRAW					
		MOTOR RUNNING (STEADY STATE)	amp	1.5			
		MOTOR START SURGE CURRENT	amp	3.0			
		TIME AVERAGE POWER DRAW (PER HELIOSTAT INCL ELECTRONICS)	WATTS	~39			
		INDIVIDUAL HELIOSTAT AVAILABILITY	--	0.9999			
		<u>FIELD ELECTRONICS</u>					
		PRIMARY FEEDER POWER	VOLTAGE	4160			
		PRIMARY FEEDER CABLE	AWG	#4			
		SECONDARY FEEDER POWER	VOLTAGE	480			
		DATA NETWORK	--	FIBER OPTICS			

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281 MW COMMERCIAL PLANT

ELECTRIC POWER GENERATION

Atomics International Division
Rockwell International

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Turbine					
		Type Initial Pressure	MPa (psig)	16.5 (2400)			Tandum Compound, Double-Flow, Extraction, condensing Turbine
		Initial Temperature	^oC (^oF)	538 (1000)			
		Reheat Temperature	^oC (^oF)	538 (1000)			
		Rating	kWe	312,200			η = .4316
		Heater Extractions		7			
		Shaft Speed	rpm	3,600			
		Last Stage Bucket Size	cm (in.)	85.1 (33.5)			
		Throttle Flow Control Mode					Steam Generator/Turbine Coordinated Control
		Heat Rate	Btu/KWH	7,907			
		Generator					
		Generator Rating	(kVA)	365			
		Power Factor		0.9			
		Output Voltage	volts	22,000			
		Frequency	Hz	60			
		Cooling					Hydrogen Cooled
		Exciter					Static Excitation System
		Shaft Speed	rpm	3,600			
		Condenser					
		Type					Shell and Tube, 2-Pass
		Surface	m^2 (ft^2)	23,875 (257,000)			
		Tube Material		90-10 Copper-Ni			ASTM BIII, Alloy 706
		Tube Diameter OD		28.6 (1.125)			
		Tube Wall Thickness, 20 BWG [m (in.)]		0.89 (0.035)			

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			UNIT	VALUE			
		Condenser (Continued)					
		Tube Length, Effect	[m (ft)]	9.75 (32.0)			
		Condenser Pressure	[kPa (in.-HgA)]	6.77 (2.0)			
		Heat Rejection	[MW (Btu/hr)]	453 (1546×10^6)			
		Cooling Water Flow	[m^3/s (gpm)]	16.8 (266,500)			
		Water Velocity	[m/s (fps)]	2.1 (7.0)			
		Cooling Water In	[°C (°F)]	28.9 (84.0)			
		Cooling Water Out	[°C (°F)]	35.3 (95.6)			
		Condenser Air Removal		-			Mechanical Vacuum Pump (2-full capacity)
		Cooling Tower					
		Quantity		1			
		Type					Mechanical Draft, Cross Flow
		Number of Cells		15			
		Fan Motor Size	[kW (hp)]	5-150 (200)			
		Design Wet Bulb Temperature	[°C (°F)]	23 (74.0)			
		Cold Water Temperature	[°C (°F)]	28.9 (84.0)			
		Hot Water Temperature	[°C (°F)]	35.3 (95.6)			
		Circulating Water Flow	[m^3/s (gpm)]	17.4 (275,800)			
		Heat Rejection	[MW (Btu/hr)]	469 (1600×10^6)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Feedwater Heaters</u>					
		Low Pressure Heater Number	3				Horizontal, Stainless Steel Tubes, Carbon Steel Shell with Drain Cooler, Maximum Tube Side Pressure: 2.2 kPa (315 psia)
		Deaerator Number	1				Stainless Steel Trays and Vent Condenser, Carbon Steel Shell, Horizontal Condensate Storage Section 165 m^3 (43,600 gal) Pressure Rating; 0.45 MPa (65 psia)
		High Pressure Heaters Number	3				Horizontal, Carbon Steel Tubes, Carbon Steel Shell with Drain Cooler, Maximum Tube Side Pressure: 27.6 MPa (4,000 psia)
		<u>Feedwater Treatment</u>					
		Equipment					
		- Inline Polishing Demineralizers					2 Full-Capacity Units
		- Makeup Water Demineralizers					2 Full-Capacity Units
		Chemicals					
		- pH Control					Ammonia
		- Oxygen Scavenger					Hydrazine

FORM 706-A REV 2-74

281 MWe COMMERCIAL PLANT

MASTER CONTROL

Atomics International Division
Rockwell International

DESIGN DATA SHEET

PREPARED BY

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TITLE MASTER CONTROL (281 MW)

WBS NO.

NUMBER

PAGE 1

DATE 8-21-78

NEW REV	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
N	1	PLANT CENTRAL CONTROL CONSOLE (1)					
		LENGTH	FT.	25	X		
		DEPTH	FT.	2	X		
		HEIGHT	FT.	4	X		
N	2	CONTROL PROCESSORS (6)					
		THROUGHPUT	KOPS/SEC	350	X		
		PRIMARY STORAGE CAPACITY	16BIT WORDS	48,000	X		
N	3	SECONDARY CONTROL PROCESSOR STORAGE (6)					
		CAPACITY	MEGABITS	.25	X		
		ACCESS TIME	MSEC.	35	X		
		LATENCY	MSEC.	15	X		
N	4	HARDCOPY LOGGER (2)					
		CHARACTERS	PER LINE	132	X		
		SPEED	LINES/MIN	300	X		
N	5	RECORDERS, MAGNETIC (2)					
		DENSITY	BITS/INCH	500/800	X		
		SPEED	IN/SEC	45			
N	6	SAFING - CONTROL PANEL (1)	TBD	TBD			
N	7	SERIAL DIGITAL DATA BUS (2)					
		THROUGHPUT	KBITS/SEC	1500	X		
N	8	COLOR CRT DISPLAYS (6)					
		RASTER SCAN	NO. LINES	256 x 512	X		
		COLORS	NO.	4			

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Atomics International Division
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NEW REV	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
N	9	PID CONTROLLERS (100)					
		MICROPROCESSOR LOOP UPDATE RATE	PER SEC.	3	X		
		SCALING	%	0 - 100	X		
		RESOLUTION	BITS	12			
		OUTPUT	MV	4-20			
N	10	DISCRETE CONTROLLERS (125)					
		RESOLUTION	BITS	12	X		
		OUTPUT	MV	4 - 20			
N	11	ANALOG DATA ACQUISITION (350)			X		
		NORMAL RATE	CHAN/SEC	350			
		EMERGENCY RATE	CHAN/SEC	200,000			
		RESOLUTION	BITS	12			
		MULTIPLEXING	TYPE	SEQUENTIAL			
N	12	ANALOG OUTPUTS (TBD)	TBD	TBD	X		
N	13	CLOSED CIRCUIT TELEVISION (4)			X		
		MONITOR SIZE	IN	19			
		CAMERA	TBD	TBD			
		AUTO PAN/TILT	DEGREES	90			
		ZOOM	TBD	TBD			
N	14	UNINTERRUPTIBLE POWER SOURCE					
		10 INPUT	VAC	115 ± 10%			
		REGULATED 10 OUTPUT	VAC	115 ± 2%			
		STORAGE BATTERY CAPACITY	HRS	.5			
		DERATED POWER	KVA	TBD			

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		WBS NO.	DATE 8-21-78

NEW REV	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
N	15	TIME OF DAY REFERENCE					
		INPUT-WWV SYNCH.	HERTZ	1000	X		
		OUTPUT - TIME OF DAY BCD FORMAT	BITS	32	X		
N	16	ANNUNCIATOR PANEL	FUNCTIONS	25	X		
N	17	LOCAL WEATHER STATION WIND			X		
		BAROMETRIC PRESSURE	MPH	80			
			DEGREES	360			
		HUMIDITY	IN/HG	26 - 34			
		SOLAR RADIATION	PERCENT/REL	0 - 100			
		PRECIPITATION	9M/CM^2/MIN	.36 - 2.0 MICRONS			
		TEMPERATURE	IN	20			
			DEG F	-15, +50			

FORM 106-A REV 2-74

APPENDIX E

STEAM GENERATOR SYSTEM CONCEPTUAL DESIGN

AI Technical Information

Document N272TI000002

APPENDIX E

Rockwell International
Atomics International Division

SUPPORTING DOCUMENT

NUMBER
N272TI000002

REV LTR/CHG NO.
SEE SUMMARY OF CHG

PROGRAM TITLE
Advanced Central Receiver Power System (ACRPS)

DOCUMENT TYPE
Technical Information

KEY NOUNS
Solar, Steam Generator

DOCUMENT TITLE
Steam Generator System Conceptual Design

ORIGINAL ISSUE DATE
March 8, 1978

GO NO.	S/A NO.	PAGE 1 OF 30 TOTAL PAGES 31
09272	12000	REL. DATE 3-9-78 BK

PREPARED BY/DATE — DEPT — MAIL ADDR
M. J. Gabler MJ Gabler

IR&D PROGRAM? YES ☐ NO ☒ IF YES, ENTER TPA NO.________

APPROVALS — DATE
E. Moody 2/27/78
TLJohnson 3/2/78
3/7/78

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ABSTRACT

The conceptual design of the steam generator modules for the ACRPS is presented. Supporting materials used in the selection of the reference steam cycle are included. The ACRPS employs liquid sodium as a heat transfer medium, so the steam generators are sodium heated.

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FORM 734-C REV. 11-75

CONTENTS

FORM 719-P REV. 3-75

I. INTRODUCTION

This study considers various aspects of the steam generator system for the Advanced Central Receiver Power System (ACRPS). The ACRPS employs sodium as a heat transfer medium, so the steam operators are sodium heated, Requirements for the steam generator system are somewhat similar to those of the Liquid Metal Fast Breeder Reactor (LMFBR) systems resulting in a broad base for design of the steam generator system for the ACRPS. However, the ACRPS steam generator application places some new requirements on the steam generator system and on the steam generator modules in particular. These requirements in the areas of steam cycle, transients, startup/shutdown, and component design are discussed in this report.

II. STEAM CYCLE CONSIDERATIONS

A. PAST TRADE STUDIES

Previous trade studies and applicable reports on the subject of reheat and steam cycle selection were reviewed. The earlier AI studies always showed the sodium reheat cycle to be the most advantageous, but the desire for a high probability of success led DOE to select a non-reheat cycle approach in 1972 for the demonstration plant. Since that time sodium reheat has not been seriously considered by AI for LMFBR application. A brief synopsis of several reports and trade studies follows.

1. "Reheat vs Nonreheat Trade Study," November 1971 (Reference 1)

This trade study compared sodium reheat, steam reheat, and nonreheat cycles with the objective of presenting relative merits regarding the selection of the steam cycle for the FBR Demonstration Plant. The sodium reheat cycle was shown to have advantages relative to (1) efficiency and (2) capital and operating costs relative to the steam reheat and nonreheat. The steam reheat cycle traded off risk in sodium components for risk in steam components, while the nonreheat cycle was shown to have an advantage in control and operational simplicity.

The study considered five cycles:

1) sodium reheat (2500 psig/900°F/900°F)
2) live steam reheat (2400 psig/900°F/635°F)
3) extraction steam reheat (2400 psig/900°F/600°F)
4) no reheat (2400 psig/900°F)
5) no reheat (1450 psig/900°F)

The fourth cycle, high pressure/nonreheat, was eliminated due to required turbine development and external moisture separator complexity required for that cycle. The fifth cycle, low pressure/nonreheat, was found to require the minimum overall sodium-to-steam heat transfer surface area due to larger sodium-to-steam temperature difference.

It was concluded that the only cycle considered that could employ a standard turbine was the sodium reheat cycle. The other cycles would require significant changes to standard turbine designs.

The report also summarized previous studies, showing that most prior studies had concluded that commercial plants should employ sodium reheat because of improved overall economics. This summary is presented in Table 1.

2. <u>"Status of LMFBR Reheat in Western Europe – 1972" (Reference 2)</u>

This trip report discussed the findings of a US delegation during a trip to France, Germany, Netherlands, and UK. The purpose of the trip was to determine the status of European LMFBR sodium/steam cycles as input to US selection for the Demonstration Plant (CRBRP).

Initial use of sodium reheat by the Europeans was based upon the availability of turbines. (As noted in the prior trade study, sodium reheat was necessary to utilize a standard turbine.) Subsequent reevaluation of the selection of sodium reheat was made by the SNR consortium and the French, and showed both economic and reliability advantages

TABLE 1. : SUMMARY OF PREVIOUS STEAM CYCLE STUDIES

STUDY	ALTERNATIVES CONSIDERED	PREFERRED CYCLE		REMARKS
		Demonstration Plant	Commercial Plant	
United Engineers 500 Mw and 1000 Mw 1966 - Ref. 3	Sodium Reheat { 1. 3500/1000/1000 2. 2400/1000/1000 3. 2400/950/950 4. 1800/900/900 Non-Reheat { 1. 1450/1000 2. 1000/Dry and saturated	Sodium reheat: 2400/1000/1000 (lowest $/kw)	-Same-	
Westinghouse 1000 Mw 1968 - Ref. 4.	Sodium Reheat (2400/900/900) Non-reheat (2400/900) Steam Reheat (2400/900/TBD) less depth		Non-Reheat (2400/900), with external and internal moisture separation	Sodium reheat case penalized since steam generator combined evaporator and superheater (small LMTD in reheater). See also Ref. 6, 10, below. Steam reheat was ~ same as non-reheat, ∴ non-reheat selected. Cross compound turbine for sodium reheat (3600/1800 rpm), tandem compound for non-reheat (further penalizes cost of sodium reheat).
Brown-Boveri 500 Mw 1968 - Ref. 5	Sodium Reheat (2400/900/900) Evaporator Steam Reheat (2400/900/635)	Sodium Reheat: 2400/900/900		Evaporator Steam: { (Best steam cycle (Brown Boveri) (Worst steam cycle (Bechtel - Ref. 9)
AI - Internal Report 500 Mw 1968 - Ref. 6	Sodium Reheat (2400/900/900) Non-Reheat (2400/900)	Sodium Reheat: 2400/900/900		Non-reheat preferred if evaporator and superheater are combined into single unit (see also Ref. 2 above)
Babcock and Wilcox 1000 Mw 1968 - Ref. 7	Sodium Reheat { 1. 3500/1000/1000 2. 2400/1000/1000 3. 2400/950/950 4. 1800/900/900 Live Steam Reheat (2400/950/850) Non-Reheat { 1. 2400/950 2. 1450/1000 3. 1000/dry and saturated		Sodium Reheat: 2400/950/950	Only brief attention to steam reheat and here they put the high pressure steam (2300 psig) on the shell side....? Reactor outlet temp. varied from 1050 to 1150F. There exists a "definite incentive for reheat" for the 2400/950/NRH cycle.
General Electric 1000 Mw 1969 - Ref. 8.	Sodium Reheat (2400/950/950) Non-Reheat (2400/variable (975F optimum)		Sodium Reheat: 2400/950/950	Separate evap/sup. allowed optimum Na reheater arrangement.
Bechtel 500 Mw 1970 - Ref. 9	Sodium Reheat (2400/900/900) Live steam reheat (2400/900/635) Internal steam reheat (2400/900/600) Evaporator steam reheat (2400/900/635)	Sodium Reheat: (2400/900/900)		"While the sodium reheat cycle is more complex than a non-reheat cycle, the control problems involved appear to be manageable." Internal reheat is the "best" steam steam reheat cycle and is still inferior to a non-reheat cycle. (Reason appears to be mainly due to low capital cost estimate from W on turbine price quote).
Westinghouse 1000 Mw 1971 - Ref. 10	Many (15 total): All variations of sodium reheat, including recirc. vs. once-through, combined vs. separate evap/superheater. Also, internal steam reheat and non-reheat (no moisture separator since it's 2400/1000)			Only a new steam generator concept was recommended (modular units, J-tube, separate evap/S.H. modules). This report also summarizes principal reasons why conclusions in Ref. 4 above are no longer valid. (Early once-through, single shell, serpentine tube steam generator not advised anymore).

TABLE 1. : SUMMARY OF PREVIOUS STEAM CYCLE STUDIES (Cont.)

STUDY	ALTERNATIVES CONSIDERED	PREFERRED CYCLE		REMARKS
		Demonstration Plant	Commercial Plant	
Keratoom (SNR) 300 Mwe 1971 - Ref. 11	Sodium Reheat (2400/930/930) Live Steam Reheat (2400/930/785) Internal Steam Reheat (2400/930/590) Non-reheat (2400/930 + External Moist. Sep.) Non-reheat (2400/930 + Internal moist. sep.)	"Push"		"As there are no major technical difficulties in the cycles compared here, the choice has to be based on the kw-hr price". Authors' opinion is that sodium reheat should be discarded since economics is a draw.
General Electric 350 Mwe 1971 - Ref. 12	Sodium Reheat { 1. 2400/900/900 2. 1800/900/900 3. 1450/900/900 Non-Reheat { 1. 2400/900 2. 1800/900 3. 1450/900	Non-Reheat (1450/900)		Economics favored 1800 & 2400 psig sodium reheat systems. Concept selected was more costly than four others. Reason stated was "conservative design, favoring reliability over economics." Note: Least expensive system in trade study had 1050F reactor outlet, 900F initial and reheat steam, at 2400 psig employing sodium reheat.
French (CEA et al), - Geneva Conference - 1971 - Ref. 13	?	Sodium Reheat: (Phenix)	Two steam cycles are suitable for fast reactor plants: 1. Sodium reheat (a'la Phenix) 2. Internal steam reheat	"The choice can only be made by studying the power plant as a whole and preliminary steam generator studies have been conducted around the two solutions."
European Trip Report - AEC Components Team (France) 1971 - Ref. 14	—		Indications are that 1000 Mwe commercial plants will not use sodium reheat	The alternate to be selected was apparently not mentioned. They will keep temperatures down and probably use ferritic metals for both evap. and superheater. (Recent French visitors to AI, however, see no reason to drop sodium reheat since tests at Le Renardieres have revealed no technical problem areas).
Interatom (SNR) 300 Mw, 1000 Mw -Geneva Conference 1971 - Ref. 15, 16	Sodium Reheat (2500/variable/variable-5 cases) Live Steam Reheat (2500/950/?) Thermal drying (after IP stage) with extraction steam (2400/875-900/sat.(?) Non-Reheat (1765/950)	Thermal drying: 2500/930/sat.(?)	-same-	Until recently SNR was to employ sodium reheat recent Trip Report (see Ref. 14) indicated that they plan to drop it. "In spite of the reduced efficiency, the cost savings with thermal drying or steam reheat are larger than with sodium reheat. This is true if one uses the expected fuel costs of large breeders as the basis."
Westinghouse 350 Mw 1971 - Ref. 17	?	Non-Reheat: (2400/900) with two external moisture separators		Unless HP steam expands all the way down to ~25-50 psia, there is not sufficient moisture to merit removal. Since these pressures are far removed from conventional practice (~180-200 psi), the whole cycle is somewhat "suspicious."
	Totals (Where applicable):	Sodium Reheat: 5 Non-reheat: 2 Thermal Drying: 1	Sodium Reheat: Internal Steam Reheat: Thermal Drying: Non-Reheat	4-5 1 1 1-0

of steam reheat over sodium reheat. Nonreheat was considered too costly an option.

Turbine development for steam reheat was not considered to be a significant problem, and in fact a steam reheat turbine was considered to be lower in cost than a sodium reheat turbine.

3. "Steam Pressure Selection for Demonstration Plant," January 1973 (Reference 3)

This trade study assessed the effects of steam pressure on the steam generator design and performance, and recommended a reference AI steam pressure for CRBRP. Sodium reheat was excluded from consideration, but not based upon AI's technical conclusions. Nonreheat, extraction-steam reheat, and main-stream reheat were considered. Steam pressures of 1450, 1800 and 2400 were considered.

The recommended steam cycle for the Demonstration Plant was 2400 psig/900°F with extraction steam reheat. The second choice was the 1450 psig/900°F nonreheat cycle (which was selected for CRBRP by WARD).

Main-steam reheat was rejected because of the opinion that the higher temperature and pressure moisture separator/steam reheater design represented considerable extrapolation from proven LWR experience. High pressure (above 1800 psi) nonreheat was rejected because of high moisture in the turbine exhaust.

4. "PLBR/CBR Design Point Trade Study," July 1976 (Reference 4)

This trade study selected the design point for PLBR, Phases I and II. The design point was selected based upon detailed evaluation of economics, safety and licensability, reliability and availability, maintainability, inspectability, operability, risk, development requirements, and schedule. From a consideration of all these constraints, reactor outlet temperature, steam cycle, and material selections were made. Reactor outlet temperature was the dominant feature selected, and steam cycle was selected second. The steam cycle studies excluded sodium reheat, as a result of the general swing away from sodium reheat throughout the world, and the desire of DOE not to consider sodium reheat for the commercial LMFBR program. Steam reheat and nonreheat cycles were considered ranging in steam pressure from 1300 to 2400 psig and in steam temperature from 750 to 950°F.

The selection of reactor outlet temperature included consideration of overall economics, fuel cycle cost and breeding gain variations, upper internals considerations, reliability and availability, maintainability, and structural analysis. Economics, including fuel cycle costs and the effects of unavailability and inelastic analysis, favored operation at the highest possible reactor outlet temperature (1050°F). Optimizing the breeding gain for mature CBR's with advanced cladding alloys suggested a reactor outlet temperature of about 940-950°F. Upper internals problems favored low temperature operation. The component activity due to mass transfer in the primary loop is minimized at low reactor outlet temperatures. The design flexibility consideration suggested a reactor outlet temperature of 950°F or lower. Also, the plant should generally be easier to license at lower temperatures. Considering all these factors, a reactor outlet temperature of 950°F was selected for PLBR/CBR as the best compromise. (Subsequent program decisions modified this number to 930°F.)

Economic optima for the various steam cycles studied are shown in Figure 1. For the recommended PLBR/CBR reactor outlet temperatures of 950°F, optimum economics narrow the desirable steam cycles to those with the following turbine conditions:

1) 2400 psig/800-850°F steam
2) 1800 psig/800-850°F steam
3) 1100 psig/saturated steam

The prime advantage of the 1100 psi cycle is that is uses available LWR turbine technology. However, this cycle was rejected because of (1) the desire to utilize the developed LMFBR steam generator technology, (2) to minimize steam generator tube wall thermal stress, and (3) to minimize thermal pollution.

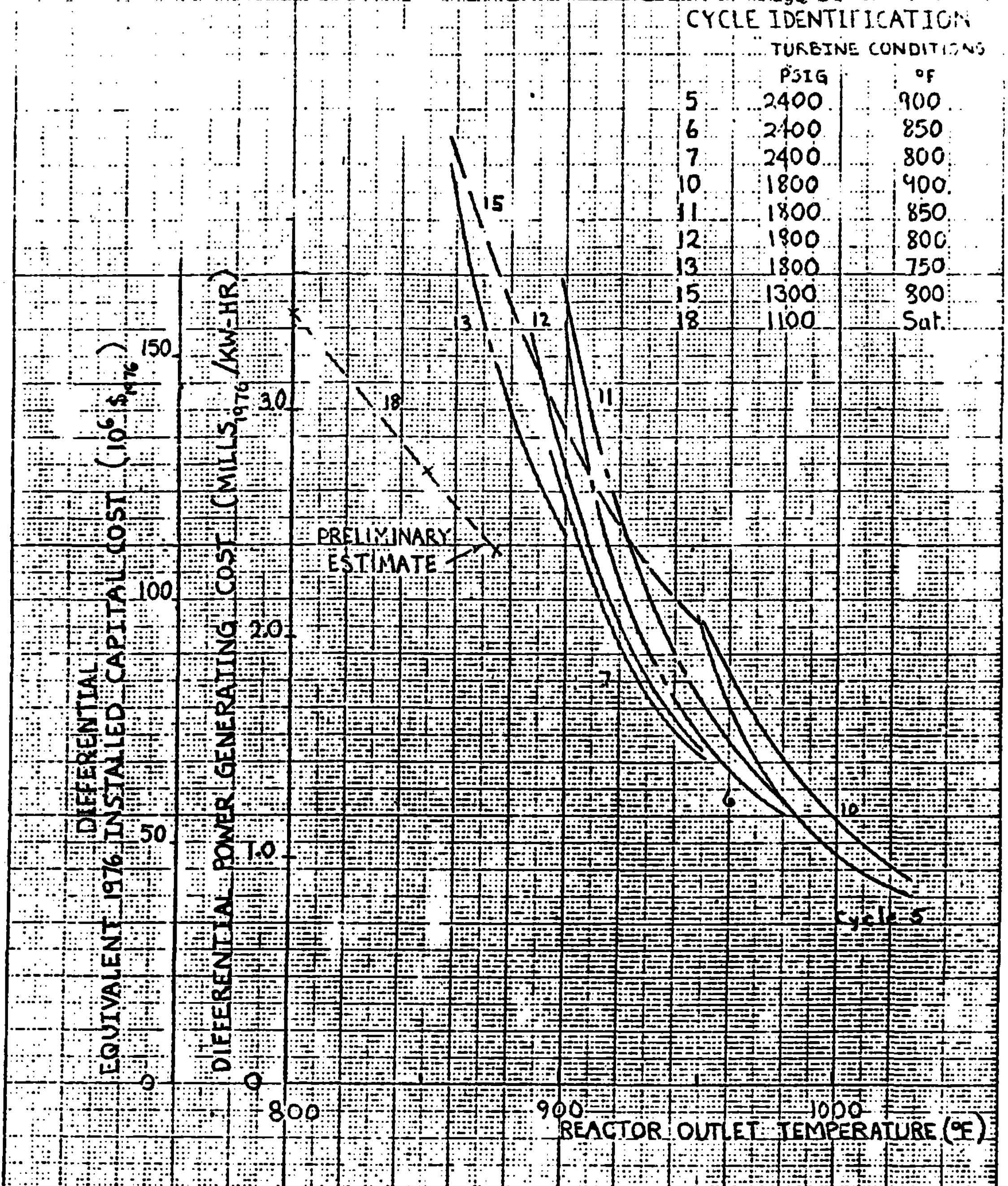


FIGURE I.1
ECONOMIC COMPARISON OF SS SYSTEMS

In the remaining cycles, 850°F steam is preferred over 800°F steam because thermal stresses, thermal pollution and plant control requirements are minimized. Factors affecting the pressure selection include relative economics, steam generator tube-to-tubesheet weldability and turbine generator availability. Relative economics, as seen in Figure 1, slightly favor the 2400 psi cycle (5.5 x 10^6 1976 dollars). Only Allis Chalmers has indicated interest in developing a large 1800 psi/850°F tandem compound turbine for delivery to PLBR/CBR whereas Allis Chalmers, GE, and Westinghouse all indicated that they could supply 2400 psi tandem compound turbines. Therefore, it appears at present that a 2400 psi/850°F turbine with steam reheat would be preferrable. (Subsequent program decisions resulted in a selection of 2200 psig/850°F steam conditions.)

B. CONSIDERATIONS FOR ARCPS STEAM CYCLE SELECTION

Due to the relatively high capital cost of the ARCPS, high efficiency is a strict necessity. For this reason, high temperatures and sodium reheat are strongly favored. The selection of the 2200 psi/850°F steam cycle with steam reheat for PLBR is based upon significantly different requirements, and thus is not necessarily indicative of the direction in which the ARCPS stream system should proceed.

Consideration of four factors is made here for use in steam cycle selection in the ARCPS:

1) Steam generator material selection
2) Effect of sodium reheat/steam reheat/non reheat
3) Benson vs Sulzer Cycle
4) Steam cycle pressure

1. Steam Generator Material

The structural materials listed in Table 2 are considered as candidate materials for steam generator construction. Reviews of alternate structural materials are given in References 4, 5, and 6. The selection of material for the ARCPS steam generator modules is more difficult than for the current

TABLE 2
STRUCTURAL MATERIAL CANIDATES

Ferritic	2-¼ Cr - 1 Mo, unstabilized Advanced Ferritics (9 Cr)
Austenitic	304 stainless steel 316 stainless steel
Nickel Base	Alloy 800 H

generation of LMFBR's since the trend there is to lower temperatures (<900°F) in the steam generator system, while for ARCPS the desired temperatures are 1100°F sodium and 1000°F steam.

Unstabilized 2-1/4 Cr - 1 Mo ferritic material has had the greatest application in LMFBR steam generators both in the U.S. and abroad. This is due to its excellent chloride stress corrosion cracking (SCC) resistance, thermal properties, relative economics, and experience. It is ASME coded to 1200°F, but due to poor properties at the higher temperatures it has little design application for normal operating temperatures in excess of 950°F. For this reason, it is unacceptable as a material in the ACRPS steam generator modules except for use in an evaporator module.

Advanced ferritic materials have been extensively used in European steam generators. The advanced ferritic alloys of interest are 8-14%-Cr. Specifically, the European alloys are 9 Cr alloys (R-8 and EM-12) and 12 Cr alloys (HT-9). A development program (Reference 6) at CE is being conducted to optimize the 9-12 Cr ferritic steel composition. CE has found that EM-12 and HT-9 have excessively low ductility. This and other factors such as poor weldability and higher Cr usage have eliminated the 12 Cr alloy from consideration. At present, the CE study indicated 9 Cr - 1 Mo to be the preferred candidate.

The advanced ferritic 9 Cr - 1 Mo appears to be an attractive alternate to 2-1/4 Cr - 1 Mo for temperatures in excess of ~900°F. The limiting design temperature for 9 Cr - 1 Mo is higher than that for 2-1/4 Cr - 1 Mo, but may not be much over 1000^{O}F. Thus, it is not clear whether the 9 Cr - 1 Mo alloy would be acceptable for other than evaporator application. In addition, 9 Cr - 1 Mo will probably take 5-10 years to develop as an ASME Section III Class 1 material. While the steam generator for the ACRPS system will probably be designed to Section VIII of the code, critical components in the steam-sodium pressure boundary will be analyzed to the intent of 1592, so a complete set of material properties will be required. Advantages of 9 Cr - 1 Mo relative to 2-1/4 Cr - 1 Mo include similar SCC resistance, higher strength, similar conductivity, and less inelastic analysis.

The austenitic materials, types 316 and 304 stainless steel, are excellent materials for the ARCPS steam generators from the standpoint of the high operating temperature. In addition, they are state-of-the-art steels with well established records. A significant problem exists with austenitic materials — they are prone to chloride and caustic SCC. This requires that if they are used in a steam generator application, careful consideration must be given to water chemistry. Slight through wall cracks in a sodium-heated steam generator have been shown to grow, and eventually lead to sudden large leaks (Reference 7). Under normal operating conditions the feedwater in a plant can be controlled to maintain very low chlorine content, but off normal operation and startup would make use of austenitics in the evaporator module unwise. The use of austenitics would be feasible in a superheater or reheater unit if special precautions were taken. Since chlorine is almost insoluable in steam, a steam separator could be used to minimize the amount of carryover by water droplets from the evaporator to the superheater. In addition, protective sleeves could be used in the steam inlet end of the superheater and reheater to collect the remaining chloride carried over into these units.

The nickel based alloy 800H provides both elevated temperature strength and improved resistance to chloride stress-corrosion cracking.

The resistance to SCC is higher than that of the austenitics, but worse than that of 2-1/4 Cr - 1 Mo. Thus, it would seem that the same SCC protective measures would be taken for alloy 800H as would be applicable to the austenitics. Also, the cost of alloy 800H is significantly greater than that of the other materials. While prototype material costs would not vary significantly with alloy selection, the costs for multiple plant unit type production are expected to vary as shown in Table 3. Material costs for alloy 800H appear to be excessive, and alloy 800H doesn't appear to have a significant advantage over stainless steel.

Considerations for material selection are summarized in Table 4.

TABLE 3
RELATIVE MATERIAL COSTS

Material	Material Cost	Fabrication Cost
2-1/4 Cr – 1 Mo	1.0 (base)	1.0 (base)
9 Cr – 1 Mo	2.0	1.0
316 stainless steel/304 stainless steel	2.0	0.8
Alloy 800H	6.0	0.8

2. Reheat

Reheat, and in particular sodium reheat, is evaluated in this study from the standpoint of its effect on steam generator design. Sodium reheat is considered necessary, along with high inlet temperatures, to produce high efficiencies and minimize the capital cost of the plant. The steam cycles considered in this study have gross efficiencies from 42 to 44%, utilizing 1100°F sodium to produce 1000°F steam and a single reheat.

The use of a second, low pressure reheat stage could be employed to boost efficiency, or alternatively decrease sodium temperatures without decreasing efficiency. For example, a cycle has been designed (Reference 8) that would produce 42% efficiency with a sodium inlet temperature of

TABLE 4

STEAM GENERATOR MATERIAL CONSIDERATIONS

	2-1/4 Cr – 1 Mo	9 Cr – 1 Mo	I-800H	Type 304ss/ 316ss
Current Status	Widely used and accepted for LMFBRS or application	Being Developed be CE Use in Europe (EM12)	Limited use in steam generators	Some use in steam generators
ASME Code Approvel	Yes	No	Yes	Yes
CREEP Properties	Poor	Fair?	Good	Good
Operating Temperature Limit (for practical design)	950^{0}F	1100	1200	1200
SCC Resistance	Virtually immune	Virtually immune	Better than austenitics	Very sensitive—chloride or caustic
Metallurgical Stability in Sodium	Decarburizes, which lowers design properties	Good	Good	Good
Compatibility with S.H. Steam	Excellent	Good	Good	Good (if no chloride carryover)
Compatibility with Feedwater	Excellent	Good	Poor-Fair	Poor
Cost	Low	Medium	High	Medium

900^{o}F and two reheat stages. Such a cycle would allow use of 2-1/4 Cr - 1 Mo throughout much of the sodium systems, but would increase the size of the heat storage system. Additionally, the low pressure reheater would require a new design, perhaps looking similar to a FFTF DHX, and the turbine may require development if a second reheat stage is not standard.

3. Optimization

Optimization studies were performed for three representative steam cycles selected from Reference 9, which are presented in Table 5. The cycles are called the 2400, 1800, and 1450 psig cycles in this report. The steam generator module designs were optimized for these three cycles on the basis of capital cost. The steam generator designs were calculated using the STEAM subroutine of SOC—II, and the capital cost were calculated with the COSTSG subroutine of SOC—II (Reference 10). The following assumptions were made in the optimization process:

1) Evaporator material is 2-1/4 Cr - 1 Mo.
2) Reheater and superheater material is either 316 SS or I-800H.
3) Only costs considered are the evaporator, superheater, and sodium reheater.
4) The efficiency with and without sodium reheat is assumed the same for purposes of sizing and costing the steam generator modules since this information was not available. This produces a maximum error of 5% for a 2% efficiency improvement.

Three system arrangements were employed, as shown in Figure 2. For sodium reheat, only a separate evaporator/superheater arrangement was considered, since the inlet steam temperature to the reheater is significantly hotter than the desired sodium cold leg temperature (550^{o}F). The separate evaporator and superheater concepts are called Sulzer arrangements, although these cycles could be operated in either the once through (i.e., slight superheat in the evaporator) or in the True Sulzer Mode

FIGURE 2
ALTERNATIVE SYSTEM ARRANGEMENTS

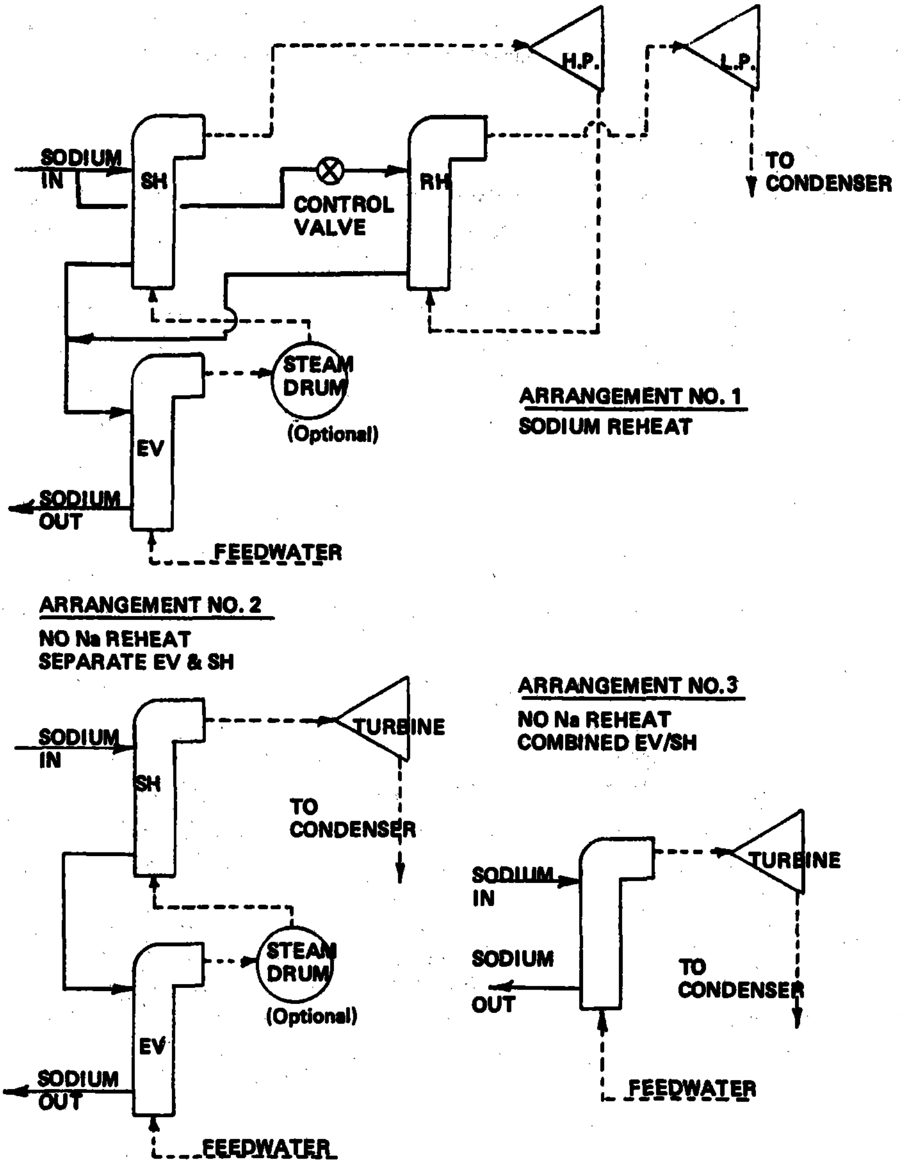


TABLE 5
STEAM CYCLES CONSIDERED

Cycle # (Reference 10)	1	2	6
Throttle Pressure (psig)	1450	1800	2400
Throttle Temperature (^{O}F)	1000	1000	1000
Throttle Flow (lbm/h)	776,417	765,396	762,350
Reheat Pressure (psig)	374.1	440.6	528.7
Reheat Temperature (^{O}F)	1000	1000	1000
Reheat Flow (lbm/h)	681,474	668,601	671,385
Final Feedwater Temperature (^{O}F)	433.1	449.7	467.5
Gross Cycle Efficiency (%)	42.25	43.09	43.94

(5-10% moisture in the evaporator exit steam). The combined evaporator and superheater arrangement is called the Benson arrangement. Temperature profiles for the with and without sodium reheat are presented in Figure 2A.

Results of the economic evaluation for steam pressure, Benson vs Sulzer, sodium reheat, and superheater/reheater material are shown in Figure 3 and Table 6. Figure 3 summarizes the economic trends for the six variations of the above variables. Sodium reheat is shown to cost an additional \$1 - 3 million in module costs, but this does not take into account other system costs, such as sodium valves (for the sodium reheat cases) nor the loss in efficiency, higher turbine cost, or steam reheater costs (for the non-sodium reheat cases). For non-sodium reheat, the Sulzer arrangement is most attractive economically, since it can employ a 2-1/4 Cr - 1 Mo evaporator, where as the steam generator unit in the Benson arrangement is all of I-800H or Type 316 stainless steel. Alloy 800H is significantly more expensive, by \$1-4 million, than Type 316 stainless steel as a material for construction in the superheater and reheater modules.

FIGURE 2A

STEAM GENERATOR
TEMPERATURE PROFILES
(1800 psi CYCLE)

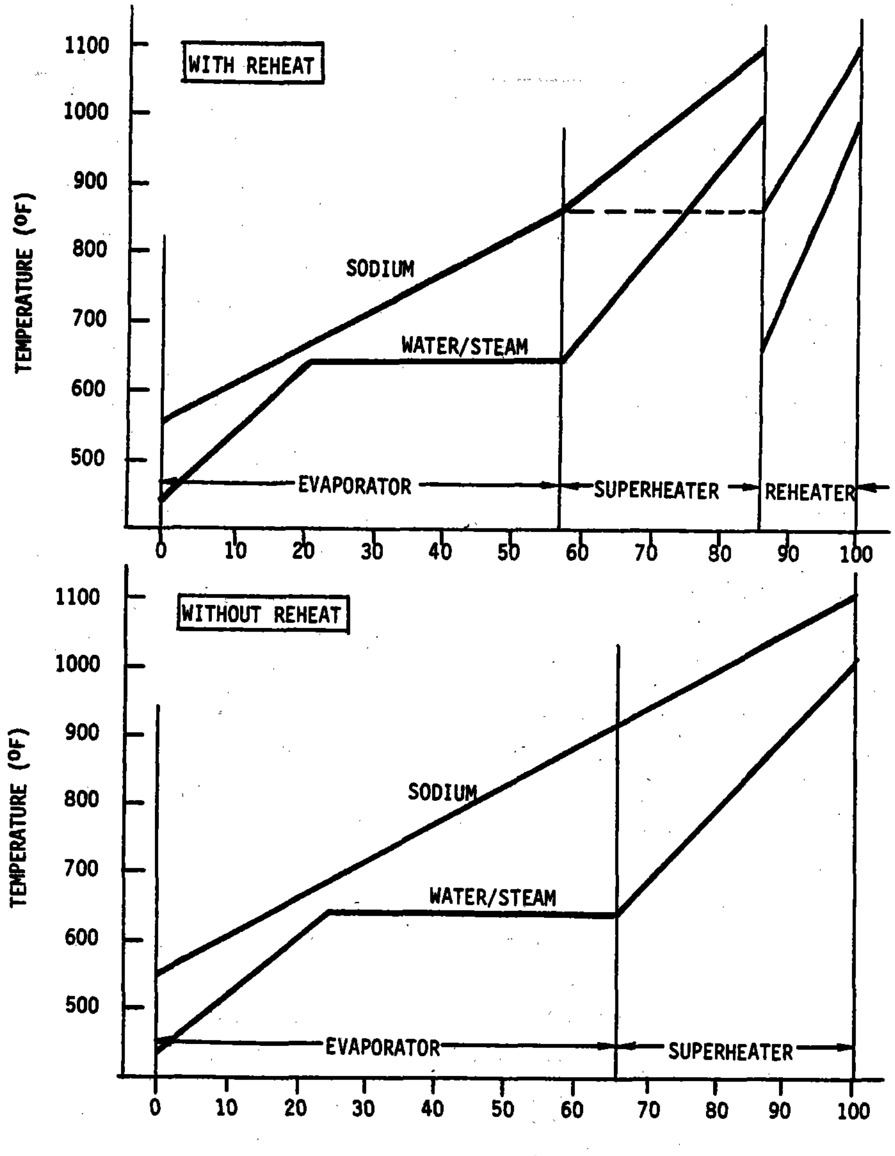
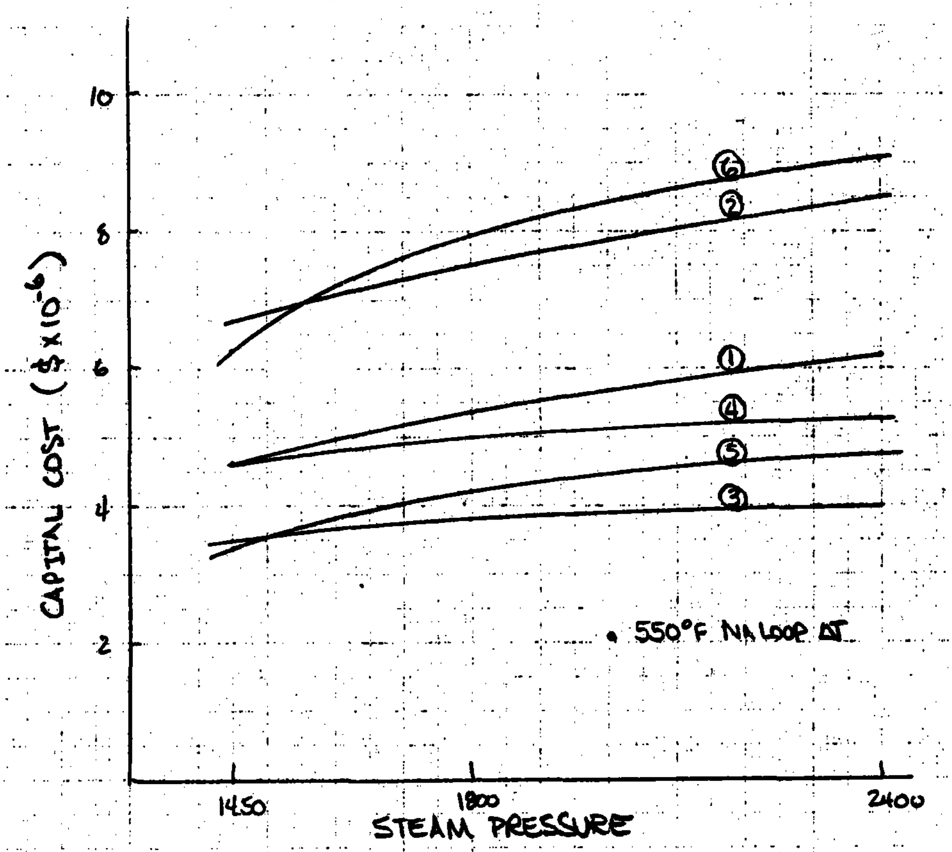


FIGURE 3.

ECONOMIC COMPARISONS AS
FUNCTION OF STEAM PRESSURE



CURVE	SODIUM R/H	ARRANGEMENT	MATERIALS
①	YES	SULZER	2¼Cr-1Mo, 316SS, 316SS
②	YES	SULZER	2¼Cr-1Mo, I800H, I800H
③	NO	SULZER	2¼Cr-1Mo, 316 SS
④	NO	SULZER	2¼Cr-1Mo, I800H
⑤	NO	BENSON	316 SS
⑥	NO	BENSON	I800H

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Table 6 gives a breakdown of the module costs for each option considered as well as sizing information. Optimum tube sizes are shown in the table for each case. Due to the high temperature of operation, the tube wall thicknesses for the superheater are significantly greater (20-30%) with the Type 316 stainless steel material than the wall thickness that is welded on the CRBRP steam generator (0.109-in) with an autogenous - butt weld from the ID. Tube-to-tubesheet weld development is probably necessary for either Type 316 stainless steel or I-800H, but additional measures such as using larger than optimum diameter tubes may be necessary for the Type 316 stainless steel superheater.

Results of an evaluation of sodium loop ΔT as it affects the steam generator module cost are shown in Figure 4 and Table 7. Economics tends to favor the lower steam pressure due to the larger sodium-steam temperature difference that exists at saturation in the evaporator. For the same reason, the lower sodium loop ΔT (higher cold leg temperature) is favored.

III. OPERATING CONSIDERATIONS

A. NORMAL POWER OPERATION

Normal power operation of the solar plant steam generator system will be desirable over a wide load range, probably 20-100% power. The steam generator modules should have no difficulty achieving this requirement, but the lower limit in operating range will probably be set by flow meters, pumps, and valves. In the solar plant, the sodium inlet temperature to the steam generator system is essentially fixed at storage temperature, or 1100°F, for normal power operation, and sodium flowrate can be adjusted for part power operation.

For the Sulzer cycle, operation at part power will result in the outlet steam temperature approaching the sodium inlet temperature (because sodium inlet temperature is fixed).

FIGURE 4.

EFFECT OF LOOP ΔT ON STEAM GENERATOR ECONOMICS

(1100°F HOT LEG)

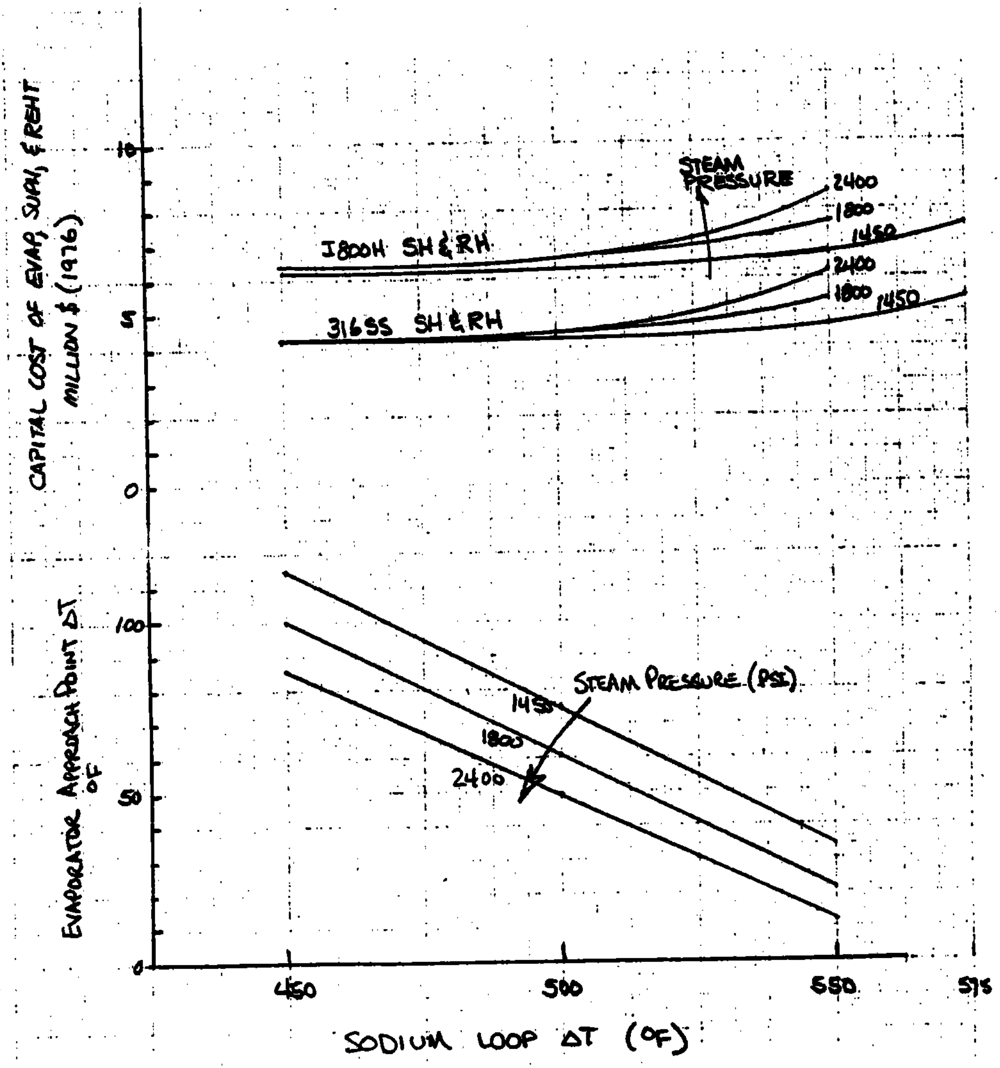

TABLE 6

DESIGN AND ECONOMIC OPTIMIZATION SUMMARY
(Sheet 1 of 2)

Benson/ Sulzer*	Sodium Reheat	Material			Steam Pressure	Optimum Tube Size			Optimum Tube Length (Active)			Number Tubes		
		EV	SH	RH		EV	SH	RH	EV	SH	RH	EV	SH	RH
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	2400	5/8 x 0.082	5/8 x 0.135	1-3/8 x 0.110	78.1	77.7	58.3	1491	376	160
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1800	5/8 x 0.075	3/4 x 0.132	1-1/2 x 0.107	78.1	67.6	52.9	1100	276	156
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1450	5/8 x 0.070	7/8 x 0.132	1-3/4 x 0.108	78.3	67.1	56.9	775	220	132
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	2400	5/8 x 0.082	5/8 x 0.123	1-1/4 x 0.096	78.1	78.4	52.4	1491	367	192
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1800	5/8 x 0.075	3/4 x 0.121	1-1/2 x 0.098	78.1	71.7	53.6	1100	252	152
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1450	5/8 x 0.070	3/4 x 0.112	1-1/2 x 0.093	78.3	55.4	47.1	775	296	184
Sulzer	No	2-1/4 Cr - 1 Mo	Type 316 SS	—	2400	5/8 x 0.091	5/8 x 0.135	—	78.5	65.4	—	874	444	—
Sulzer	No	2-1/4 Cr - 1 Mo	Type 316 SS	—	1800	5/8 x 0.087	3/4 x 0.132	—	77.9	59.8	—	866	320	—
Sulzer	No	2-1/4 Cr - 1 Mo	Type 316 SS	—	1450	3/4 x 0.092	3/4 x 0.122	—	78.0	46.9	—	684	372	—
Sulzer	No	2-1/4 Cr - 1 Mo	I800H	—	2400	5/8 x 0.091	5/8 x 0.123	—	78.5	71.3	—	874	392	—
Sulzer	No	2-1/4 Cr - 1 Mo	I800H	—	1800	5/8 x 0.087	5/8 x 0.111	—	77.9	46.7	—	866	464	—
Sulzer	No	2-1/4 Cr - 1 Mo	I800H	—	1450	3/4 x 0.092	3/4 x 0.112	—	78.0	49.8	—	684	340	—
Benson	No	Type 326 SS		—	2400	5/8 x 0.135		—	77.8		—	1868		—
Benson	No	Type 326 SS		—	1800	5/8 x 0.121		—	77.8		—	1658		—
Benson	No	Type 326 SS		—	1450	5/8 x 0.113		—	78.2		—	1322		—
Benson	No	I800H		—	2400	5/8 x 0.123		—	77.6		—	1846		—
Benson	No	I800H		—	1800	5/8 x 0.111		—	78.0		—	1632		—
Benson	No	I800H		—	1450	5/8 x 0.103		—	78.1		—	1301		—

*Used to denote combined SH/EV or separate EV and SH

TABLE 6

DESIGN AND ECONOMIC OPTIMIZATION SUMMARY

(Sheet 2 of 2)

Benson/ Sulzer*	Sodium Reheat	Material			Steam Pressure	Shell Diameter			H.T. Area ($Ft^3 \times 10^{-3}$)				Capital Cost			
		EV	SH	RH					EV	SH	RH	Total	EV	SH	RH	Total
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	2400	54.4	31.3	31.0	19.1	4.8	3.4	27.3	3.38	1.51	1.30	6.19
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1800	48.1	30.5	32.3	14.1	3.7	3.2	21.0	2.70	1.33	1.32	5.35
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1450	42.3	30.3	33.3	9.9	3.4	3.4	16.7	2.09	1.23	1.30	4.62
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	2400	54.4	31.1	31.5	19.1	4.7	3.3	27.1	3.38	2.74	2.40	8.52
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1800	48.1	29.6	31.9	14.1	3.5	3.2	20.8	2.70	2.36	2.47	7.53
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1450	42.3	31.3	34.6	9.9	3.2	3.4	16.5	2.09	2.19	2.43	6.71
Sulzer	No	2-1/4 Cr - 1 Mo	Type 316 SS	-	2400	44.0	35.0	-	11.2	4.8	-	16.0	2.36	1.65	-	4.01
Sulzer	No	2-1/4 Cr - 1 Mo	Type 316 SS	-	1800	43.9	34.7	-	11.0	3.8	-	14.8	2.33	1.48	-	3.81
Sulzer	No	2-1/4 Cr - 1 Mo	Type 316 SS	-	1450	43.7	35.6	-	10.5	3.4	-	13.9	2.13	1.39	-	3.52
Sulzer	No	2-1/4 Cr - 1 Mo	I800H	-	2400	44.0	34.0	-	11.2	4.6	-	15.8	2.36	2.90	-	5.26
Sulzer	No	2-1/4 Cr - 1 Mo	I800H	-	1800	43.9	35.6	-	16.0	3.5	-	14.8	2.33	2.68	-	5.01
Sulzer	No	2-1/4 Cr - 1 Mo	I800H	-	1450	43.7	35.3	-	10.5	3.3	-	13.8	2.13	2.46	-	4.59
Benson	No	Type 316 SS		-	2400	60.0		-	23.8			23.8	4.73		-	4.73
Benson	No	Type 316 SS		-	1800	57.1		-	21.1			21.1	4.22		-	4.22
Benson	No	Type 316 SS		-	1450	52.1		-	16.9			16.9	3.40		-	3.40
Benson	No	I800H		-	2400	59.7		-	23.4			23.4	9.03		-	9.03
Benson	No	I800H		-	1800	56.7		-	20.8			20.8	7.95		-	7.95
Benson	No	I800H		-	1450	51.8		-	16.6			16.6	6.28		-	6.28

*Used to denote combined SH/EV or separate EV and SH.

TABLE 7

EFFECT OF SODIUM LOOP ΔT ON STEAM GENERATOR DESIGN AND COST
(Sheet 1 of 2)

Benson/ Sulzer	Sodium Reheat?	Material			Steam Pressure	Sodium Loop ΔT (°F)	Optimum Tube Size (in.)			Optimum Tube Length (ft)			Number Tubes		
		EV	SH	RH			EV	SH	RH	EV	SH	RH	EV	SH	RH
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	2400	550	5/8 x 0.082	5/8 x 0.135	1-3/8 x 0.110	78.1	77.7	58.3	1491	376	160
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	2400	500	5/8 x 0.085	5/8 x 0.135	1-3/8 x 0.110	78.7	71.2	54.6	515	376	160
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	2400	450	5/8 x 0.090	5/8 x 0.135	1-3/8 x 0.110	63.1	65.8	51.4	436	376	160
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1800	550	5/8 x 0.075	3/4 x 0.132	1-1/2 x 0.107	78.1	67.6	51.9	1100	276	156
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1800	500	5/8 x 0.079	3/4 x 0.132	1-1/2 x 0.107	70.0	63.9	49.9	624	276	156
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1800	450	3/4 x 0.096	3/4 x 0.132	1-1/2 x 0.107	66.7	60.7	47.3	436	276	156
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1450	575	5/8 x 0.068	7/8 x 0.132	1-5/8 x 0.105	78.2	68.8	53.2	1257	220	156
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1450	550	5/8 x 0.070	7/8 x 0.132	1-3/4 x 0.108	78.3	67.1	56.9	757	220	132
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1450	500	3/4 x 0.083	7/8 x 0.132	1-5/8 x 0.105	70.1	64.3	49.0	524	220	156
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1450	450	7/8 x 0.099	7/8 x 0.132	1-5/8 x 0.105	67.5	61.7	46.6	392	220	156
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	2400	550	5/8 x 0.082	5/8 x 0.123	1-1/4 x 0.096	78.1	78.4	52.4	1491	367	192
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	2400	500	5/8 x 0.085	5/8 x 0.123	1-1/4 x 0.096	78.7	77.5	49.1	515	332	192
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	2400	450	5/8 x 0.090	5/8 x 0.123	1-1/4 x 0.096	63.1	71.7	46.1	436	332	192
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1800	550	5/8 x 0.075	3/4 x 0.121	1-1/2 x 0.098	78.1	71.7	53.6	1100	252	152
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1800	500	5/8 x 0.079	3/4 x 0.121	1-1/2 x 0.098	70.0	67.9	50.6	624	252	152
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1800	450	3/4 x 0.096	5/8 x 0.111	1-1/2 x 0.098	66.7	47.5	48.0	436	400	152
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1450	575	5/8 x 0.068	7/8 x 0.121	1-5/8 x 0.096	78.2	72.2	53.9	1257	204	152
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1450	550	5/8 x 0.070	3/4 x 0.112	1-1/2 x 0.093	78.3	55.4	47.1	757	296	184
Sulzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1450	500	3/4 x 0.083	3/4 x 0.112	1-5/8 x 0.096	70.2	52.9	49.7	524	296	152
Selzer	Yes	2-1/4 Cr - 1 Mo	I800H	I800H	1450	475	7/8 x 0.099	3/4 x 0.112	1-5/8 x 0.096	67.5	50.6	47.3	392	296	152

TABLE 7

EFFECT OF SODIUM LOOP ΔT ON STEAM GENERATOR DESIGN AND COST
(Sheet 2 of 2)

Benson/ Sulzer	Sodium Reheat?	Material			Steam Pressure	Sodium Loop ΔT (°F)	Shell Diameter (ID) (in.)			H.T. Area (Ft x 10^{-3})				Capital Cost ($ x 10^{-6})			
		EV	SH	RH			EV	SH	RH	EV	SH	RH	Total	EV	SH	RH	Total
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	2400	550	54.4	31.3	31.0	19.1	4.8	3.4	27.3	3.38	1.51	1.30	6.19
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	2400	500	37.0	31.8	31.2	6.6	4.4	3.1	14.1	1.71	1.47	1.27	4.45
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	2400	450	36.6	32.3	31.4	4.5	4.0	3.0	12.5	1.51	1.46	1.26	4.23
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1800	550	48.1	30.5	32.3	14.1	3.7	3.2	21.0	2.70	1.33	1.32	5.35
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1800	500	39.5	30.9	32.5	7.1	3.4	3.1	13.6	1.84	1.31	1.31	4.46
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1800	450	38.2	32.0	32.7	5.7	3.3	2.9	11.9	1.62	1.33	1.28	4.23
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1450	575	50.8	30.1	33.9	16.1	3.5	3.5	23.1	2.87	1.23	1.32	5.42
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1450	550	42.3	30.3	33.3	9.9	3.4	3.4	16.7	2.09	1.23	1.30	4.62
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1450	500	40.2	31.4	34.2	7.2	3.2	3.3	13.7	1.76	1.23	1.28	4.27
Sulzer	Yes	2-1/4 Cr - 1 Mo	Type 316 SS	Type 316 SS	1450	450	39.5	32.6	34.4	6.1	3.1	3.1	12.3	1.60	1.27	1.28	4.15
Sulzer	Yes	2-1/4 Cr - 1 Mo	1800H	1800H	2400	550	54.4	31.1	31.5	19.1	4.7	3.3	27.1	3.38	2.74	2.40	8.52
Sulzer	Yes	2-1/4 Cr - 1 Mo	1800H	1800H	2400	500	37.0	30.5	31.7	6.6	4.2	3.1	13.9	1.71	2.60	2.34	6.65
Sulzer	Yes	2-1/4 Cr - 1 Mo	1800H	1800H	2400	450	36.6	31.2	32.0	4.5	3.9	2.9	11.3	1.51	2.56	2.32	6.39
Sulzer	Yes	2-1/4 Cr - 1 Mo	1800H	1800H	1800	550	48.1	29.6	31.9	14.1	3.5	3.2	20.8	2.70	2.36	2.47	7.53
Sulzer	Yes	2-1/4 Cr - 1 Mo	1800H	1800H	1800	500	39.5	30.5	32.1	7.1	3.4	3.0	13.5	1.84	2.38	2.44	6.66
Sulzer	Yes	2-1/4 Cr - 1 Mo	1800H	1800H	1800	450	38.2	33.0	32.4	5.7	3.1	2.9	11.7	1.62	2.41	2.40	6.43
Sulzer	Yes	2-1/4 Cr - 1 Mo	1800H	1800H	1450	575	50.8	29.6	33.5	16.1	3.4	3.5	23.0	2.87	2.18	2.44	7.49
Sulzer	Yes	2-1/4 Cr - 1 Mo	1800H	1800H	1450	550	42.3	31.3	34.6	9.9	3.2	3.4	16.5	2.09	2.19	2.43	6.71
Sulzer	Yes	2-1/4 Cr - 1 Mo	1800H	1800H	1450	500	40.2	31.7	33.8	7.2	3.1	3.2	13.5	1.76	2.19	2.38	6.33
Sulzer	Yes	2-1/4 Cr - 1 Mo	1800H	1800H	1450	475	39.5	32.6	34.1	6.1	3.0	3.1	12.2	1.60	2.22	2.37	6.17

the steam outlet temperature will rise from 1000^{o}F power to 1100^{o}F at part load. Unless this is acceptable to the turbine, attemperators will be required on the outlet of the superheater and sodium reheater.

The Benson cycle is advantageous in that the steam and sodium flows can be adjusted to produce the desired power level and steam temperature at part load without use of an attemperator.

B. TRANSIENTS

Plant transients that affect the steam generator are listed in Table 8. These were obtained by reviewing the CRBRP transient lists. Most accident events that affect the receiver portion of the plant will not directly impose a transient, other than a normal shutdown, on the steam generator system, because the steam generator takes sodium from the storage tank. Operation of the steam generator system is not required in the solar plant following an accident event, as it is in an LMFBR to provide decay heat removal. The preferred approach following an accident event in the steam generator system is to stop both the sodium and steam flows, thereby minimizing any down transients for the hot end of the superheater and reheater or up transients for the cold end of the superheater and reheater and the evaporator. The large loop ΔT (550^{o}F) poses the potential for severe transients, but the number of such transients can be minimized by stopping flows.

C. STARTUP/SHUTDOWN

Startup and shutdown of the steam generator system is desired (from an overall plant viewpoint) on a daily basis. The preferred approach from the standpoint of the steam generator system is to continue steaming during the night hours using stored heat, since this would greatly reduce the number of startup and shutdown events. The steam generator modules can be shut down leaving them hot by a rapid stoppage of flow from a low power condition. Termperature profiles will not significantly change in the following 12-hour period due to heat losses through the insulation. For example, cooldown rates of a typical superheater module are shown in Figure 5. Using 12-in of

TABLE 8
PRELIMINARY TRANSIENT LIST FOR THE STEAM GENERATOR SYSTEM

NORMAL

1. Dry System Heatup and Fill
2. Startup/Shutdown
3. Load Swing

UPSET

1. Loss of Sodium Pump Power
2. Isolation and Blowdown of Evaporator
3. Isolation and Blowdown of Superheater
4. Isolation and Blowdown of Reheater
5. Inadvertent opening of steam relief valve
6. FW Throttle Valve fails open
7. Loss of FW flow
8. Loss of Power

EMERGENCY

TBD

insulation, the hot end of the superheater decreases by 100°F in the 12-hour period.

Startup would therefore be simplified as the component would be "at temperature," and once proportional flows were established, power level could be increased rapidly.

IV. REFERENCE SYSTEM DESIGN

The reference steam cycle was selected based upon overall system considerations as the 1800 psi steam cycle with sodium reheat and a 550°F sodium loop ΔT, (Reference 11). A description of the steam generator design and operating conditions is presented in Table 9.

FIGURE 5.
SUPERHEATER COOLDOWN

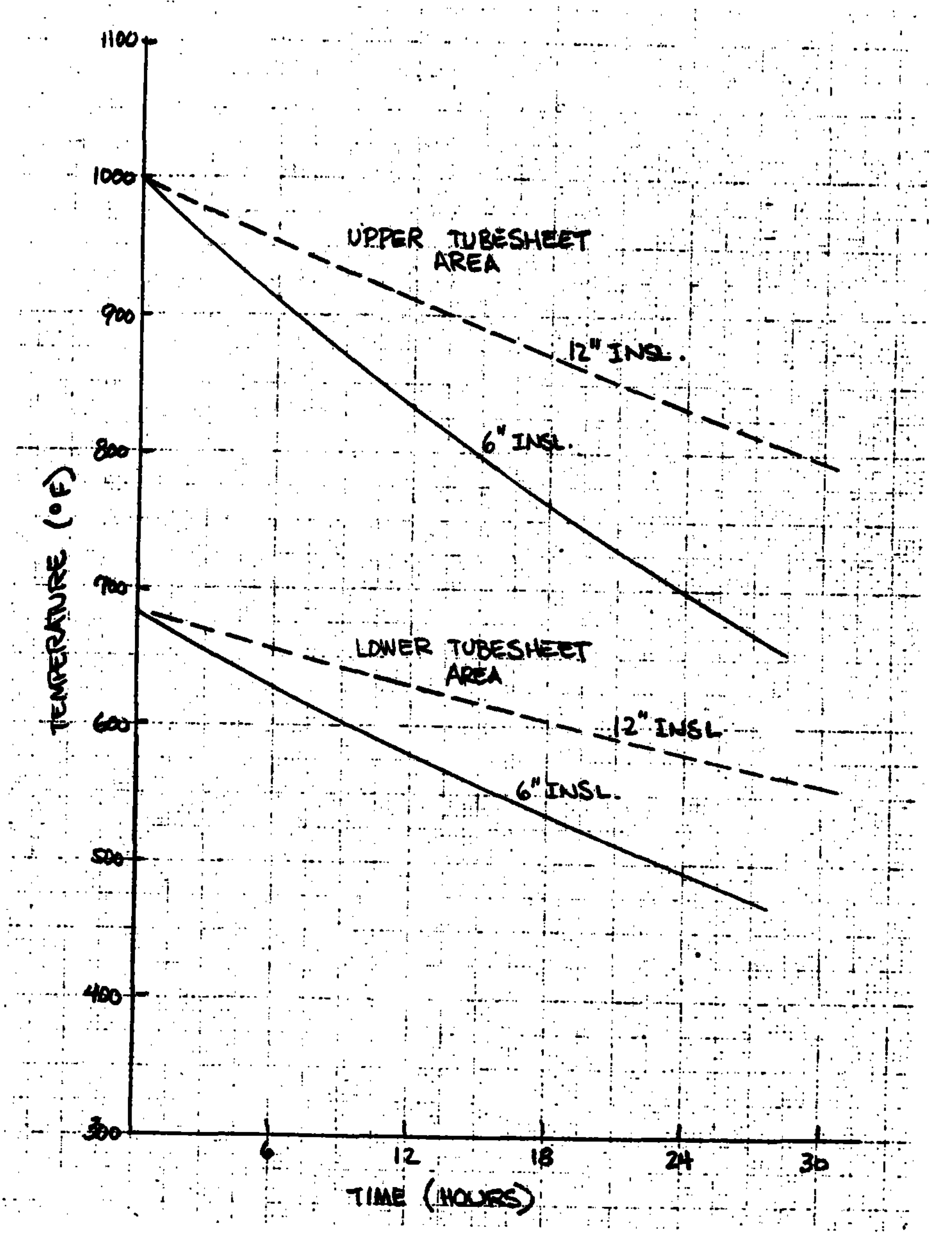

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TABLE 9
DESIGN AND OPERATING CONDITIONS FOR THE STEAM GENERATOR MODULES

	Evaporator	Superheater	Reheater
Physical Description			
Quantity	1	1	1
Type	Tube & Shell Hockey Stick	Tube & Shell Hockey Stick	Tube & Shell Hockey Stick
Height (ft)	95	91	66
Width (ft)	16	15	18
Shell Diameter (ID) (in.)	48	30	32
Heat Transfer Area (ft^2)	14039	4334	3329
Active Heat Transfer Length (ft)	78	78	53
No. Tubes	1100	283	163
Tube Diameter (in.)	5/8	3/4	1-1/2
Tube Wall Thickness (in.)	0.075	0.132	0.107
Material	2-1/4 Cr - 1 Mo	Type 316 ss	Type 316 ss
Tubesheet Diameter (in.)	48	30	32
Tubesheet Thickness (in.)	12	8	5
Module Weight Dry (Tons)	64	22	24
Operating Conditions			
Sodium Side:			
Flow (lbm/h)	5,542,000	3,785,000	1,757,000
Inlet Temperature (°F)	864	1100	1100
Outlet Temperature (°F)	550	864	864
Pressure Drop (psi)	30	30	30
Duty (MWt)	155.7	79.7	37.0
Water/Steam Side:			
Flow (lbm/h)	765,396	765,396	668,601
Inlet Temperature (°F)	450	646	657
Outlet Temperature (°F)	646	1000	1000
Pressure Drop (psi)	30*	256	22
Outlet Pressure (psia)	2170	1865	463
Exit Steam Velocity (fps)	27	250	250

*Includes Orifices

The best choice for evaporator material is clearly 2-1/4 Cr - 1 Mo, considering operating conditions and economics. The choice of material for the superheater and reheater is more difficult. Type 316 stainless steel was selected due to the significant cost advantage it shows over alloy 800H. However, alloy 800H remains a viable alternative, especially in light of its increased resistance to SCC. It is recommended that a thorough evaluation of the candidate materials be carried out by the Materials and Processes group during preliminary design of the steam generator system.

The steam generator modules should be designed and constructed in accordance with Section VIII, Class 1 of the ASME BPVC, with adders included to cover analysis of critical components for cyclic events and construction of the steam-sodium boundary. The critical components should include as a minimum the tubes and the tubesheets.

V. REFERENCES

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APPENDIX F

HEAT LOSSES FROM SOLAR RECEIVER SURFACE

AI Technical Information
Document N272TI000004

APPENDIX F

No. 650-78-083

Rockwell International
Atomics International Division

SUPPORTING DOCUMENT

NUMBER N272TI000004

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PROGRAM TITLE
Solar Central Receiver Power Systems

DOCUMENT TYPE
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KEY NOUNS
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DOCUMENT TITLE
Heat Losses from Solar Receiver Surface

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IR&D PROGRAM? YES ☐ NO ☐ IF YES, ENTER TPA NO.______

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ABSTRACT

Calculations have been made to determine the heat losses from the surface of the receiver of the Central Receiver Solar Power System. The heat losses considered are: reflection of incident heat flux, combined natural and forced convection, and thermal radiation.

The receiver analyzed is in the form of a vertical cylinder, 16 meters (52.5 ft) in diameter, and 16 meters (52.2 ft) in height--the reference dimensions at the time the analysis was made. Sodium is circulated through the receiver as a heat transport medium.

The tube surface properties are: α (absorptivity) = 0.95 and ϵ(emissivity) = 0.90. The ambient temperature is 60°F.

The heat losses, in megawatts and as a percentage of thermal power incident on the receiver, have been determined for a variety of conditions: thermal power absorbed by the sodium up to 429 MWt, wind velocities up to 16.3 meters/second (= 53.4 fps = 36.4 mph), and sodium inlet/outlet temperatures ranging from $550^{\circ}/1100^{\circ}$F to $850^{\circ}/1400^{\circ}$F.

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CONTENTS

FIGURES

TABLES

INTRODUCTION

The central receiver solar power system is planned to have a central tower placed in the midst of a field of mirrors. The mirrors are moved by heliostats throughout the course of the day and year such that sunlight is continuously reflected to the receiver at the top of the tower (258 meters above the ground). The receiver analyzed is comprised of 2,640 tubes of 3/4 in. OD, vertically oriented and forming a cylindrical shape, 16 meters in diameter, and 16 meters in height (reference configuration at the time that the analysis was performed).

The tubes are sodium cooled. That is, cool sodium (e.g., 550°F) enters at the bottom, is heated by the concentrated solar heat flux directed to the tube surface, and hot sodium (e.g., 1100°F) leaves at the top. Sodium inlet/outlet temperature pairs of 650°/1200°F, 750°/1300°F, and 850°/1400°F are also considered. The receiver has a high-temperature surface area of approximately 8,664 ft^2, exposed to winds and "seeing" the surroundings at ambient temperature. Part of the concentrated solar heat flux incident on the surface of the receiver does not get absorbed in the sodium stream--it is lost.

The losses occur by three modes: 1) reflection of a portion of the solar radiation heat flux incident on the receiver, 2) thermal radiation emitted from the receiver surface, and 3) thermal convection, either forced (wind) or natural.

Sodium flow in the tubes is assumed to be adjusted such that the desired inlet/outlet temperatures are maintained. However, there is a temperature drop across the tube wall and sodium film dependent on the magnitude of the heat flux. Thus, at high power, the outside surface temperature of the tubes is somewhat higher (and consequently somewhat higher losses) than at lower powers, for the same sodium temperature distribution within the tubes.

SUMMARY

Calculations of heat losses from the receiver of the Central Receiver Solar Power System have been made. Three modes of heat transfer are considered:

1) Reflection of heat flux radiation incident on the receiver (absorptivity, $\alpha = 0.95$). This amounts to 5% of the incident thermal energy.
2) Thermal radiation from the surface of the receiver (effective emissivity $\epsilon = 0.90$).
3) Convection,- both forced convection (for wind velocities up to 16.3 meters/sec = 53.4 ft/sec = 36.4 mph) and natural convection.

A range of sodium inlet/outlet temperatures for the receiver is taken into account. The reference condition is for sodium inlet at the bottom of the receiver tubes at 550°F, and sodium outlet at the top of the receiver tubes at 1100°F. The sodium flow rate in the various tubes is varied so as to maintain the desired inlet/outlet temperatures. Cases with sodium inlet/outlet temperatures of 650°/1200°F, 750°/1300°F, and 850°/1400°F are also investigated.

Heat flux distribution to the receiver surface is based on University of Houston data (Reference 1). Axial and circumferential heat flux distribution for "equinox noon" is used, but total heat loads to the sodium stream ranging from 100 MWt to 429 MWt are accounted for.

Values of heat losses (in MWt) are determined, with a summary presented in Tables X-a, X-b, X-c, and X-d of the appendix.

Heat losses, as a percentage of thermal power incident on the receiver surface are shown in Figures 5, 6, and 7. Figure 5 has 12 plots. Heat loss percentage versus heat absorbed is shown for the three individual modes of heat loss. Each sheet is for a different wind velocity and sodium temperature profile.

Figure 6 has four plots. Percent total heat loss is shown versus wind velocity for various sodium absorbed powers. Each sheet is for a different sodium temperature profile.

Figure 7 has three plots. Percent heat loss versus sodium operation temperature range is shown for various sodium abosrbed powers. Each sheet is for a different wind condition.

The heat loss percentage is quite high for the low power conditions. This is because for a given operating temperature condition, the heat loss variation as a function of incident power is small. Thus, at low incident power levels, the heat losses are a sizable fraction of the total; wheras, at high operating powers, the loss can be a relatively small fraction of the total.

ANALYSIS

The heat flux distribution has been obtained by the University of Houston researchers, Reference 1. It is shown in a normalized form in Figure 1. The normalized heat flux is shown as a function of axial position and by quadrant (circumferential position) on the receiver. The normalization is based on having the heat flux equal to 1.0 at mid-elevation on the north face. The curves were based on "equinox noon," and the heat flux is lower at other times of the day and year. However, it has been assumed that the normalized curves maintain the same relative position to each other, regardless of the actual magnitude of the heat flux.

In the three charts of Table I (I-a, I-b, and I-c), the heat flux curves are integrated. The axial temperature distribution of sodium in the tubes is determined on the basis of assuming that the thermal power entering the sodium is proportional to the local heat flux. (This neglects the fact that the upper portion of the tube has higher heat losses due to its higher temperature.) On Page A-5 of the appendix, the fraction of the total power going into each quadrant is determined, as well as the sodium flow rate required for a sodium thermal power of 429 MWt and temperature rise of 550°F. The calculations are carried out on the basis of assuming four quadrants on the receiver. (Actually, the receiver cylinder is formed of 24 flat panels, each with 110 tubes.)

Because of the heat flow from the tube surface to the sodium within the tube, there is a surface-to-sodium temperature drop. This is made up of sodium film convection drop, and a conduction drop through the tube wall.

The effective heat transfer coefficients for conduction and sodium convection have been determined on Pages A-7 through A-9. They are tabulated in Table II for each quadrant, and at three locations axially.

In Table III, the ΔT (wall and Na) are determined for each quadrant, at a series of axial locations. The ΔT values indicate how much hotter the outside tube surface is relative to the local sodium temperature. Figure 2 shows this ΔT value versus axial position, by quadrant. Figure 3 presents the axial temperature profiles for the receiver for the inlet/outlet sodium temperatures of $550^0/1100^0$F, for a heat input to the sodium of 429 MWt. The solid lines represent the sodium temperature, as determined in Tables I-a, I-b, and I-c. The dashed curves represent the receiver external surface temperatures for a 429 MWt heat input to the sodium (Tna(x) + ΔT(x)), that is, the "Full Power" condition. The solid curves represent the receiver surface temperature for Q(Na) = 0, that is, the "No Power" condition. Of course, the "No Power" condition has no steady-state significance; it is used in making linear interpolations for intermediate powers; Q(Na) between 0 and 429 MWt.

In Table IV, the axially averaged temperatures of the receiver are determined. (T(Na)) represents the surface temperature at the "No Power" condition, and T(surf) represents the surface temperature at the "full power" condition. For example, consider the calculations for the North quadrant. Table IV-(a-1) shows the mean sodium and full power surface temperatures for 20 axial segments. The table applies to the sodium 550^0F inlet/1100^0F outlet case. (For higher inlet/outlet temperatures, it is assumed that the same profile shape is maintained, merely raised the appropriate number of degrees.) Then, on Table IV-(a-2), the axially averaged temperatures are determined. Notice that different mean temperatures are obtained for convection and for radiation calculations. The mean temperatures are defined by:

$$\underset{{}^\circ F}{\bar{\bar{T}}}(\mathrm{CONV}) = \frac{\sum_{i=1}^{n} T_i({}^\circ F)}{n} \qquad \underset{{}^\circ F}{\bar{\bar{T}}}(\mathrm{RAD}) = \left(\frac{\sum_{i=1}^{n} (T_{i_{{}^\circ R}})^4}{n} \right)^{\frac{1}{4}} - 460^\circ$$

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where n = 20 (20 axial segments). Axially averaged temperatures are determined for both convection and radiation, for "no power" (Q = 0) and "full power" (Q = 429) conditions, and for a series of sodium inlet/outlet temperatures. This is done for all quadrants.

In Table V, the effective mean surface temperatures for the receiver are determined. Actually this represents the circumferential averaging. Thus, for each sodium inlet/outlet temperature condition, the mean convection and mean radiation temperatures are determined and shown.

On Page A-20, the calculation of radiation heat losses are set up, and the results are shown in Table VI. Radiation heat losses are shown for sink temperatures of 60°F and 0°R. The 60°F sink temperature results are circled, and used in further tabulation and plots. The 0°R sink temperature calculations were made merely to show that radiation heat losses are very insensitive to the assumed sink temperature.

On Page A-22, calculations are made for the natural convection heat loss coefficients. A value of h(Nat. Conv.) = 1.40 Btu/hr ft^2 °F is to be used for all cases.

Figure 4 shows a forced convection heat transfer correlation for vertical cylindrical geometry. The plot goes to rather high Reynolds numbers. This is necessary because of the large characteristic length (D = 16 meters = 52.5 ft) of the receiver. Even so, some extrapolation was required. The data is extracted from References 5 and 6.

The Reference 5 data (Achenbach) given Nusselt number for several surface roughness conditions. The receiver surface, being composed of 3/4-in. OD tubes, has an equivalent surface roughness of 60 x 10^{-5}. The Nu vs Re curve for surface roughness of 100 x 10^{-5}, with an extrapolation, was used in the forced convection calculation.

On Pages A-25 and A-26, forced convection heat loss coefficients are determined for a variety of wind speeds, using the correlation of Figure 4.

As a mater of conservatism, it was assumed that both natural and forced convection heat losses could occur simultaneously. If either natural or forced convection were to be used alone, there is the possibility of underestimating the convective heat loss. Therefore, an effective convection heat loss coefficient was determined according to the expression

$$\underset{\substack{\text{effective}\\\text{convection}\\\text{loss}}}{h} = \sqrt{\underset{\substack{\text{forced}\\\text{conv.}}}{h^2} + \underset{\substack{\text{nat.}\\\text{conv.}}}{h^2}}$$

In Table VIII, the calculated convection heat losses are shown. There are the "combined convection" losses. Values are shown for a range of wind velocities, and sodium inlet/outlet temperatures. Three different wind velocities have been considered: 5.70 meters/sec, 16.28 meters/sec, and an intermediate velocity. The lower and upper limit velocities are based on "ground" (elevation = 10 meters) velocities of 3.5 and 10.0 meters/sec. There, velocities are translated to the receiver elevation of 258 meters by the expression:

$$V(H) = V(H = 10m)\left(\frac{H}{H\ (10m)}\right)^{0.15}$$

This gives limiting wind velocities of 5.70 meters/sec (18.70 fps) and 16.28 meters/sec (53.42 ft/sec) as shown on Page A-25.

In Table IX, the combined radiation and convection heat losses are shown. "No power" and "full power" cases are shown (which refer to different tube surface temperatures due to temperature drop across the tube wall and sodium film). A range of wind velocities and sodium inlet/outlet temperatures are covered.

In Tables X (Xa through Xd) additional heat loss calculations are made. Sodium input powers from 100 MWt to 429 MWt are considered. For these intermediate powers, linear interpolations were made of the heat loss values in Table IX. Heat losses by radiation and convection are shown. In addition, the heat loss by reflection from the receiver surface (based on $\alpha_s = 0.95$) is also shown. The total heat loss and the total heat power incident on the receiver surface are determined. Heat losses are also shown as a percentage of the thermal power incident on the receiver surface. Calculations are shown for a range of wind velocities and sodium inlet/outlet temperatures.

In Figure 5 (12 plots), heat losses as a percent of incident power are shown as a function of thermal power input to the sodium. Heat losses by convection, reflection and radiation are plotted, as well as the total loss. Each plot is for a different combination of wind velocity and sodium inlet/outlet temperature.

In Figure 6 (4 plots), heat losses as a function of wind velocity are shown for various sodium thermal power inputs. There is one plot for each sodium inlet/outlet temperature condition.

In Figure 7 (3 plots), heat losses vs sodium inlet/outlet temperature ranges are shown. There is one sheet for each wind velocity considered.

Notice that the plots of Figures 5, 6, and 7 are all absed on the data presented in Tables X, with the data crossed plotted in different ways.

CONCLUSIONS

The results of the analysis are presented in Tables X (4 charts) and Figures 5 (12 plots), Figures 6 (4 plots), and Figures 7 (3 plots).

It is observed that convection heat losses are relatively low, so that wind velocity is not a particularly strong contributor to receiver operation degradation. Radiation losses tend to be higher than convection losses, particularly when the receiver is being operated at the higher temperatures. Reflection loss is constant at 5% of the total losses (as a direct consequence of assuming $\alpha = 0.95$).

The percentage heat losses increase markedly with decreasing system power. This is because even when the total thermal power incident on the receiver decreases sharply, the sodium flow is assumed to be adjusted so that the inlet/outlet temperatures remain unchanged. Thus, the receiver surface temperatures and the heat loss remain approximately the same. But now, this essentially unchanged heat loss becomes a much higher percentage of the greatly reduced incident power. Therefore, one observes that the receiver thermal efficiency declines substantially as the system operating power goes down.

REFERENCES

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   6b. W. H. McAdams, Heat Transmission, Third Edition, McGraw-Hill, 1954, Pages 266-267

7. E. M. Mouradian, personal notes on thermal properties of air, including natural convection behavior. Based on correlations from Reference 6b, Pages 172-180; and:

   7a. F. Kreith, Principles of Heat Transfer, Second Edition, International Text Book Company, 1966, Page 595

APPENDIX

Calculations and Results

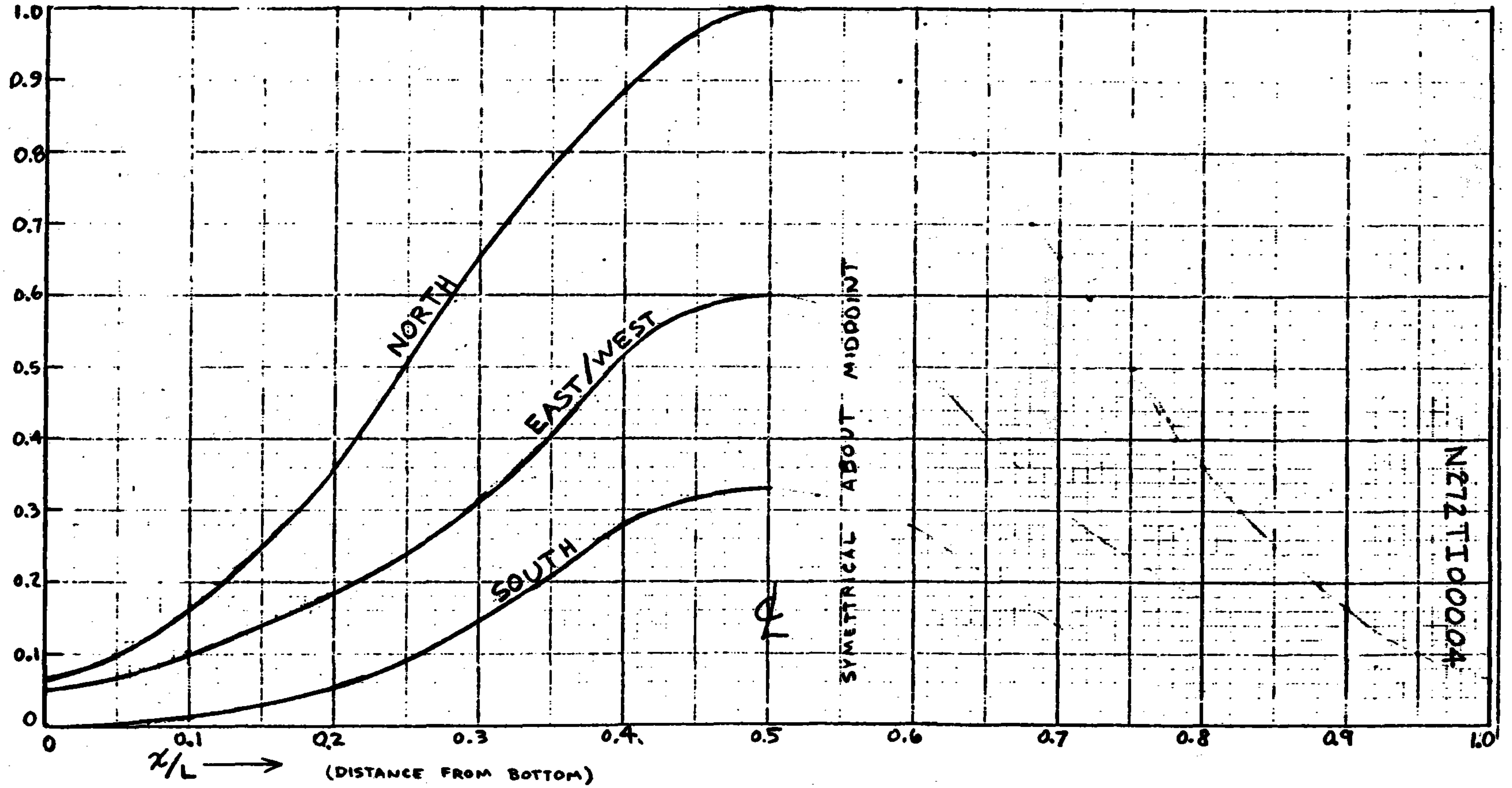

FIGURE 1 NORMALIZED RECEIVER HEAT FLUX PROFILES; BASED ON EQUINOX NOON. (Ref. 1) University of Houston data.

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TABLE I-a NORTH QUADRANT
HEAT FLUX INTEGRATION

NORTH

INTEGRATION OF HEAT FLUX CURVES (Figure 1)

$q''(\frac{x}{L})$ (spares) Amplitude i	$\int_0^{x/L} q\, d\xi$ Σ Amp (i) Running Summation	$\frac{\int_0^{x/L} q\, d\xi}{\int q\, d\xi}$ $\frac{\Sigma Amp(i)}{\Sigma Amp}$	↓x/L	T_{Na} °F x/L = 0 → .5 $[550 + 550(\frac{\Sigma A_i}{\Sigma Amp})]$	x/L ↑	T_{Na} °F x/L = 1.0 → .5 $[1100 - 550(\frac{\Sigma A_i}{\Sigma Amp})]$
			0	500.0	1.0	1100.0
3.3	3.3	0.00127		550.7		1099.3
3.6	6.9	0.00266		551.5		1098.5
3.9	10.5	0.00405		552.2		1097.8
4.2	14.7	0.00567		553.1		1096.9
4.6	19.3	0.00745	.05	554.1	.95	1095.9
5.4	24.7	0.00953		555.2		1094.8
5.8	30.5	0.01177		556.5		1093.5
6.4	36.9	0.0143		557.9		1092.1
7.0	43.9	0.01694		559.3		1090.7
7.5	51.4	0.0198	.10	560.9	.90	1089.1
8.4	59.8	0.0231		562.7		1087.3
9.0	68.8	0.0265		564.6		1085.4
10.0	78.8	0.0304		566.7		1083.3
11.0	89.8	0.0346		569.0		1081.0
11.9	101.7	0.0392	.15	571.6	.85	1078.4
12.9	114.6	0.0442		574.3		1075.7
13.9	128.5	0.0496		577.3		1072.7
15.0	143.5	0.0554		580.5		1069.5
16.0	159.5	0.0615		583.8		1066.2
17.1	176.6	0.06814	.20	587.5	.80	1062.5
18.5	195.1	0.0753		591.4		1058.6
20.0	215.1	0.0830		595.7		1054.3
21.5	236.6	0.0913		600.2		1049.8
23.0	259.6	0.1002		605.1		1044.9
24.5	284.1	0.1096	.25	610.3	.75	1039.7
26.0	310.1	0.1196		615.8		1034.2
27.5	337.6	0.1303		621.7		1028.3
29.0	366.6	0.1414		627.8		1022.2
30.5	397.1	0.1532		634.3		1015.7
32.0	429.1	0.1656	.30	641.1	.70	1008.9
33.5	462.6	0.1785		648.2		1001.8
34.6	497.2	0.1918		655.5		994.5
36.0	533.2	0.2057		663.1		986.9
37.2	570.4	0.2201		671.1		978.9
38.4	608.8	0.235	.35	679.3	.65	970.7
39.5	648.3	0.250		687.5		962.5
40.5	688.8	0.2658		696.2		953.8
41.6	730.4	0.282		705.1		944.9
42.6	773.0	0.298		713.9		936.1
43.6	816.6	0.315	.40	723.3	.60	926.7
44.9	861.5	0.332		732.6		917.4
45.6	907.1	0.350		742.5		907.5
46.4	953.5	0.368		752.4		897.6
47.2	1000.7	0.386		762.3		887.7
48.0	1048.7	0.4046	.45	772.5	.55	877.5
48.6	1097.3	0.4234		782.9		867.1
49.2	1146.5	0.4424		793.3		856.7
49.6	1196.1	0.4615		803.8		846.2
49.8	1245.9	0.4807		814.9		835.1
50.0	1295.9	0.5000	.50	825.0	.50	825.0

AVERAGE VALUE: 25.92

TOTAL $\int_0^1 q\, d(\frac{x}{L})$ 2591.8

TABLE I-b EAST/WEST QUADRANTS
HEAT FLUX INTEGRATION

EAST/WEST

INTEGRATION OF HEAT FLUX CURVES

(Figure 1)

$q(\frac{x}{L})$ (Spaces) Amplitude i	$\int_0^{x/L} q\, d\frac{x}{L}$ Σ Amp (i) Running Summation	$\frac{\int_0^{x/L} q\, d\xi}{\int q\, d\xi}$ ΣAmp (i) / Σ Amp	↓x/L	T_{No} °F x/L = 0 → .5 [550 + 550(ΣAi/ΣAmp)]		T_{No} °F x/L = 1.0 → .5 [1100 − 550(ΣAi/ΣAmp)]
			•	550	1.0	1100
2.5	2.5	0.00175		551		1099
2.6	5.1	0.00356		552		1098
2.8	7.9	0.00552		553		1097
3.0	10.9	0.0076		554.2		1095.8
3.2	14.1	0.00985	.05	555.4	.95	1094.6
3.5	17.6	0.0123		556.8		1093.2
3.8	21.4	0.01495		558.2		1091.8
4.0	25.4	0.01774		559.8		1090.2
4.4	29.8	0.0208		561.4		1088.6
4.7	34.5	0.0241	.10	563.3	.90	1086.7
5.2	39.7	0.0277		565.2		1084.8
5.6	45.3	0.0316		567.4		1082.6
6.0	51.3	0.0358		569.7		1080.3
6.4	57.7	0.0403		572.2		1077.8
6.7	64.4	0.0450	.15	574.8	.85	1075.3
7.1	71.5	0.050		577.5		1072.5
7.6	79.1	0.0553		580.4		1069.6
8.0	87.1	0.0608		583.4		1066.6
8.5	95.6	0.0668		586.7		1063.3
8.9	104.5	0.0730	.20	590.2	.80	1059.9
9.5	114.0	0.0796		593.8		1056.2
10.0	124.0	0.0866		597.6		1052.4
10.5	134.5	0.0940		601.7		1048.3
11.0	145.5	0.1016		605.9		1044.1
11.6	158.1	0.1105	.25	610.8	.75	1039.2
12.2	170.3	0.119		615.5		1034.6
13.0	183.3	0.128		620.4		1029.6
13.6	196.9	0.138		625.9		1024.1
14.4	211.3	0.1476		631.2		1018.8
15.1	226.4	0.158	.30	636.9	.70	1013.1
16.0	242.4	0.169		624.9		1007.1
16.6	259.0	0.181		649.6		1000.4
17.6	276.6	0.193		656.2		993.8
18.5	295.1	0.206		663.3		986.7
19.6	314.7	0.220	.35	671.0	.65	979.0
20.6	335.3	0.234		678.7		971.3
21.7	357.0	0.249		686.9		963.1
23.0	380.0	0.265		695.8		954.2
24.0	404.0	0.282		705.1		944.9
25.2	429.2	0.300	.40	715.0	.60	935.0
26.3	455.5	0.318		724.9		925.1
27.0	482.5	0.337		735.4		914.6
27.7	510.2	0.356		745.8		904.2
28.4	538.6	0.376		756.8		893.2
28.8	567.4	0.396	.45	767.8	.55	882.2
29.3	596.7	0.417		779.4		870.6
29.5	626.2	0.437		790.4		859.6
29.7	655.9	0.458		801.9		848.1
29.8	685.7	0.479		813.5		836.5
30.0	715.7	0.500	.50	825.0	.50	825.0
AVERAGE VALUE 14.31	TOTAL $\int_0^1 q\, d(\frac{x}{L})$ 1431.4				x/L ↑	

TABLE I-c **SOUTH QUADRANT**

HEAT FLUX INTEGRATION

SOUTH

INTEGRATION OF HEAT FLUX CURVES

(Figure 1)

$q(\frac{x}{L})$ Amplitude i	$\int_0^{x/L} q\,d\frac{x}{L}$ Σ Amp (i) Running Summation	$\frac{\int_0^{x/L} q\,d\xi}{\int_0^1 q\,d\xi}$ $\frac{\Sigma Amp(i)}{\Sigma Amp}$	↓x/L	T_{Na} °F x/L = 0 → .5 $\left[550 + 350\left(\frac{\Sigma A_i}{\Sigma Amp}\right)\right]$		T_{Na} °F x/L = 1.0 → .5 $\left[1100 - 350\left(\frac{\Sigma A_i}{\Sigma Amp}\right)\right]$
0.	0.	0.0		550.	1.0	1100.
0.	0.	0.0		550.		1100.
0.	0.	0.0		550.		1100.
0.	0.	0.0		550.		1100.
0.1	0.1	0.00015	.05	550.1	.95	1099.9
0.1	0.2	0.00031		550.2		1099.8
0.2	0.4	0.00062		550.3		1099.7
0.3	0.7	0.00108		550.6		1099.4
0.4	1.1	0.0017		550.9		1099.1
0.6	1.7	0.0026	.10	551.4	.90	1098.6
0.8	2.5	0.00386		552.1		1097.8
0.9	3.4	0.00525		552.9		1097.1
1.0	4.4	0.0068		553.7		1096.3
1.1	5.5	0.0085		554.7		1095.3
1.3	6.8	0.0105	.15	555.8	.85	1094.2
1.5	8.3	0.0128		557.0		1093.0
1.7	10.0	0.0155		558.5		1091.5
2.0	12.0	0.0185		560.2		1089.8
2.2	14.2	0.0219		562.0		1088.0
2.5	16.7	0.0258	.20	564.2	.80	1085.8
2.8	19.5	0.03013		566.6		1083.4
3.1	22.6	0.0349		569.2		1080.8
3.5	26.1	0.0403		572.2		1077.8
3.8	29.9	0.0462		575.4		1074.6
4.2	34.1	0.0527	.25	579.0	.75	1071.0
4.7	38.8	0.060		583.0		1067.0
5.2	44.0	0.068		587.4		1062.6
5.7	49.7	0.0768		592.2		1057.8
6.4	56.1	0.0867		597.7		1052.3
7.0	63.1	0.0975	.30	603.6	.70	1046.4
7.6	70.7	0.109		609.9		1040.0
8.1	78.8	0.122		617.1		1032.9
8.6	87.4	0.135		624.3		1025.7
9.5	96.9	0.150		632.5		1017.5
10.0	106.9	0.165	.35	640.8	.65	1009.2
10.5	117.4	0.181		649.6		1000.4
11.4	128.8	0.199		659.5		990.5
12.1	140.9	0.218		669.9		980.1
13.0	153.9	0.238		680.9		969.1
13.6	167.5	0.259	.40	692.5	.60	957.6
14.1	181.6	0.281		704.5		945.6
14.6	196.2	0.303		716.6		933.4
15.0	211.2	0.326		729.3		920.7
15.4	226.6	0.350		742.5		907.5
15.6	242.2	0.374	.45	755.7	.55	894.3
16.0	258.2	0.399		769.5		880.5
16.2	274.4	0.424		783.2		866.8
16.3	290.7	0.449		797.0		853.0
16.4	307.1	0.4745		811.0		839.0
16.5	323.6	0.500	.50	825.0	.50	825.0
AVERAGE VALUE	TOTAL $\int_0^1 q\,d(\frac{x}{L})$				$\frac{x}{L}$ ↑	

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SODIUM FLOW RATE, Enthalpy Rise

Dimensionless Power Input Distribution: (See Tables I)

NORTH	2591.8	÷ 6101.8 =	0.424 760 0
EAST/WEST	1431.4		0.234 586 5
EAST/WEST	1431.4		0.234 586 5
SOUTH	647.2		0.106 067 0
TOTAL	6101.8		1.00

Fraction of Total Energy Into Each Quddrant.

Deal with average energy in each quadrant, without looking for finer θ direction variation.

Consider Sodium Flow:

Thermal Power: $429 \text{ MW}_{th} = 1.46418 \times 10^9 \frac{\text{BTU}}{\text{hr}}$

Sodium Temperature Rise $= 1100 - 550 = 550°\text{F}$

Enthalpy Rise: out $T = 1100°$ $h_{Na} = 486.88$ BTU/lb_m (Ref. 2)

in $T = 550°$ $h_{Na} = 319.44$ BTU/lb_m

$\delta T = 550°\text{F}$ $\Delta h_{Na} = 167.44$ BTU/lb_m

$$\bar{C}_p = \frac{\Delta h}{\delta T} = \frac{167.44}{550} = 0.304436 \text{ BTU}/lb_m\,°\text{F}$$

$$Q = \dot{w}\Delta h, \quad \dot{w}_{Na} = \frac{Q}{\Delta h_{Na}}$$

$$\dot{W}_{Na} = \frac{Q}{\Delta h} = \frac{1.46418 \times 10^9 \text{ BTU/hr}}{167.44 \text{ BTU}/lb_m} = 8{,}744{,}500 \frac{lb_m}{hr}$$

$$\boxed{\dot{W}_{Na} = 8{,}744{,}500 \frac{lb_m}{hr} \quad \text{TOTAL SODIUM FLOW}}$$

$$\boxed{Q_{TOTAL} = 429 \text{ MW}_t = 1.46418 \times 10^9 \frac{\text{BTU}}{\text{hr}}}$$

$\frac{1}{4}(1100)+\frac{1}{2}(825)+\frac{1}{4}(550)$

SODIUM PROPERTIES: (Ref. 2)

	T = 1100°F	T = 550°F	$T = \frac{1100+550}{2} = 825°$	MEAN PROPERTY
$\rho \ \frac{lb_m}{ft^3}$	50.553	55.116	52.845	52.84
$h \ \frac{BTU}{lb_m}$	486.88	319.44		
$\mu \ \frac{lb_m}{ft\ hr}$	0.5039	0.8591	0.62855	.65503
$k \ \frac{BTU}{hr\ ft\ °F}$	36.17	44.60	40.23	40.308
P_r	.0041766	.0060176	^.0046701	0.004997
C_p	0.2998	0.3124	.3035	.304436

24 panels, 4 quadrants. ∴ 6 panels per quadrant.
Each panel has 110 tubes.
∴ Each quadrant has 660 tubes. (Ref. 1)
Total = 2640 tubes.

TUBE:

BWG 18, 3/4"
$$\begin{cases} OD = 0.75" \\ t_w = 0.049" \\ ID = 0.652" \end{cases}$$

Flow Area; 1 tube:

$$A_{\text{FLOW}_1} = \frac{\pi}{4}(ID)^2 = \frac{\pi}{4}\left(\frac{.652}{12}\right)^2 = .0023186\ ft^2$$

Flow Area; 1 Quadrant (660 tubes)

$$A_{\text{FLOW QUAD}} = 1.5302645\ ft^2 \qquad 1.5303\ ft^2$$

Total Flow Area: (2640 Tubes)

$$A_{\text{FLOW QUAD}} = 6.12106\ ft^2$$

QUADRANT	Flow Fraction	$\dot{W}_{QUAD}$ Flow in Quadrant lbm/hr frac*(8744500)	$G = \frac{\dot{W}}{A_{Flow}}$ $\frac{lbm}{hr\ ft^2}$ $\frac{\dot{W}(QUAD)}{1.53026}$	Heat Input into each Quadrant? $Q_{Quad} = frac * (1.46418 \times 10^9)$ BTU/hr
NORTH	0.424760	3,714,314	2,427,237	6.219238×10^8
EAST/WEST	0.2345865	2,051,342	1,340,515	3.434762×10^8
EAST/WEST	0.2345865	2,051,342	1,340,515	3.434762×10^8
SOUTH	0.106067	927,502	606,106	1.553009×10^8
		8,744,500		

$$G_{QUAD} = \frac{\dot{W}}{A_{FLOW\ QUAD}} \qquad Vel = \frac{G}{\rho} \qquad Re = \frac{G\, d_{in}}{\mu}$$

$$Nu = 7 + \frac{1}{40}\left(Pr\, Re\right)^{0.8}$$

Reference 3
Liquid Metal Heat
Transfer Correlation

$$h_{Na} = \frac{Nu\, k}{d_{in}} = \frac{Nu\, k}{\left(\frac{.652}{12}\right)} = 18.40491(Nu)(k)$$

Based on ID.

$$h_{Na\ \text{BASED ON OD}} = \frac{.652}{.75}\, h_{Na\ \text{BASED ON ID}}$$

Assume that $\frac{1}{2}$ of circumference of tube is acting for heat transfer through tube into sodium.

$$A\left(\text{Effective Inner Surface}\right) = \left(n_{\text{TUBES in QUAD}}\right)\left(\frac{180^\circ}{360^\circ}\right)\pi\, d_{in}\, L = (660)\left(\tfrac{1}{2}\right)(\pi)\left(\frac{.652}{12}\right)L$$
$$= 56.3288\, L\ ft^2$$

$$A\left(\text{Effective Outer Surface}\right) = n\left(\frac{180}{360}\right)\pi\, d_{oot}\, L = (660)\left(\tfrac{1}{2}\right)(\pi)\left(\frac{.75}{12}\right)L = 64.79535\, L\ ft^2$$

FOR CONDUCTION THROUGH WALL:

$$q = \frac{2\pi k L}{\ln \frac{r_o}{r_i}} \Delta T = h_{\substack{eff\\cond\\OUTER}} A_{out} \Delta T$$

$$h_{eff\left(\substack{COND\\OUTER}\right)} = \frac{2k}{D_o \ln \frac{D_o}{D_I}} = \frac{2k}{\frac{.75}{12} \ln \frac{.750}{.652}} = 228.5247\,k$$

Effective h for Conduction through, based on outer area.

304 STAINLESS STEEL: (REF. 4, Pg. 52)

T °F	k $\frac{BTU}{hr\ ft\ °F}$	$h_{\substack{eff\\cond}} = 228.5247k$ BASED ON OD.
550°	10.48	2395 BTU/hr ft² °F
825°	11.68	2669
1100°	12.88	2943

$$\boxed{h_{\substack{COMBINED\\\text{Based on OD}}} = \frac{1}{\frac{1}{h_{\substack{Na\\CONV}}} + \frac{1}{h_{COND}}}}$$

Effective outer surface area of one quadrant of tubes.

$OD = 0.75'' = \frac{1}{16}$ ft.

$n_T \left(\substack{\text{TUBES in}\\\text{one quadrant}}\right) = 660$

$L = 16$ meters $= 52.5$ ft

Assume $\frac{1}{2}$ of tube circumference is effective.

$$A_{\substack{surface\\Outer}} = n_t (.5) \pi D_o L$$

$$A = 660(.5)\pi\left(\frac{.75}{12}\right)(52.5) = 3401.8\ ft^2$$

$$\boxed{\begin{array}{c}\text{Effective Outer Surface Area}\\ \text{of one quadrant of tubes}\\ \text{For heat transport to Na}\\ 3400\ ft^2\end{array}}$$

"Average Heat Flux"

QUAD	ΣQ BTU/hr	$(Q/A)_{AVG} = \frac{\Sigma Q}{3400}$ $\frac{BTU}{hr\ ft^2}$
N	6.21924×10^8	182,900
E/W	3.434762×10^8	101,000
S	1.553009×10^8	45,680

TABLE II

CALCULATION OF SODIUM SIDE h and COMBINED h.

(To determine ΔT through wall and Na film.)

		$\dot{W}_{Na}$ lb/hr 660 Tubes	$G = \dot{W}/A$ $lb_m/hr\ ft^2$	ρ_{Na} lb_m/ft^3	VELOCITY G/ρ ft/sec	μ_{Na} $lb_m/hr\ ft$	$D_{inner} = .652''$. $Re = \frac{GD_{in}}{\mu}$	Pr_{Na}	$Nu = 7 + \frac{(Pr\,Re)^{0.8}}{40}$	k (Na) Btu/hr ft °F	$18.404(Nu)(k)$ Btu/hr ft² °F h_{Na} BASED on ID	h_{Na} Based on OD	$h_{eff\ cond}$ Based on OD	h COMBINED
NORTH Quadrant														
HOT	1100°F	3,714,314	2,427,237	50.553	13.34	.5039	261,720	.0041766	13.743	36.17	9149	7953	2943	2148
MEAN		"	"	52.845	12.76	.6550	201,330	.0049473	13.260	40.31	9837	8552	2669	2034
COLD	550°F	"	"	55.116	12.23	.8591	153,510	.0060176	12.894	44.60	10,584	9201	2395	1900
EAST/WEST (2 Quadrants)														
HOT	1100°F	2,051,342	1,340,515	50.553	7.37	.5039	144,540	.0041766	11.194	36.17	7452	6478	2943	2024
MEAN		"	"	52.845	7.05	.6550	111,190	.0049473	10.893	40.31	8081	7025	2669	1934
COLD	550°F	"	"	55.116	6.76	.8591	84,780	.0060176	10.665	44.60	8755	7611	2395	1822
SOUTH Quadrant														
HOT	1100°F	927,502	606,106	50.553	3.33	.5039	65,350	.0041766	9.222	36.17	6139	5337	2943	1897
MEAN		"	"	52.845	3.19	.6550	59275	.0049473	9.063	40.31	6724	5847	2669	1832
COLD	550°F	"	"	55.116	3.06	.8591	38,330	.0060176	8.942	44.60	7340	6381	2395	1741

TABLE III.

DETERMINATION OF ΔT THROUGH TUBE WALL & Na FILM

QUADRANT: NORTH — $(Q/A)_{AVG} = 182,900$ BTU/hr ft²

ⓐ Axial Location x/L		ⓑ q/A Amp. See Fig.	ⓒ Heat Flux Ratio $\frac{Q/A\ Local}{Q/A\ Avg}$ ⓑ/25.92	ⓓ Local Heat Flux ⓒ*(Q/A)avg	ⓔ Local h_{eff} BTU/hr ft² °F		$\Delta T_{°F} = \frac{Q/A\ (local)}{h_{local}}$	
↓	↑				Cold End	Hot End	Cold End	Hot End
0	1.0	3.3	0.127	23,219	1900	2150	12.2	10.8
.125	.875	10.0	0.3858	70,534	1933	2121	36.5	33.3
.25	.75	25.26	0.9742	178,108	1967	2092	90.5	85.1
.375	.625	41.6	1.605	293,434	2000	2063	146.7	142.2
.50		50.0	1.929	352,699	2034		173.4	

QUADRANT: EAST/WEST — $(Q/A)_{AVG} = 101,000$ BTU/hr ft²

ⓐ Axial Location x/L		ⓑ q/A Amp. See Fig.	ⓒ Heat Flux Ratio $\frac{Q/A\ Local}{Q/A\ Avg}$ ⓑ/14.31	ⓓ Local Heat Flux ⓒ*(Q/A)avg	ⓔ Local h_{eff} BTU/hr ft² °F		$\Delta T_{°F} = \frac{Q/A\ (local)}{h_{local}}$	
↓	↑				Cold End	Hot End	Cold End	Hot End
0	1.0	2.5	.1747	17640	1822	2024	9.7	8.7
.125	.875	6.0	.4193	42336	1850	2002	22.9	21.1
.25	.75	12.0	.8386	84672	1878	1979	45.1	42.8
.375	.625	23.0	1.6073	162,287	1906	1957	85.1	82.9
.50		30.0	2.0964	211,679	1934		109.5	

QUADRANT: SOUTH — $(Q/A)_{AVG} = 45,680$ BTU/hr ft²

ⓐ Axial Location x/L		ⓑ q/A Amp. See Fig.	ⓒ Heat Flux Ratio $\frac{Q/A\ Local}{Q/A\ Avg}$ ⓑ/6.47	ⓓ Local Heat Flux ⓒ*(Q/A)avg	ⓔ Local h_{eff} BTU/hr ft² °F		$\Delta T_{°F} = \frac{Q/A\ (local)}{h_{local}}$	
↓	↑				Cold End	Hot End	Cold End	Hot End
0	1.0	0	0	0	1741	1897	0	0
.125	.875	1.0	0.15456	7056	1764	1881	4.0	3.8
.25	.75	4.45	0.6878	31,400	1787	1865	17.6	16.8
.375	.625	12.1	1.8702	85,379	1809	1848	47.2	46.2
.50		16.5	2.5502	116,426	1832		63.6	

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FIGURE 2

ΔT THROUGH TUBE WALL & Na FILM

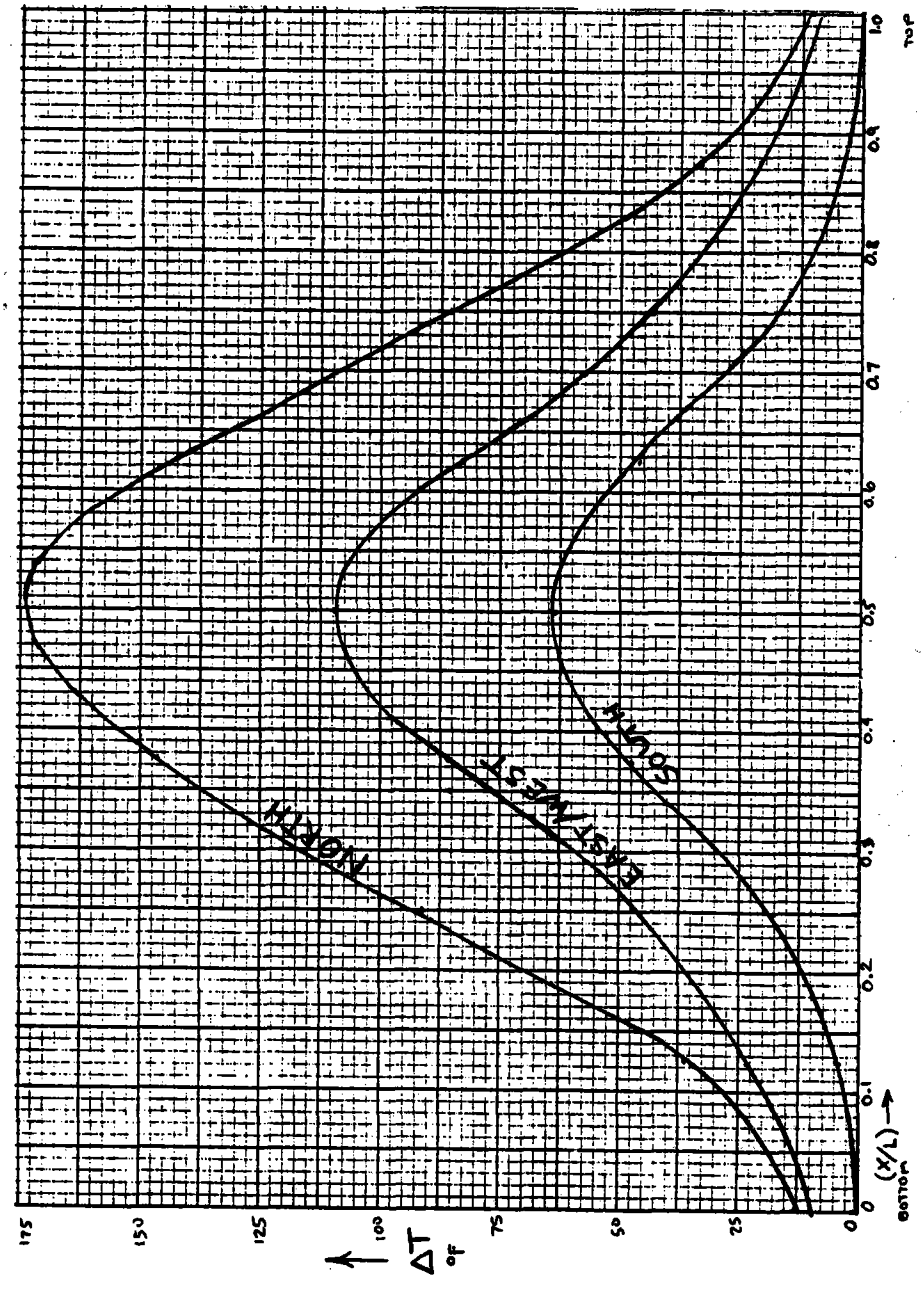

FIGURE 3

AXIAL TEMPERATURE DISTRIBUTION ON TUBES. Sodium & Surface For T_{Na} = 550° → 1100°F.

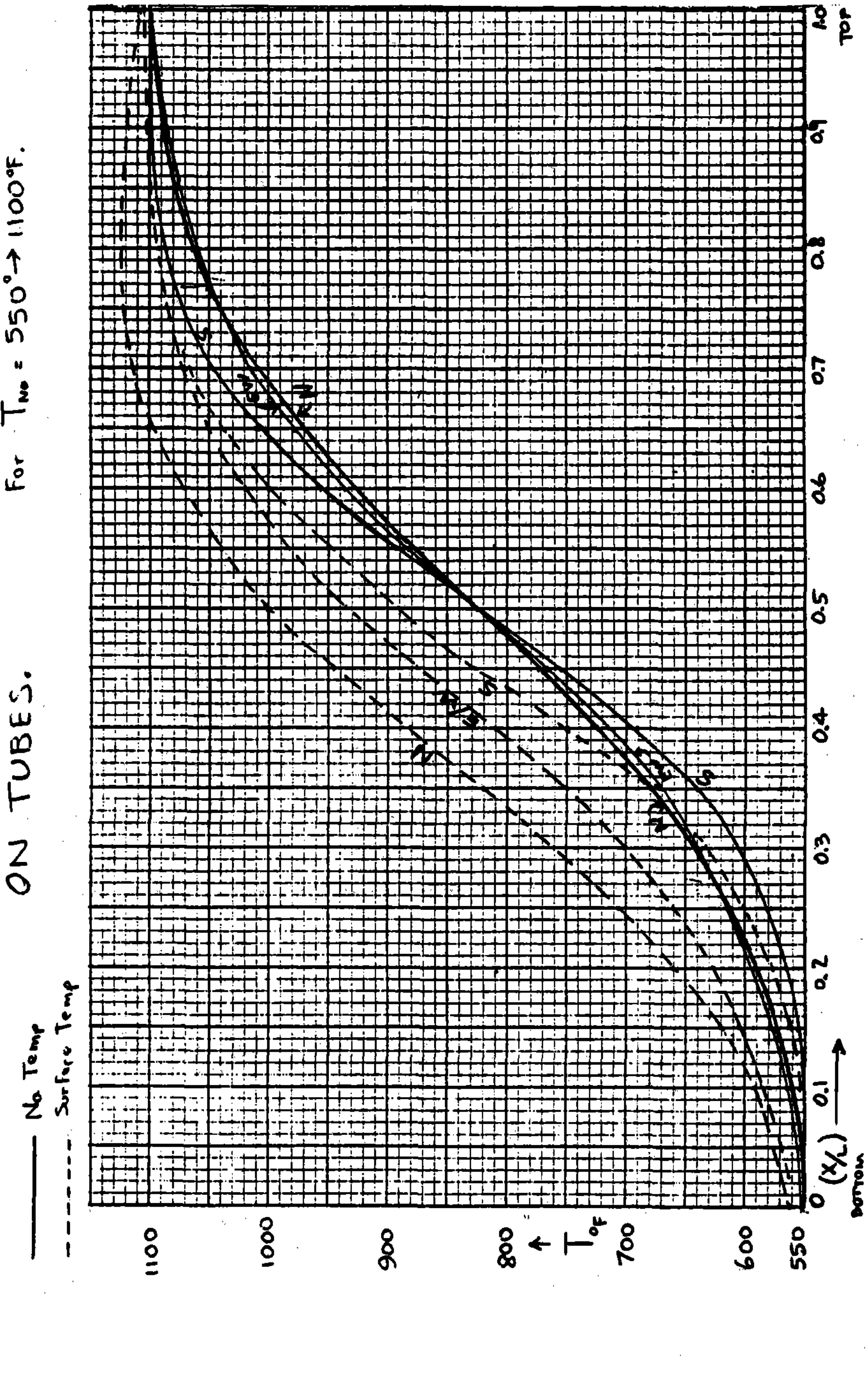

TABLE IV - (a-1)

DETERMINE AXIALLY AVERAGED TEMPERATURE

For T_{Na} = 550° F → 1100°F

QUADRANT: NORTH

	X/L	T_{Na} °F Surface Temp at Zero Power	ΔT °F Across Wall & Na Film	T_{surf} °F at Q = 429 MW
BOTTOM 1	0 — .05	552	13	565
2	.05 — .10	558	22	580
3	.10 — .15	567	36	603
4	.15 — .20	581	56	637
5	.20 — .25	601	80	681
6	.25 — .30	628	103	731
7	.30 — .35	663	127	790
8	.35 — .40	705	147	852
9	.40 — .45	752	161	913
10	.45 — .50	804	172	976
11	.50 — .55	846	172	1018
12	.55 — .60	898	158	1056
13	.60 — .65	945	140	1085
14	.65 — .70	987	119	1106
15	.70 — .75	1022	97	1119
16	.75 — .80	1049	75	1124
17	.80 — .85	1069	53	1122
18	.85 — .90	1083	34	1117
19	.90 — .95	1092	23	1115
20 TOP	.95 — 1.00	1098	13	1111

For T_{Na} = 650°F ⟶ 1200°F, Add 100°F.

For T_{Na} = 750°F ⟶ 1300°F, Add 200°F.

For T_{Na} = 850°F ⟶ 1400°F, Add 300°F.

TABLE IV - (a-2)

AXIALLY AVERAGED TEMPERATURES:

$n = 20$ Axial Divisions. **QUADRANT: NORTH**

* Based on Na Temp.

** Based on Surface Temp.

For $T_{Na} = 550^\circ F \rightarrow 1100^\circ F$,

$$\bar{\bar{T}}_{CONV} = \frac{\Sigma T_i}{20} = \begin{cases} Q=0^{*} & 825\ ^\circ F \\ Q=.429^{**} & 915.1\ ^\circ F \end{cases}$$

FOR CONVECTION

$$\bar{T}_{RAD} = \left(\frac{\Sigma (T_{oR})^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 870.4\ ^\circ F \\ Q=.429 & 958.1\ ^\circ F \end{cases}$$

FOR RADIATION

For $T_{Na} = 650^\circ F \rightarrow 1200^\circ F$

$$\bar{\bar{T}}_{CONV} = \frac{\Sigma T_i}{20} + 100 = \begin{cases} Q=0 & 925\ ^\circ F \\ Q=.429 & 1015.1\ ^\circ F \end{cases}$$

FOR CONV

$$T_{RAD} = \left(\frac{\Sigma (T_{oR}+100)^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 967.4\ ^\circ F \\ Q=.429 & 1055.5\ ^\circ F \end{cases}$$

FOR RAD

For $T_{Na} = 750^\circ F \rightarrow 1300^\circ F$

$$\bar{\bar{T}}_{CONV} = \frac{\Sigma T_i}{20} + 200 = \begin{cases} Q=0 & 1025\ ^\circ F \\ Q=.429 & 1115.1\ ^\circ F \end{cases}$$

FOR CONV

$$T_{RAD} = \left(\frac{\Sigma (T_{oR}+200)^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 1064.7\ ^\circ F \\ Q=.429 & 1153.2\ ^\circ F \end{cases}$$

FOR RAD

For $T_{Na} = 850^\circ F \rightarrow 1400^\circ F$

$$\bar{\bar{T}}_{CONV} = \frac{\Sigma T_i}{20} + 300 = \begin{cases} Q=0 & 1125\ ^\circ F \\ Q=.429 & 1215.1\ ^\circ F \end{cases}$$

FOR CONV

$$T_{RAD} = \left(\frac{\Sigma (T_{oR}+300)^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 1162.4\ ^\circ F \\ Q=.429 & 1251.2\ ^\circ F \end{cases}$$

FOR RAD

TABLE IV - (b-1)

DETERMINE AXIALLY AVERAGED TEMPERATURE

For T_{Na} = 550°F → 1100°F

QUADRANT: EAST/WEST

	X/L	T_{Na} °F Surface Temp at Zero Power	ΔT °F Across Wall & Na Film	T_{surf} °F at Q = 429 MW
BOTTOM 1	0 — .05	553	11	564
2	.05 — .10	560	16	576
3	.10 — .15	570	23	593
4	.15 — .20	584	31	615
5	.20 — .25	602	39	641
6	.25 — .30	626	52	678
7	.30 — .35	653	68	721
8	.35 — .40	693	86	779
9	.40 — .45	746	99	845
10	.45 — .50	802	108	910
11	.50 — .55	848	108	956
12	.55 — .60	904	97	1001
13	.60 — .65	954	83	1037
14	.65 — .70	997	65	1062
15	.70 — .75	1024	50	1074
16	.75 — .80	1048	38	1086
17	.80 — .85	1066	28	1094
18	.85 — .90	1080	22	1102
19	.90 — .95	1090	14	1104
20 TOP	.95 — 1.00	1097	10	1107

For T_{Na} = 650°F → 1200°F, Add 100°F.

For T_{Na} = 750°F → 1300°F, Add 200°F.

For T_{Na} = 850°F → 1400°F, Add 300°F.

TABLE IV - (b-2)

AXIALLY AVERAGED TEMPERATURES:

$n = 20$ Axial Divisions.   QUADRANT: EAST/WEST

For T_{Na} = 550° F → 1100°F,

$$\bar{\bar{T}}_{CONV} = \frac{\Sigma T_i}{20} = \begin{cases} Q=0 & 825\ °F \\ Q=429 & 877.3\ °F \end{cases}$$

FOR CONVECTION

$$\bar{T}_{RAD} = \left(\frac{\Sigma (T_{oR})^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 870.5\ °F \\ Q=429 & 920.8\ °F \end{cases}$$

FOR RADIATION

For T_{Na} = 650°F → 1200°F

$$\bar{\bar{T}}_{CONV} = \frac{\Sigma T_i}{20} + 100 = \begin{cases} Q=0 & 925\ °F \\ Q=429 & 977.3\ °F \end{cases}$$

FOR CONV

$$T_{RAD} = \left(\frac{\Sigma (T_{oR}+100)^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 967.5\ °F \\ Q=429 & 1018.1\ °F \end{cases}$$

FOR RAD

For T_{Na} = 750°F → 1300°F

$$\bar{\bar{T}}_{CONV} = \frac{\Sigma T_i}{20} + 200 = \begin{cases} Q=0 & 1025\ °F \\ Q=429 & 1077.3\ °F \end{cases}$$

FOR CONV

$$T_{RAD} = \left(\frac{\Sigma (T_{oR}+200)^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 1064.8\ °F \\ Q=429 & 1115.7\ °F \end{cases}$$

FOR RAD

For T_{Na} = 850°F → 1400°F

$$\bar{T}_{CONV} = \frac{\Sigma T_i}{20} + 300 = \begin{cases} Q=0 & 1125\ °F \\ Q=429 & 1177.3\ °F \end{cases}$$

FOR CONV

$$T_{RAD} = \left(\frac{\Sigma (T_{oR}+300)^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 1162.5\ °F \\ Q=429 & 1213.5\ °F \end{cases}$$

FOR RAD

TABLE IV - (c-1)

DETERMINE AXIALLY AVERAGED TEMPERATURE

For T_{Na} = 550°F → 1100°F

QUADRANT: SOUTH

	X/L	T_{Na} °F Surface Temp at Zero Power	ΔT °F Across Wall & Na Film	T_{surf} °F at Q = 429 MW
BOTTOM 1	0 — .05	550	1	551
2	.05 — .10	551	2	553
3	.10 — .15	554	4	558
4	.15 — .20	560	8	568
5	.20 — .25	572	13	585
6	.25 — .30	593	22	615
7	.30 — .35	625	33	658
8	.35 — .40	670	47	714
9	.40 — .45	730	57	787
10	.45 — .50	797	62	859
11	.50 — .55	853	62	915
12	.55 — .60	920	55	975
13	.60 — .65	980	45	1025
14	.65 — .70	1025	33	1058
15	.70 — .75	1057	22	1079
16	.75 — .80	1078	13	1091
17	.80 — .85	1090	7	1097
18	.85 — .90	1096	3	1099
19	.90 — .95	1099	2	1101
20 TOP	.95 — 1.00	1100	1	1101

For T_{Na} = 650°F → 1200°F, Add 100°F.

For T_{Na} = 750°F → 1300°F, Add 200°F.

For T_{Na} = 850°F → 1400°F, Add 300°F.

TABLE IV - (c-2)

AXIALLY AVERAGED TEMPERATURES:

$n = 20$ Axial Divisions. QUADRANT: SOUTH

For $T_{Na} = 550°F \rightarrow 1100°F$,

$$\bar{T}_{CONV} = \frac{\Sigma T_i}{20} = \begin{cases} Q=0 & 825\ °F \\ Q=.429 & 849.6\ °F \end{cases}$$

FOR CONVECTION

$$\bar{T}_{RAD} = \left(\frac{\Sigma (T_{oR})^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 878.6\ °F \\ Q=.429 & 901.8\ °F \end{cases}$$

FOR RADIATION

For $T_{Na} = 650°F \rightarrow 1200°F$

$$\bar{T}_{CONV} = \frac{\Sigma T_i}{20} + 100 = \begin{cases} Q=0 & 925\ °F \\ Q=.429 & 949.6\ °F \end{cases}$$

FOR CONV

$$T_{RAD} = \left(\frac{\Sigma (T_{oR}+100)^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 975.1\ °F \\ Q=.429 & 998.5\ °F \end{cases}$$

FOR RAD

For $T_{Na} = 750°F \rightarrow 1300°F$

$$\bar{T}_{CONV} = \frac{\Sigma T_i}{20} + 200 = \begin{cases} Q=0 & 1025\ °F \\ Q=.429 & 1049.6\ °F \end{cases}$$

FOR CONV

$$T_{RAD} = \left(\frac{\Sigma (T_{oR}+200)^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 1072.1\ °F \\ Q=.429 & 1095.6\ °F \end{cases}$$

FOR RAD

For $T_{Na} = 850°F \rightarrow 1400°F$

$$\bar{T}_{CONV} = \frac{\Sigma T_i}{20} + 300 = \begin{cases} Q=0 & 1125\ °F \\ Q=.429 & 1149.6\ °F \end{cases}$$

FOR CONV

$$T_{RAD} = \left(\frac{\Sigma (T_{oR}+300)^4}{20}\right)^{1/4} - 460 = \begin{cases} Q=0 & 1169.3\ °F \\ Q=.429 & 1193.0\ °F \end{cases}$$

FOR RAD

TABLE V

EFFECTIVE MEAN TEMPERATURES (All Four Quadrants)

$$\bar{T}_{\substack{RAD\\ ^\circ F}} = \left\{\frac{(\bar{T}_{Rad_N}+460)^4 + 2(\bar{T}_{Rad_{E/W}}+460)^4 + (\bar{T}_{Rad_S}+460)^4}{4}\right\}^{1/4} - 460$$

$$\bar{T}_{\substack{CONV\\ ^\circ F}} = \left\{\frac{\bar{T}_{CONV_N} + 2\bar{T}_{CONV_{E/W}} + \bar{T}_{CONV_S}}{4}\right\}$$

		"No Power" (RAD)	"Full Power" (RAD)	"No Power" (Conv)	"Full Power" (Conv)
550°	N	870.4	958.1	825	915.1
↓	E/W	870.5	920.8	825	877.3
1100°	E/W	870.5	920.8	825	877.3
	S	878.6	901.8	825	849.6

$\bar{T}_{RAD} = \begin{cases}1332.5\,^\circ R\\ 872.5\,^\circ F\end{cases}$ $\bar{T}_{RAD} = \begin{cases}1385.8\,^\circ R\\ 925.8\,^\circ F\end{cases}$ $\bar{T}_{CONV} = 825\,^\circ F$ $\bar{T}_{CONV} = 879.8\,^\circ F$

		"No Power" (RAD)	"Full Power" (RAD)	"No Power" (Conv)	"Full Power" (Conv)
650°	N	967.4	1055.5	925	1015.1
↓	E/W	967.5	1018.1	925	977.3
1200°	E/W	967.5	1018.1	925	977.3
	S	975.1	998.5	925	949.6

$\bar{T}_{RAD} = \begin{cases}1429.4\,^\circ R\\ 969.4\,^\circ F\end{cases}$ $\bar{T}_{RAD} = \begin{cases}1483.0\,^\circ R\\ 1023.0\,^\circ F\end{cases}$ $\bar{T}_{CONV} = 925\,^\circ F$ $\bar{T}_{CONV} = 979.8\,^\circ F$

		"No Power" (RAD)	"Full Power" (RAD)	"No Power" (Conv)	"Full Power" (Conv)
750°	N	1064.7	1153.2	1025	1115.1
↓	E/W	1064.8	1115.7	1025	1077.3
1300°	E/W	1064.8	1115.7	1025	1077.3
	S	1072.1	1095.6	1025	1049.6

$\bar{T}_{RAD} = \begin{cases}1526.6\,^\circ R\\ 1066.6\,^\circ F\end{cases}$ $\bar{T}_{RAD} = \begin{cases}1580.5\,^\circ R\\ 1120.5\,^\circ F\end{cases}$ $\bar{T}_{CONV} = 1025\,^\circ F$ $\bar{T}_{CONV} = 1079.8\,^\circ F$

		"No Power" (RAD)	"Full Power" (RAD)	"No Power" (Conv)	"Full Power" (Conv)
850°	N	1162.4	1251.2	1125	1215.1
↓	E/W	1162.5	1213.5	1125	1177.3
1400°	E/W	1162.5	1213.5	1125	1177.3
	S	1169.3	1193.0	1125	1149.6

$\bar{T}_{RAD} = \begin{cases}1624.2\,^\circ R\\ 1164.2\,^\circ F\end{cases}$ $\bar{T}_{RAD} = \begin{cases}1678.2\,^\circ R\\ 1218.7\,^\circ F\end{cases}$ $\bar{T}_{CONV} = 1125\,^\circ F$ $\bar{T}_{CONV} = 1179.8\,^\circ F$

HEAT LOSSES:

RADIATION HEAT LOSSES:

For radiation heat loss, considered projected surface area of receiver.

24 panels:

Each panel;

Length = 52.5 ft

Width = 110 tubes * 0.75 $\frac{\text{inch width}}{\text{tube}}$ * $\frac{1}{12}\frac{\text{ft}}{\text{inch}}$ = 6.875 ft.

Projected area of one panel:

$A = (52.5\text{ ft})(6.875\text{ ft}) = 360.94\text{ ft}^2/\text{per panel}$

Each quadrant has 6 panels: $6 \times 360.94 = 2165.6\text{ ft}^2/_{\text{Quad}}$.

RADIATION HEAT LOSS PROJECTED AREA, FOR ONE QUADRANT	=	2166 ft²

Total Radiation Area, 4 Quadrants = 8664 ft²

RADIATION HEAT LOSS $= F\,\epsilon_{eff}\,\sigma A\left(\overline{T}^4_{\underset{°R}{H}} - T^4_{\underset{°R}{SINK}}\right)$

$Q = 3.9365 \times 10^{-12}\left(T^4 - 7.3116\,10^{10}\right)$

$F = 1.0$

$\epsilon_{eff} = 0.90$

$A\,(1\text{ Quad}) = 2166\text{ ft}^2$ $A\,(\text{All 4 Quad}) = 8664\text{ ft}^2$

$T_{SINK} = 60°F = 520°R$

$\sigma = .1713 \times 10^{-8}\ \text{BTU}/_{\text{hr ft}^2\,°R^4}$

$$\underset{\text{BTU/hr}}{Q_{\substack{RAD\\LOSS}}} = (1.0)(.90)\underset{\text{BTU/hr °R}^4\text{ ft}^2}{(.1713\times10^{-8})}\underset{\text{ft}^2}{(8664)}\left[\underset{°R}{\overline{T}^4_{RAD}} - \underset{°R}{(520)^4}\right]$$

$$\underset{\text{BTU/hr}}{Q} = 1.33573\times10^{-5}\left\{\overline{T}^4_{°R} - 7.3116\times10^{10}\right\}$$

$$\underset{\text{RAD LOSS}}{Q_{MW}} = \frac{Q^{\text{BTU}/\text{hr}}}{3.413\times10^{6}}$$

$$Q_{MW} = 3.9365\times10^{-12}\left(T^4_{°R} - 520^4\right)$$

$$\left\{\begin{array}{ll}\text{LOSS TO 60°F.} & Q_{\substack{RAD\\LOSS\\MW}} = 3.91365 \times 10^{-12}\left(\bar{T}_{°R}^{4} - 520^{4}\right) \\ \text{LOSS TO 0°R} & Q_{MW} = 3.91365 \times 10^{-12}\left(\bar{T}_{°R}^{4}\right)\end{array}\right.$$

TABLE VI

RADIATION HEAT LOSSES.

	"NO POWER"				"FULL POWER"			
TEMPERATURE CASE	$\bar{T}_{RAD}$ °F	$Q_{RAD\ LOSS}$ (To 60°F)	$Q_{RAD\ LOSS}$ (To 0°R)	$\frac{Q(\text{To } 60F)}{Q(\text{To } 0°R)}$	$\bar{T}$ °F	$Q_{RAD\ LOSS}$ (To 60°F)	$Q_{RAD\ LOSS}$ (To 0°R)	$\frac{Q(\text{To } 60F)}{Q(\text{To } 0°R)}$
		MWt				MWt		
550° — 1100°F	872.5	12.052	12.338	.97681	925.8	14.148	14.434	.98018
650° — 1200°F	969.4	16.052	16.338	.98249	1023.0	18.644	18.930	.98488
750° — 1300°F	1066.6	20.970	21.256	.98654	1120.5	24.135	24.421	.98828
850° — 1400°F	1164.2	26.950	27.236	.98949	1218.2	30.756	31.043	.99078

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NATURAL CONVECTION: (Vertical Cylinder)

$$Nu = 0.13\,(Gr\,Pr)^{1/3}$$

$$h_{\substack{NAT\\CONV}} \frac{BTU}{hr\ ft^2\ {}^\circ F} = (.13\,FACT)\,\Delta T^{1/3}$$

Ref. 7 $$(.13\,FACT) = 0.13\,k\left(\frac{g\,\beta\,\rho^2}{\mu^2}\,Pr\right)^{1/3}$$

"No Power"

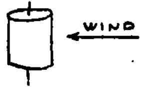
CASE	$\bar{T}_{CONV}$	T_F $\left(\frac{\bar{T}+60}{2}\right)$	ΔT $(\bar{T}-60)$	(.13 FACT) Based on T_F	$h_{\substack{NAT\\CONV}}$ BTU/hr ft² °F $= (.13\,FACT)\Delta T^{1/3}$
550→1100°	825	442	765	0.152	1.390
650→1200°	925	492	865	0.147	1.401
750→1300°	1025	542	965	0.142	1.403
850→1400°	1125	592	1065	0.137	1.399
"Full Power"					
550→1100°	880	470	820	0.149	1.395
650→1200	980	520	920	0.144	1.401
750→1300	1080	570	1020	0.139	1.399
850→1400	1180	620	1120	0.1345	1.397

$\bar{h} \cong 1.40$ BTU/hr ft² °F

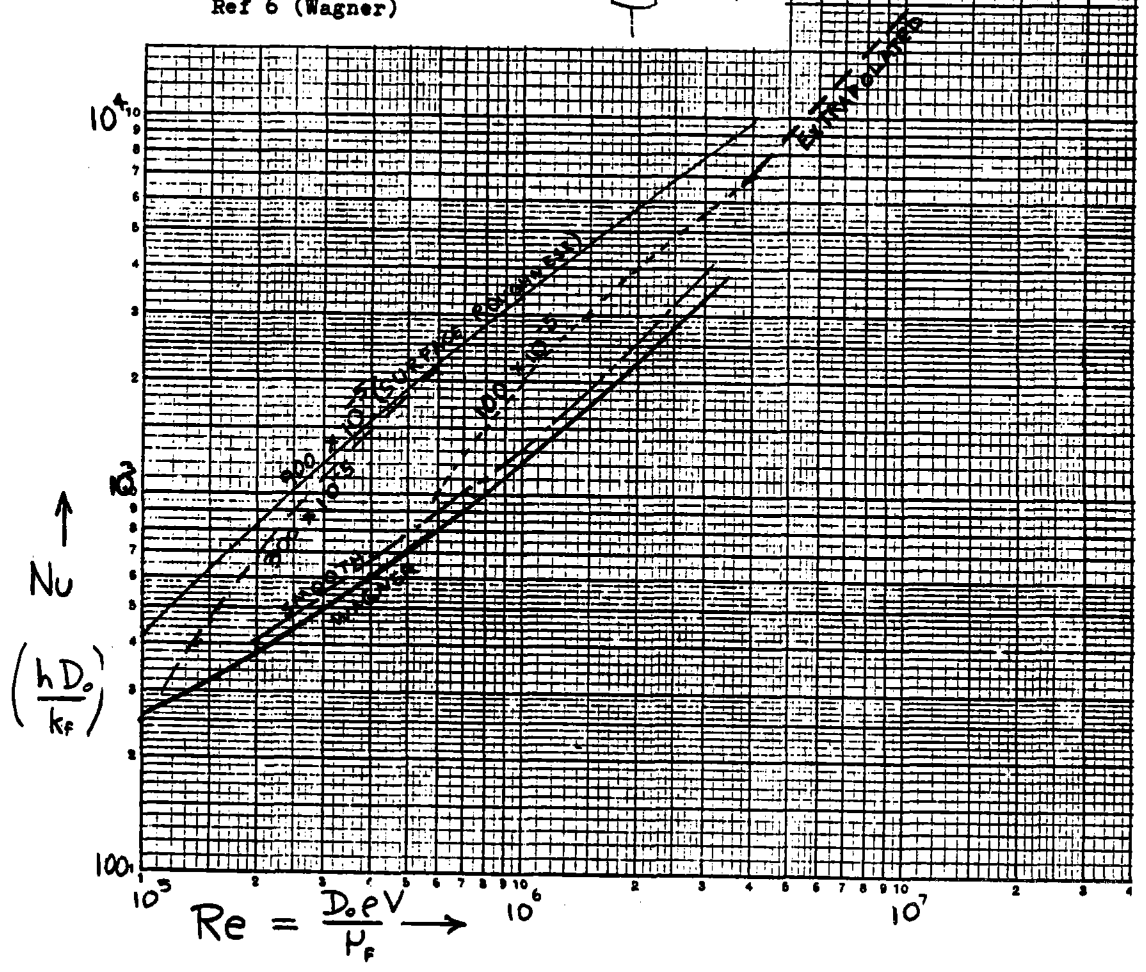
$$\boxed{\text{SAY: } h_{\substack{NAT\\CONV}} = 1.40\ \frac{BTU}{hr\ ft^2\ {}^\circ F}}$$

FIGURE 4 FORCED CONVECTION HEAT TRANSFER CORRELATION

Nu_f versus Re_f
Flow normal to cylinder axis



From: Ref 5 (Achenbach)
Ref 6 (Wagner)



FORCED CONVECTION HEAT LOSSES:

For convection heat loss, do not consider the actual "bumpy" surface area ($\pi/2\ d\ell$ of each tube), but only the projected area ($d\ell$ of each tube). The arc of the tube can be considered a "surface roughness", and influence h in that way.

Notice that the protuberence ($d/2$) of each tube in a panel is very small when compared to the diameter of the receiver as a whole.

RECEIVER DIAMETER $D = 52.5\ \text{ft} = 630\ \text{inches}$

"SURFACE ROUGHNESS", $k = d/2 = \frac{0.75}{2} = 0.375$ inch

$$\left(\begin{matrix}\text{SURFACE ROUGHNESS}\\ \text{PARAMETER}\end{matrix}\right) = \frac{0.375}{630} = .000595 = 60 \times 10^{-5}$$

$$\boxed{\left(\begin{matrix}\text{SURFACE}\\ \text{ROUGHNESS}\end{matrix}\right) = 60 \times 10^{-5}}$$

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FORCED CONVECTION:

Evaluate air properties at "FILM" temperature. Average film temperature varies from 440° to 620°F.

Say: $T_F \cong 500°F$

$D = 16 \text{ meters} = 52.5 \text{ ft.}$

Ref. 7

$\rho = 0.04133 \quad lb_m/ft^3 \quad (1.0 \text{ atm})$

$k = 0.02310 \quad BTU/hr\ ft\ °F$

$C_p = 0.24700 \quad BTU/lb_m\ °F$

$\mu = 0.06804 \quad lb_m/ft\ hr$

$\nu = 1.6465 \quad ft^2/hr$

$P_r = 0.7272$

$$\underset{\text{REYNOLDS}}{Re} = \frac{V\frac{ft}{sec}\ D ft\ 3600\frac{sec}{hr}}{\nu\ \frac{ft^2}{hr}} = \frac{V_{FPS}(52.5ft)(3600\frac{s}{h})}{1.6465\frac{ft^2}{h}} = 114,790\ \underset{FPS}{V}$$

$$\underset{\text{NUSSELT}}{Nu} = \frac{hD}{k} \qquad \underset{\frac{BTU}{hr\ ft^2\ °F}}{h} = Nu\frac{k^{\frac{BTU}{hr\ ft\ °F}}}{D_{ft}} = \frac{Nu(.02310)}{52.5} = 0.00044\ Nu$$

WIND VELOCITIES TO CONSIDER:

Note: $\left(\frac{258}{10}\right)^{0.15} = 1.628332$

$1.0\frac{m}{sec} = 3.28084\frac{ft}{sec}$

① $3.5\frac{m}{sec}$ at Elev = 10 meters.

At Elev = 258m, $V = V_0\left(\frac{H}{H_0}\right)^{0.15}$

$V = 3.5\left(\frac{258}{10}\right)^{0.15} = 5.70\frac{m}{sec} = \underline{18.70\ ft/sec}$ ①

② Intermediate:

$\underline{36.06\ ft/sec}$ ②

③ $10.0\frac{m}{sec}$ at Elev = 10 meters

At Elev = 258m, $V = 10.0\left(\frac{258}{10}\right)^{0.15} = 16.28\frac{m}{sec} = \underline{53.42\ ft/sec}$ ③

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TABLE VII CONVECTION HEAT TRANSFER COEFFICIENTS

	V VELOCITY FPS	Re $114790 V_{FPS}$	Nu FROM PLOT	$h_{FORCED\ CONV}$ BTU/hr ft² °F .00044 Nu	
(5.7 m/s)	18.70	2.15×10^6	4200	1.848	FORCED CONVECTION COEFFICIENT
(11.0 m/s)	36.06	4.14×10^6	7400	3.256	
(16.28 m/s)	53.42	6.13×10^6	11,000	4.840	

To take some account for additional losses occuring due to natural convection, the following relationship has been assumed:

$$h_{EFF} \cong \sqrt{h^2_{FORCED\ CONV} + h^2_{NAT\ CONV}}$$

V FPS	$h_{FORCED\ CONV}$	$h_{NAT\ CONV}$	h_{EFF} $\frac{BTU}{hr\ ft^2\ °F}$	
18.70	1.848	1.40	2.318	"COMBINED" CONVECTION COEFFICIENT
36.06	3.256	1.40	3.544	
53.42	4.840	1.40	5.038	

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TABLE VIII
CONVECTION HEAT LOSSES.

$$\underset{\substack{CONV\\LOSS}}{Q} = h A \Delta T$$

$$\underset{MW}{Q_{\substack{CONV\\LOSS}}} = \underset{\frac{BTU}{hr\,ft^2\,°F}}{h} \; \underset{ft^2}{8664} \; \underset{°F}{\Delta T} \; \frac{1}{3.413\times10^{6}} \frac{hr\,MW}{BTU}$$

$$\underset{MW}{Q} = 0.0025385 \; h_{eff} \; \Delta T$$

TEMP CASE	VEL ft/sec	h_{eff} $\frac{BTU}{hr\,ft^2\,°F}$	"NO POWER"			"FULL POWER"		
			$\bar{T}_{CONV}$	ΔT $(\bar{T}-60)$	Q_{LOSS} MW	$\bar{T}$	ΔT	Q_{LOSS} MW
550-1100	18.70	2.318	825	765	4.501	880	820	4.825
	36.06	3.544	"	"	6.882	"	"	7.377
	53.42	5.038	"	"	9.784	"	"	10.487
650-1200	18.70	2.318	925	865	5.090	980	920	5.414
	36.06	3.544	"	"	7.782	"	"	8.277
	53.42	5.038	"	"	11.063	"	"	11.766
750-1300	18.70	2.318	1025	965	5.678	1080	1020	6.002
	36.06	3.544	"	"	8.682	"	"	9.176
	53.42	5.038	"	"	12.341	"	"	13.045
850-1400	18.70	2.318	1125	1065	6.267	1180	1120	6.590
	36.06	3.544	"	"	9.581	"	"	10.076
	53.42	5.038	"	"	13.620	"	"	14.324

CONVECTION HEAT LOSSES.

"COMBINED" Natural & Forced.

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COMBINED RADIATION & CONVECTION LOSSES.

		$Q_{Na} = 0$ "NO POWER"			$Q_{Na} = 429\ MW_t$ "FULL POWER"		
TEMP CASE	WIND VEL. Ft/sec	Q CONV MW	Q RAD MW	Q RAD + CONV MW	Q CONV MW	Q RAD MW	Q RAD + CONV MW
550 1100	18.7	4.501	12.052	16.553	4.825	14.148	18.973
	36.06	6.882	"	18.934	7.377	"	21.525
	53.12	9.784	"	21.836	10.487	"	24.635
650 1200	18.7	5.090	16.052	21.142	5.414	18.644	24.058
	36.06	7.782	"	23.834	8.277	"	26.921
	53.12	11.063	"	27.115	11.766	"	30.410
750 1300	18.7	5.678	20.970	26.648	6.002	24.128	30.130
	36.06	8.682	"	29.652	9.176	"	33.304
	53.12	12.341	"	33.311	13.045	"	37.173
850 1400	18.7	6.267	26.950	33.217	6.590	30.756	37.346
	36.06	9.581	"	36.531	10.076	"	40.832
	53.12	13.620	"	40.570	14.324	"	45.080

COMBINED RADIATION and CONVECTION LOSSES.

MW_t

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TABLE X-a. HEAT LOSS CALCULATIONS

TEMP RANGE (550°F → 1100°F)

	LOW VELOCITY (5.7 m/s = 18.70 fps)							INTERMEDIATE VELOCITY (11.0 m/s = 36.06 fps)							HIGH VELOCITY (16.28 m/s = 53.42 fps)					
Q_{Na} MW$_t$ ABSORBED BY SODIUM	$Q_{RAD\ LOSS}$ MW$_t$ (% of Q_{incid})	$Q_{CONV\ LOSS}$ MW$_t$ (% of Q_{incid})	$Q_1 = Q_R + Q_C + Q_{Na}$ MW$_t$	Q_{REFLEC} $\frac{5}{95} Q_1$ (% of Q_{incid})	Q_{INCID} $Q_1 + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ % $(1 - \frac{Q_{Na}}{Q_{incid}})$	$Q_{RAD\ LOSS}$ MW$_t$ (% of Q_{incid})	$Q_{CONV\ LOSS}$ MW$_t$ (% of Q_{incid})	$Q_1 = Q_R + Q_C + Q_{Na}$ MW$_t$	Q_{REFLEC} $\frac{5}{95} Q_1$ (% of Q_{incid})	Q_{INCID} $Q_1 + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ % $(1 - \frac{Q_{Na}}{Q_{incid}})$	$Q_{RAD\ LOSS}$ MW$_t$ (% of Q_{incid})	$Q_{CONV\ LOSS}$ MW$_t$ (% of Q_{incid})	$Q_1 = Q_R + Q_C + Q_{Na}$ MW$_t$	Q_{REFLEC} $\frac{5}{95} Q_1$ (% of Q_{incid})	Q_{INCID} $Q_1 + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ % $(1 - \frac{Q_{Na}}{Q_{incid}})$		
429	14.15	4.83	447.98	23.58	471.56	90.97	14.15	7.38	450.53	23.71	474.24	90.46	14.15	10.49	453.64	23.88	477.52	89.84		
	(3.00)	(1.02)		(5.00)	(42.56)	(9.03)	(2.98)	(1.56)		(5.0)	(45.24)	(9.54)	(2.96)	(2.20)		(5.0)	(48.52)	(10.16)		
400	14.01	4.81	418.82	22.04	440.86	90.73	14.01	7.35	421.36	22.18	443.54	90.18	14.01	10.44	424.45	22.34	446.79	89.53		
	(3.18)	(1.09)		(5.00)	(40.86)	(9.27)	(3.16)	(1.66)		(5.00)	(43.54)	(9.82)	(3.14)	(2.34)		(5.0)	(46.79)	(10.47)		
350	13.76	4.77	368.53	19.40	387.93	90.22	13.76	7.29	371.05	19.53	390.58	89.61	13.76	10.36	374.12	19.69	393.81	88.88		
	(3.55)	(1.23)		(5.00)	(37.93)	(9.78)	(3.52)	(1.87)		(5.00)	(40.58)	(10.39)	(3.49)	(2.63)		(5.0)	(43.81)	(11.12)		
300	13.52	4.73	318.25	16.75	335.00	89.55	13.52	7.23	320.75	16.88	337.63	88.85	13.52	10.28	323.80	17.04	340.84	88.02		
	(4.04)	(1.41)		(5.00)	(35.00)	(10.45)	(4.00)	(2.14)		(5.00)	(37.63)	(11.15)	(3.97)	(3.02)		(5.0)	(40.84)	(11.98)		
250	13.27	4.69	267.96	14.10	282.06	88.63	13.27	7.17	270.44	14.23	284.67	87.82	13.27	10.19	273.46	14.39	287.85	86.85		
	(4.70)	(1.66)		(5.00)	(32.06)	(11.37)	(4.66)	(2.52)		(5.00)	(34.67)	(12.18)	(4.61)	(3.54)		(5.0)	(37.85)	(13.15)		
200	13.03	4.65	217.68	11.46	229.14	87.28	13.03	7.11	220.14	11.59	231.73	86.31	13.03	10.11	223.14	11.74	234.88	85.15		
	(5.69)	(2.03)		(5.00)	(29.14)	(12.72)	(5.62)	(3.07)		(5.00)	(31.73)	(13.69)	(5.55)	(4.30)		(5.0)	(34.88)	(14.85)		
150	12.78	4.62	167.40	8.81	176.21	85.13	12.78	7.05	169.83	8.94	178.77	83.91	17.78	10.03	172.81	9.10	181.91	82.46		
	(7.25)	(2.62)		(5.00)	(26.21)	(14.87)	(7.15)	(3.94)		(5.00)	(28.77)	(16.09)	(7.03)	(5.51)		(5.0)	(31.91)	(17.54)		
100	12.54	4.58	117.12	6.16	123.28	81.12	12.54	7.00	119.54	6.29	125.83	79.47	12.54	9.95	127.49	6.45	128.94	77.56		
	(10.17)	(3.72)		(5.00)	(23.28)	(18.88)	(9.97)	(5.56)		(5.00)	(25.83)	(20.53)	(9.73)	(7.72)		(5.0)	(28.94)	(22.44)		
0	12.05	4.50					12.05	6.88					12.05	9.78						

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TABLE X 1 HEAT LOSS CALCULATIONS

TEMP RANGE (650°F → 1200°F)

LOW VELOCITY (5.7 $\frac{m}{s}$ = 18.70 fps)

Q_{Na} MW$_t$ ABSORBED BY SODIUM	$Q_{RAD\ LOSS}$ MW$_t$ (% of Incid)	$Q_{CONV\ LOSS}$ MW$_t$ (% of Incid)	$Q_I = Q_R + Q_C + Q_{Na}$ MW$_t$	Q_{REFLEC} $\frac{5}{95} Q_I$ (% of Incid)	Q_{INCID} $Q_I + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ % $(1 - \frac{Q_{loss}}{Q_{incid}})$
429	18.64	5.41	453.05	23.84	476.89	89.96
	(3.91)	(1.13)		(5.00)	(47.89)	(10.04)
400	18.46	5.39	423.85	22.31	446.16	89.65
	(4.14)	(1.21)		(5.00)	(46.16)	(10.35)
350	18.16	5.35	373.51	19.66	393.17	89.02
	(4.62)	(1.36)		(5.00)	(43.17)	(10.98)
300	17.86	5.31	323.17	17.01	340.18	88.19
	(5.25)	(1.56)		(5.00)	(40.18)	(11.81)
250	17.56	5.28	272.84	14.36	287.20	87.05
	(6.11)	(1.84)		(5.00)	(37.20)	(12.95)
200	17.26	5.24	222.50	11.71	234.71	85.39
	(7.37)	(2.24)		(5.00)	(34.71)	(14.61)
150	16.96	5.20	172.17	9.06	181.22	82.77
	(9.36)	(2.87)		(5.00)	(31.22)	(17.23)
100	16.65	5.16	121.81	6.41	128.22	77.99
	(12.99)	(4.02)		(5.00)	(28.22)	(22.01)
0	16.05	5.09				

INTERMEDIATE VELOCITY (11.0 $\frac{m}{s}$ = 36.06 fps)

Q_{Na} MW$_t$ ABSORBED BY SODIUM	$Q_{RAD\ LOSS}$ MW$_t$ (% of Incid)	$Q_{CONV\ LOSS}$ MW$_t$ (% of Incid)	$Q_I = Q_R + Q_C + Q_{Na}$ MW$_t$	Q_{REFLEC} $\frac{5}{95} Q_I$ (% of Incid)	Q_{INCID} $Q_I + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ % $(1 - \frac{Q_{loss}}{Q_{incid}})$
429	18.64	8.28	455.92	24.00	479.92	89.39
	(3.88)	(1.73)		(5.00)	(50.92)	(10.61)
400	18.46	8.25	426.71	22.46	449.17	89.05
	(4.11)	(1.84)		(5.00)	(49.17)	(10.95)
350	18.16	8.19	376.35	19.81	396.16	88.35
	(4.58)	(2.07)		(5.00)	(46.16)	(11.65)
300	17.86	8.13	325.99	17.16	343.15	87.43
	(5.20)	(2.37)		(5.00)	(43.15)	(12.57)
250	17.56	8.07	275.63	14.51	290.14	86.17
	(6.05)	(2.78)		(5.00)	(40.14)	(13.83)
200	17.26	8.01	225.27	11.86	237.13	84.34
	(7.28)	(3.38)		(5.00)	(37.13)	(15.66)
150	16.96	7.95	174.91	9.21	184.12	81.47
	(9.21)	(4.32)		(5.0)	(34.12)	(18.53)
100	16.65	7.90	124.55	6.56	131.11	76.27
	(12.70)	(6.03)		(5.0)	(31.11)	(23.73)
	16.05	778				

HIGH VELOCITY (16.28 $\frac{m}{s}$ = 53.42 fps).

Q_{Na} MW$_t$ ABSORBED BY SODIUM	$Q_{RAD\ LOSS}$ MW$_t$ (% of Incid)	$Q_{CONV\ LOSS}$ MW$_t$ (% of Incid)	$Q_I = Q_R + Q_C + Q_{Na}$ MW$_t$	Q_{REFLEC} $\frac{5}{95} Q_I$ (% of Incid)	Q_{INCID} $Q_I + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ % $(1 - \frac{Q_{loss}}{Q_{incid}})$
429	18.64	11.77	459.41	24.18	483.59	88.71
	(3.85)	(2.43)		(5.0)	(54.59)	(11.29)
400	18.46	11.72	430.18	22.64	452.82	88.34
	(4.08)	(2.59)		(5.0)	(52.82)	(11.66)
350	18.16	11.64	379.80	19.99	399.79	87.55
	(4.54)	(2.91)		(5.0)	(49.79)	(12.45)
300	17.86	11.56	329.42	17.34	346.76	86.52
	(5.15)	(3.33)		(5.0)	(46.76)	(13.48)
250	17.56	11.47	279.03	14.69	293.72	85.12
	(5.98)	(3.91)		(5.0)	(43.72)	(14.88)
200	17.26	11.39	228.65	12.03	240.68	83.10
	(7.17)	(4.73)		(5.0)	(40.68)	(16.90)
150	16.96	11.31	178.27	9.38	187.65	79.93
	(9.04)	(6.03)		(5.0)	(37.65)	(20.07)
100	16.65	11.23	127.88	6.73	74.29	74.29
	(12.37)	(8.34)		(5.0)	(34.61)	(25.71)
	16.05	11.06				

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TABLE X - C HEAT LOSS CALCULATIONS

TEMP RANGE (750°F → 1300°F)

LOW VELOCITY ($5.7\frac{m}{s}$ = 18.70 fps)

Q_{Na} MW$_t$ ABSORBED BY SODIUM	$Q_{RAD\ LOSS}$ MW$_t$ (% of Incid)	$Q_{CONV\ LOSS}$ MW$_t$ (% of Incid)	$Q_1 = Q_R + Q_C + Q_{Na}$ MW$_t$	Q_{REFLEC} $\frac{5}{95} Q_1$ (% of Incid)	Q_{INCID} $Q_1 + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ % $(1 - \frac{Q_{Na}}{Q_{INCID}})$
429	24.13 (4.99)	6.00 (1.24)	459.13	24.16 (5.0)	483.29 (54.29)	88.77 (11.23)
400	23.92 (5.29)	5.98 (1.32)	429.90	22.63 (5.0)	452.53 (52.53)	88.39 (11.61)
350	23.55 (5.90)	5.44 (1.36)	379.49	19.97 (5.0)	399.46 (49.46)	87.62 (12.38)
300	23.18 (6.69)	5.90 (1.70)	329.08	17.32 (5.0)	346.40 (46.40)	86.61 (13.39)
250	22.81 (7.78)	5.87 (2.00)	278.68	14.67 (5.0)	293.35 (43.35)	85.22 (14.78)
200	22.44 (9.34)	5.83 (2.43)	228.27	12.01 (5.0)	240.28 (40.28)	83.23 (16.77)
150	22.07 (11.79)	5.79 (3.09)	177.86	9.36 (5.0)	187.22 (37.22)	80.12 (19.88)
100	21.71 (16.18)	5.75 (4.29)	127.46	6.71 (5.0)	134.17 (34.17)	74.53 (25.47)
0	20.97	5.68				

INTERMEDIATE VELOCITY ($11.0\frac{m}{s}$ = 36.06 fps)

Q_{Na} MW$_t$ ABSORBED BY SODIUM	$Q_{RAD\ LOSS}$ MW$_t$ (% of Incid)	$Q_{CONV\ LOSS}$ MW$_t$ (% of Incid)	$Q_1 = Q_R + Q_C + Q_{Na}$ MW$_t$	Q_{REFLEC} $\frac{5}{95} Q_1$ (% of Incid)	Q_{INCID} $Q_1 + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ % $(1 - \frac{Q_{Na}}{Q_{INCID}})$
429	24.13 (4.96)	9.18 (1.89)	462.31	24.33 (5.0)	486.64 (57.64)	88.16 (11.84)
400	23.92 (5.25)	9.15 (2.01)	433.07	22.79 (5.0)	455.86 (55.86)	87.75 (12.25)
350	23.55 (5.85)	9.09 (2.26)	387.64	20.14 (5.0)	402.78 (52.78)	86.90 (13.10)
300	23.18 (6.63)	9.03 (2.58)	332.21	17.48 (5.0)	349.69 (49.69)	85.79 (14.21)
250	22.81 (7.69)	8.97 (3.02)	281.78	14.83 (5.0)	296.61 (46.61)	84.29 (15.71)
200	22.44 (9.21)	8.91 (3.66)	231.35	12.18 (5.0)	243.53 (43.53)	82.13 (17.87)
150	22.07 (11.59)	8.85 (4.65)	180.92	9.52 (5.0)	190.44 (40.44)	78.76 (21.24)
100	21.71 (15.80)	8.80 (6.41)	130.51	6.87 (5.0)	137.38 (37.38)	72.79 (27.21)
0	20.97	8.68				

HIGH VELOCITY ($16.28\frac{m}{s}$ = 53.42 fps).

Q_{Na} MW$_t$ ABSORBED BY SODIUM	$Q_{RAD\ LOSS}$ MW$_t$ (% of Incid)	$Q_{CONV\ LOSS}$ MW$_t$ (% of Incid)	$Q_1 = Q_R + Q_C + Q_{Na}$ MW$_t$	Q_{REFLEC} $\frac{5}{95} Q_1$ (% of Incid)	Q_{INCID} $Q_1 + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ % $(1 - \frac{Q_{Na}}{Q_{INCID}})$
429	24.13 (4.92)	13.05 (2.66)	466.18	24.54 (5.0)	490.72 (61.72)	87.42 (12.58)
400	23.92 (5.20)	13.00 (2.83)	436.92	23.00 (5.0)	459.92 (59.92)	86.97 (13.03)
350	23.55 (5.79)	12.92 (3.18)	386.47	20.34 (5.0)	406.81 (56.81)	86.04 (13.96)
300	23.18 (6.55)	12.84 (3.63)	336.02	17.69 (5.0)	353.71 (53.71)	84.82 (15.18)
250	22.81 (7.59)	12.75 (4.24)	285.56	15.03 (5.0)	300.59 (50.59)	83.17 (16.83)
200	22.44 (9.07)	12.67 (5.12)	235.11	12.37 (5.0)	247.48 (47.48)	80.81 (19.19)
150	22.07 (11.35)	12.59 (6.48)	184.66	9.72 (5.0)	194.38 (44.38)	77.17 (22.83)
100	21.71 (15.37)	12.51 (8.85)	134.22	7.06 (5.0)	141.28 (41.28)	70.78 (29.22)
0	20.97	12.34				

TABLE X-d HEAT LOSS CALCULATIONS

TEMP RANGE (850°F → 1400°F)

	LOW VELOCITY (5.7 m/s = 18.70 fps)						INTERMEDIATE VELOCITY (11.0 m/s = 36.06 fps)						HIGH VELOCITY (16.28 m/s = 53.42 fps).					
Q_{Na} MWt ABSORBED BY SODIUM	$Q_{RAD\ LOSS}$ MWt (% of Incid)	$Q_{CONV\ LOSS}$ MWt (% of Incid)	$Q_1 = Q_R + Q_C + Q_{Na}$ MWt	Q_{REFLEC} $\frac{5}{95} Q_1$ (% of Incid)	Q_{INCID} $q + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ $(1 - \frac{q_{loss}}{q_{incid}})$	$Q_{RAD\ LOSS}$ MWt (% of Incid)	$Q_{CONV\ LOSS}$ MWt (% of Incid)	$Q_1 = Q_R + Q_C + Q_{Na}$ MWt	Q_{REFLEC} $\frac{5}{95} Q_1$ (% of Incid)	Q_{INCID} $q + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ $(1 - \frac{q_{loss}}{q_{incid}})$	$Q_{RAD\ LOSS}$ MWt (% of Incid)	$Q_{CONV\ LOSS}$ MWt (% of Incid)	$Q_1 = Q_R + Q_C + Q_{Na}$ MWt	Q_{REFLEC} $\frac{5}{95} Q_1$ (% of Incid)	Q_{INCID} $q + Q_{REF}$ (TOTAL LOSS)	$\frac{Q_{Na}}{Q_{INCID}}$ $(1 - \frac{q_{loss}}{q_{incid}})$
429	30.76	6.59	466.35	24.54	490.89	87.39	30.76	10.08	469.84	24.73	494.57	86.74	30.76	14.32	474.08	24.95	499.03	85.97
	(6.27)	(1.34)		(5.0)	(61.89)	(12.61)	(6.22)	(2.04)		(5.0)	(65.57)	(13.26)	(6.16)	(2.87)		(5.0)	(70.03)	(14.03)
400	30.50	6.57	437.07	23.00	460.07	86.94	30.50	10.05	440.55	23.19	463.74	86.26	30.50	14.27	444.77	23.41	468.18	85.44
	(6.63)	(1.43)		(5.0)	(60.07)	(13.06)	(6.58)	(2.17)		(5.0)	(63.74)	(13.74)	(6.51)	(3.09)		(5.0)	(68.18)	(14.56)
350	30.06	6.53	386.59	20.35	406.94	86.01	30.06	9.99	390.05	20.53	410.58	85.25	30.06	14.19	394.25	20.75	415.00	84.34
	(7.39)	(1.60)		(5.0)	(56.94)	(13.99)	(7.32)	(2.43)		(5.0)	(60.58)	(14.75)	(7.24)	(3.42)		(5.0)	(65.0)	(15.66)
300	29.61	6.49	336.10	17.69	353.79	84.80	29.61	9.93	339.54	17.87	357.41	83.94	29.61	14.11	343.72	18.09	361.81	82.92
	(8.37)	(1.83)		(5.0)	(53.79)	65.20)	(8.28)	(2.78)		(5.0)	(57.41)	(16.06)	(8.18)	(3.90)		(5.0)	(61.81)	(17.08)
250	29.17	6.46	285.63	15.03	300.66	83.15	29.17	9.87	289.04	15.21	304.25	82.17	29.17	14.03	293.20	15.43	308.63	81.00
	(9.70)	(2.15)		(5.0)	(50.66)	(16.85)	(9.59)	(3.24)		(5.0)	(54.25)	(17.83)	(9.45)	(4.55)		(5.0)	(58.63)	(19.00)
200	28.73	6.42	235.15	12.38	247.53	80.80	28.73	9.81	238.54	12.55	251.09	79.65	28.73	13.95	242.68	12.77	255.45	78.29
	(11.61)	(2.59)		(5.0)	(47.53)	(19.20)	(11.44)	(3.91)		(5.0)	(51.09)	(20.35)	(11.25)	(5.46)		(5.0)	(55.45)	(21.71)
150	28.28	6.38	184.66	9.72	194.38	77.17	28.28	9.75	188.03	9.90	197.93	75.79	28.28	13.86	192.14	10.11	202.25	74.16
	(14.55)	(3.28)		(5.0)	(44.38)	(22.83)	(14.29)	(4.93)		(5.0)	(47.93)	(24.21)	(13.98)	(6.85)		(5.0)	(52.25)	(25.84)
100	27.84	6.34	134.18	7.06	141.24	70.80	27.84	9.70	137.54	7.24	144.78	69.07	27.84	13.78	141.62	7.45	149.07	67.08
	(19.71)	(4.49)		(5.0)	(41.24)	(29.20)	(19.23)	(6.70)		(5.0)	(44.78)	(30.93)	(18.68)	(9.24)		(5.0)	(49.07)	(32.92)
0	26.95	6.27					26.95	9.58					26.95	13.62				

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Na TEMP: 550° → 1100°F

WIND:
5.7 $\frac{m}{s}$ = 18.70 $\frac{ft}{sec}$ = 12.75mph

A-33

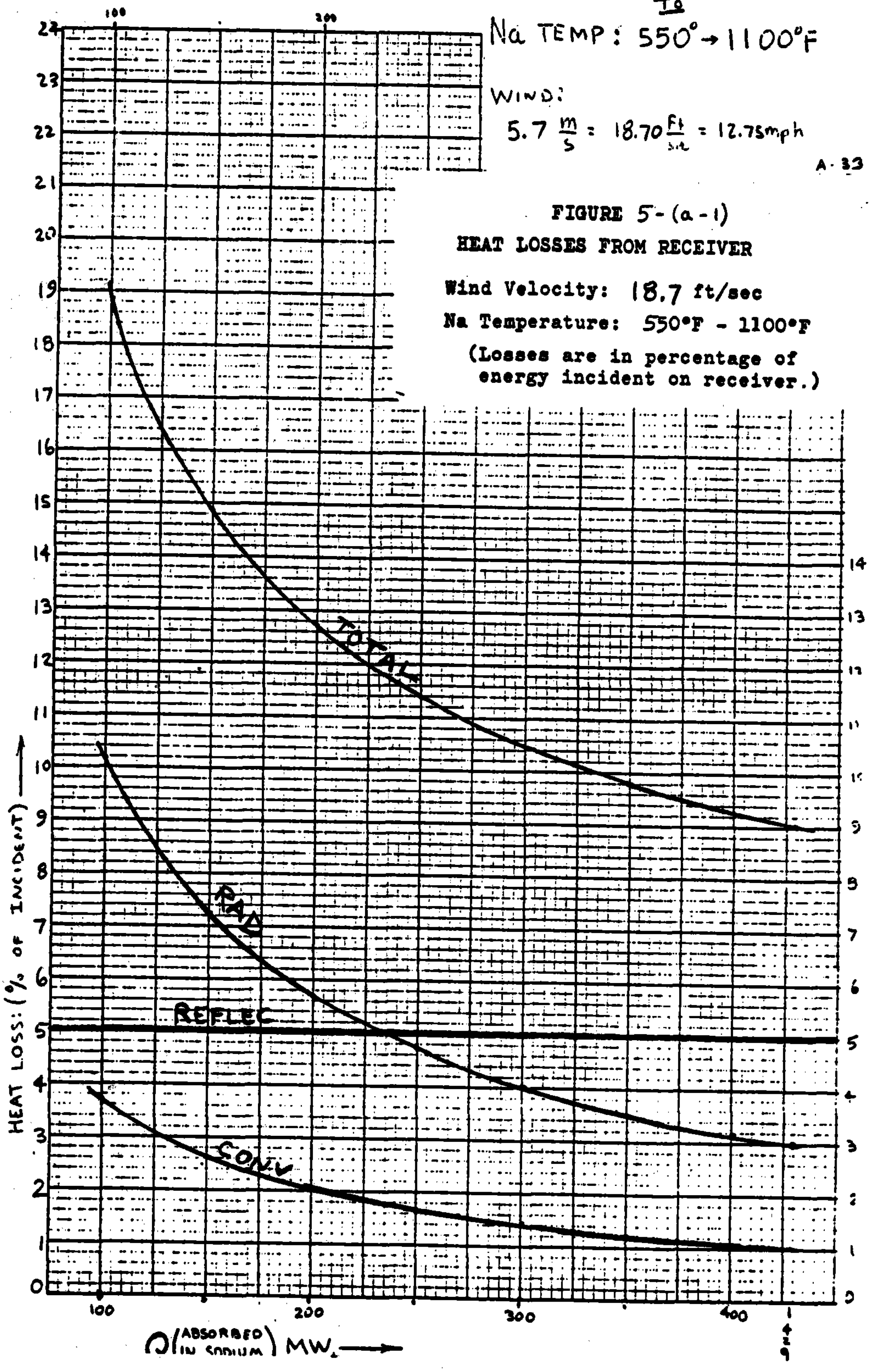

FIGURE 5-(a-1)
HEAT LOSSES FROM RECEIVER

Wind Velocity: 18.7 ft/sec
Na Temperature: 550°F - 1100°F
(Losses are in percentage of energy incident on receiver.)

Na TEMP: 550°→1100°F

WIND:
11.0 m/s = 36.1 ft/sec = 24.6 mph

A-34

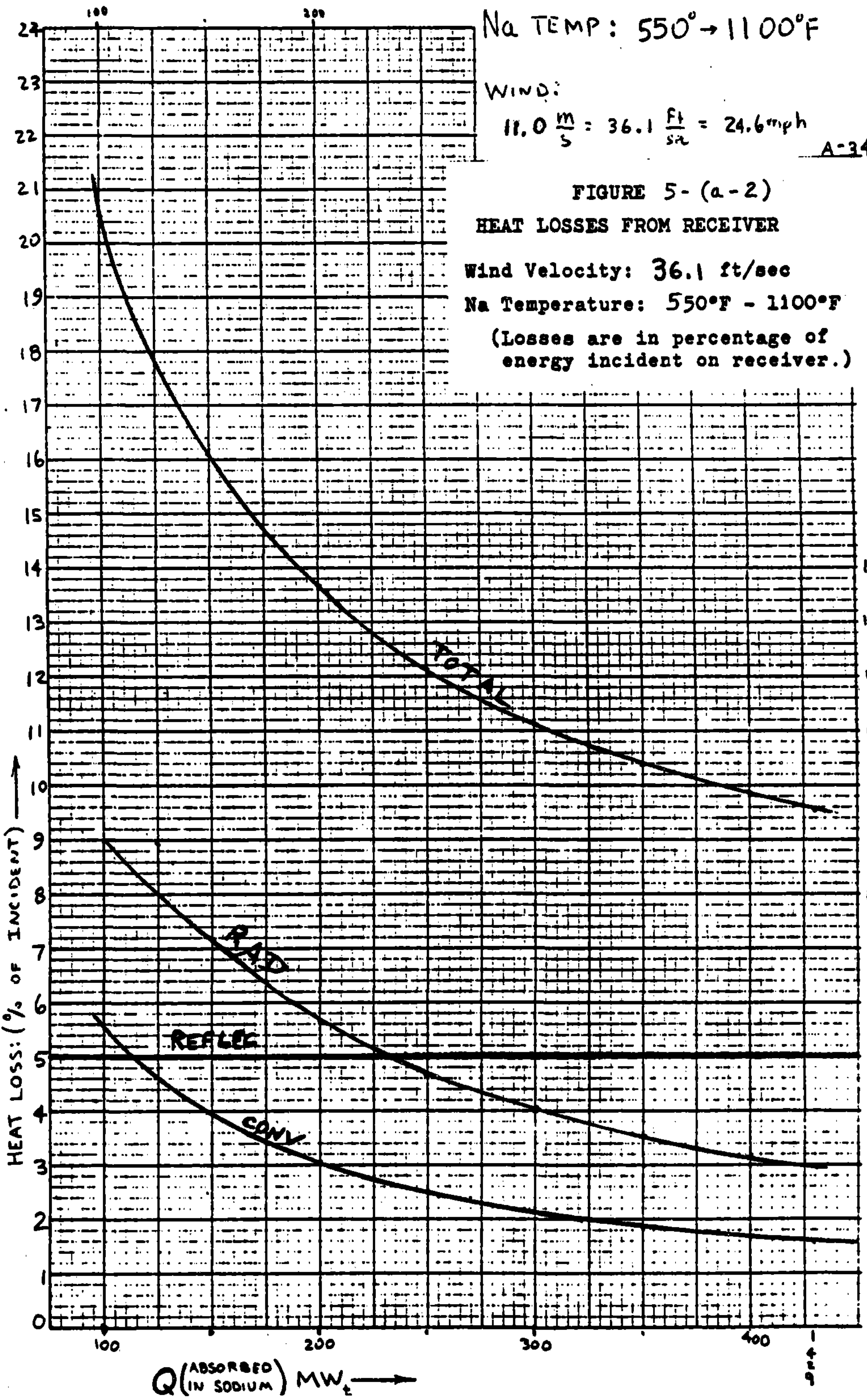

FIGURE 5-(a-2)
HEAT LOSSES FROM RECEIVER

Wind Velocity: 36.1 ft/sec
Na Temperature: 550°F - 1100°F
(Losses are in percentage of energy incident on receiver.)

50

Na TEMP: 550° → 1100°F

WIND:

16.28 $\frac{m}{s}$ = 53.4 $\frac{ft}{sec}$ = 36.4mph

A 35

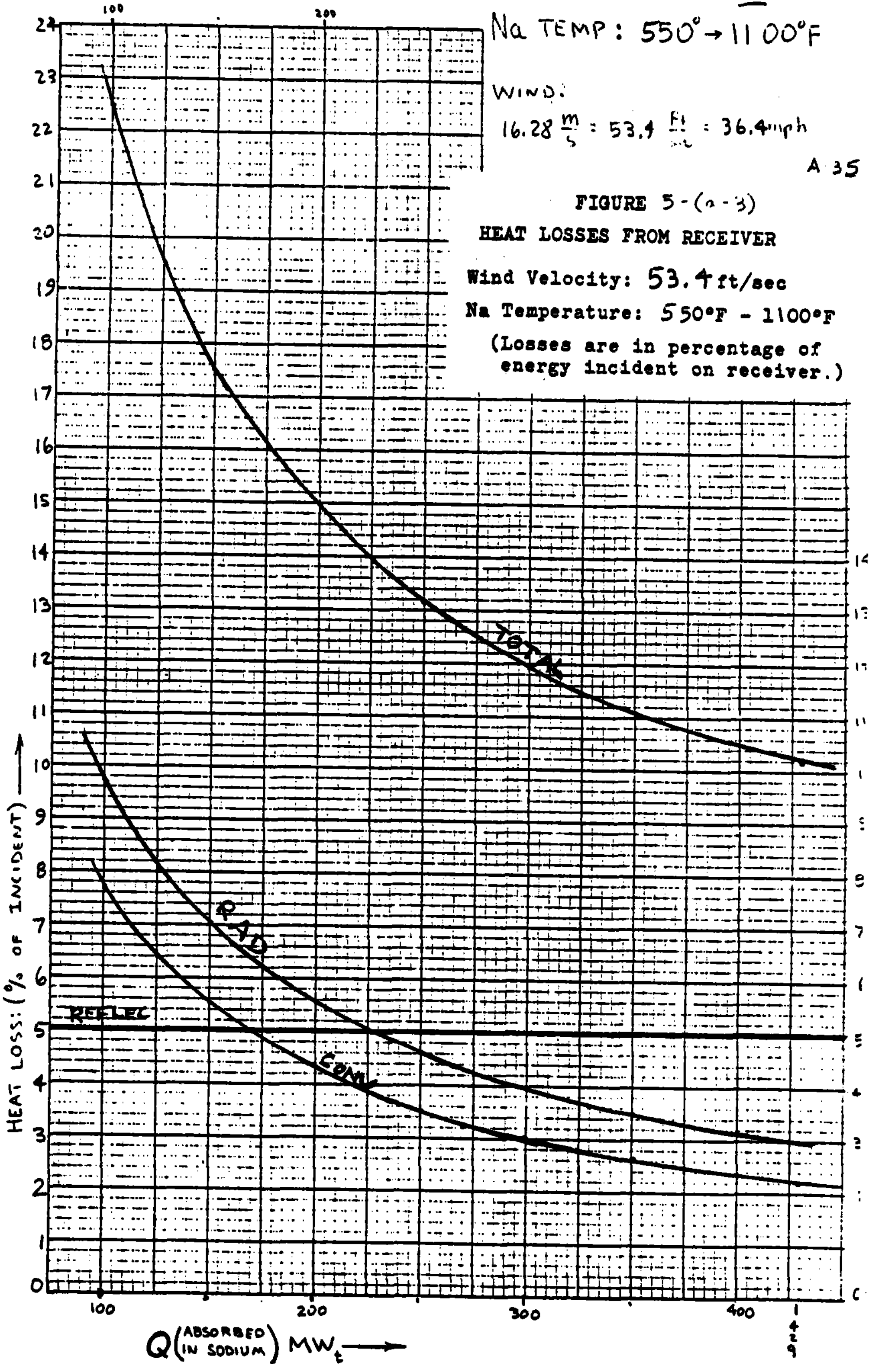

FIGURE 5-(a-3)

HEAT LOSSES FROM RECEIVER

Wind Velocity: 53.4 ft/sec

Na Temperature: 550°F - 1100°F

(Losses are in percentage of energy incident on receiver.)

Na TEMP: 650° → 1200°F

WIND:
5.7 $\frac{m}{s}$ = 18.7 $\frac{ft}{sec}$ = 12.75 mph

A-36

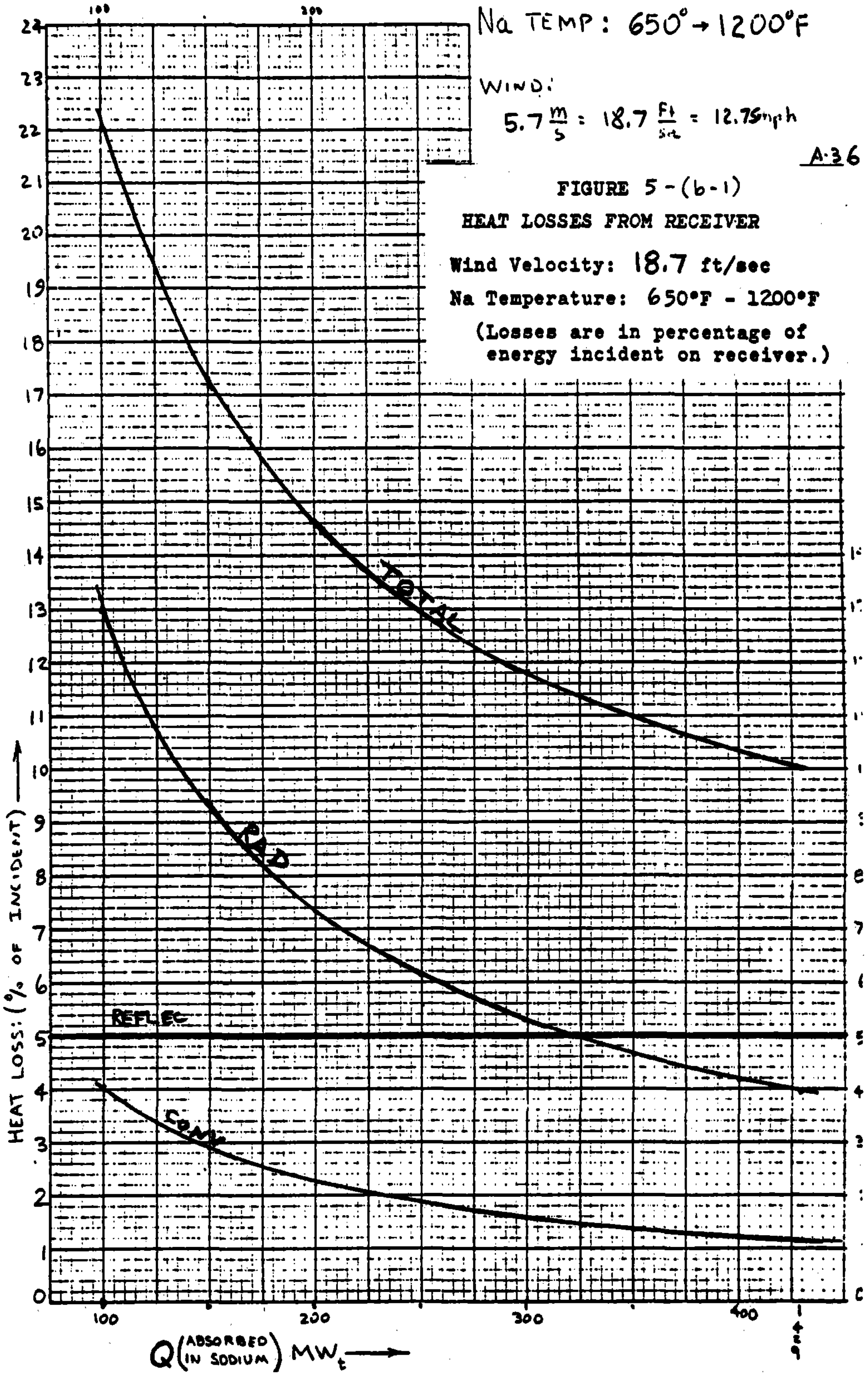

FIGURE 5-(b-1)
HEAT LOSSES FROM RECEIVER

Wind Velocity: 18.7 ft/sec

Na Temperature: 650°F - 1200°F

(Losses are in percentage of energy incident on receiver.)

52

Na TEMP: 650° → 1200°F

WIND:

$11.0 \frac{m}{s} = 36.1 \frac{ft}{sec} = 24.6$ mph

A-37

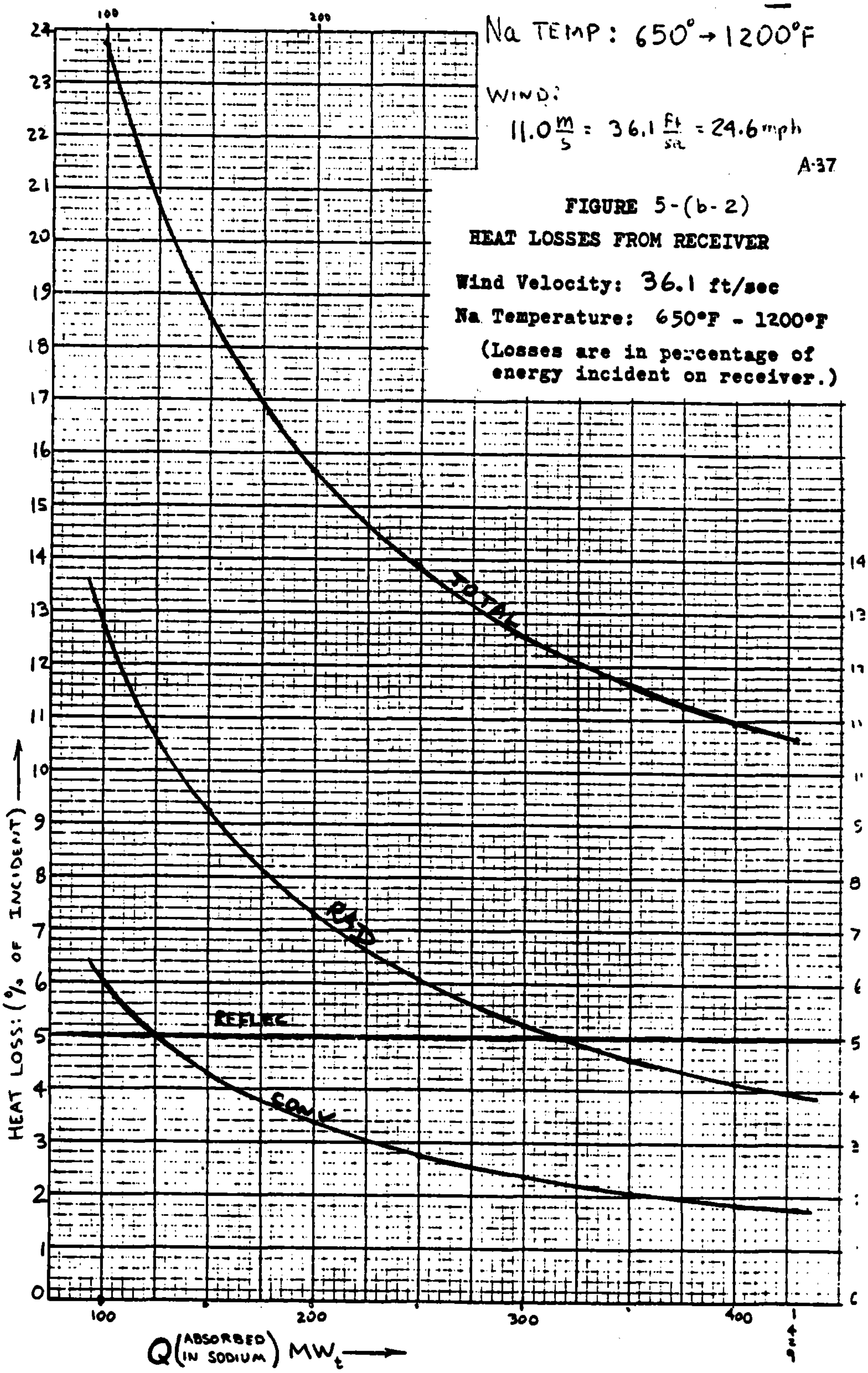

FIGURE 5-(b-2)

HEAT LOSSES FROM RECEIVER

Wind Velocity: 36.1 ft/sec

Na Temperature: 650°F - 1200°F

(Losses are in percentage of energy incident on receiver.)

Na TEMP: 650°→1200°F

WIND:
$16.28\ \frac{m}{s} = 53.4\ \frac{ft}{sec} = 36.4\ mph$
A-38

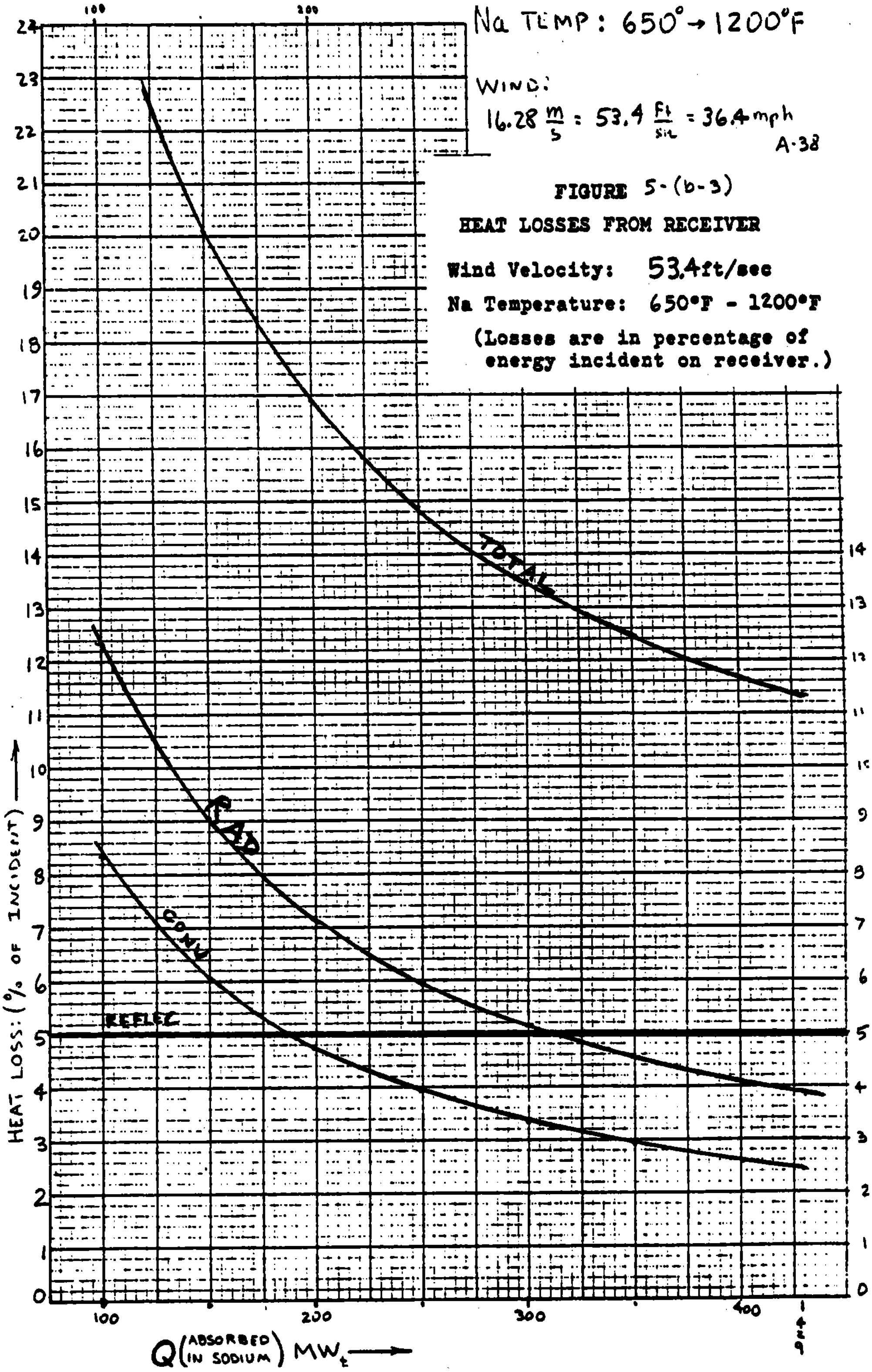

FIGURE 5-(b-3)

HEAT LOSSES FROM RECEIVER

Wind Velocity: 53.4ft/sec

Na Temperature: 650°F - 1200°F

(Losses are in percentage of energy incident on receiver.)

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54

Na TEMP: 750° → 1300°F

WIND:

$5.7 \frac{m}{s} = 18.7 \frac{ft}{sec} = 12.75$ mph

A-39

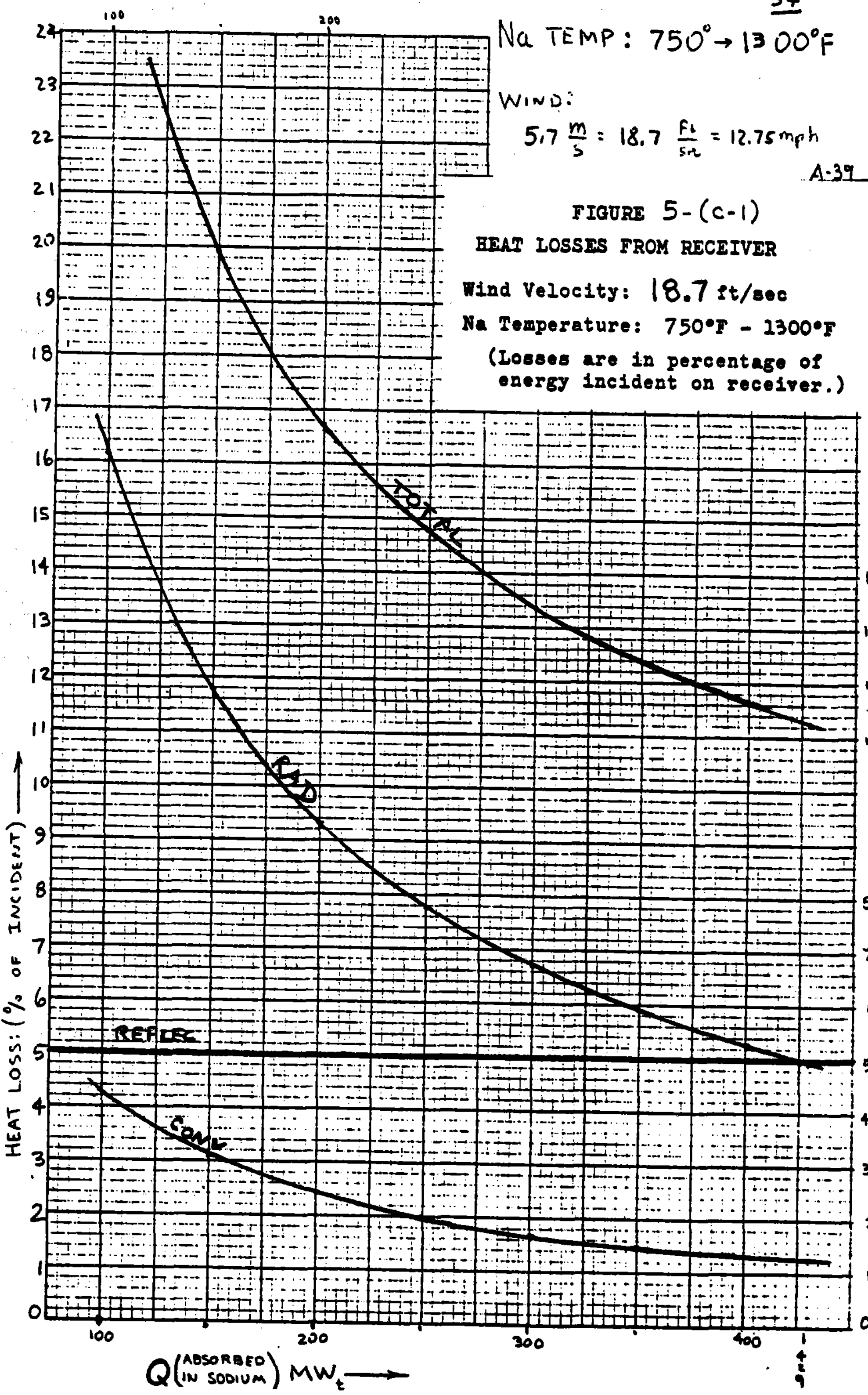

FIGURE 5-(c-1)

HEAT LOSSES FROM RECEIVER

Wind Velocity: 18.7 ft/sec

Na Temperature: 750°F - 1300°F

(Losses are in percentage of energy incident on receiver.)

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55

Na TEMP: 750°→1300°F

WIND:

$11.0 \frac{m}{s} = 36.1 \frac{ft}{sec} = 24.6 mph$

A-40

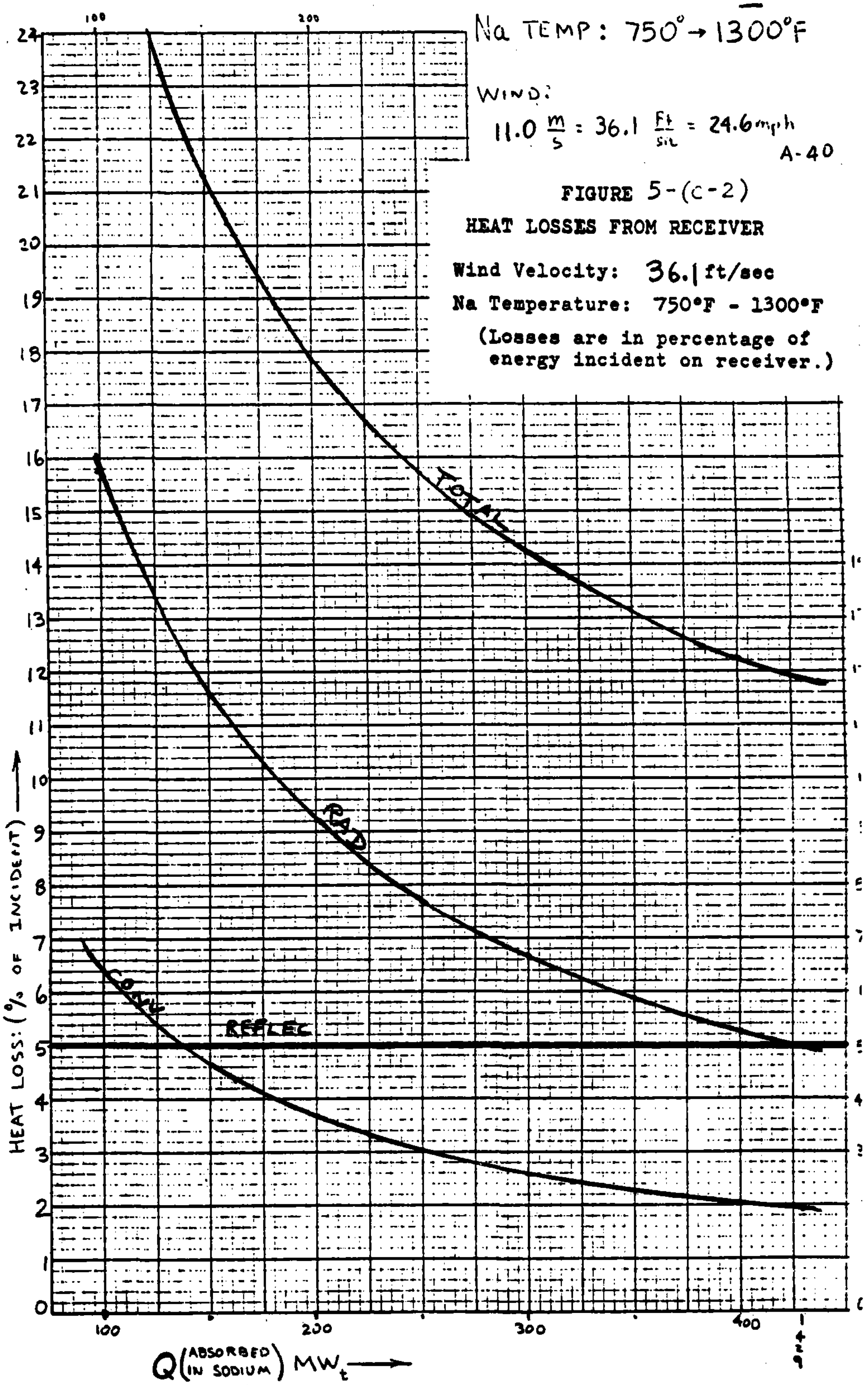

FIGURE 5-(c-2)

HEAT LOSSES FROM RECEIVER

Wind Velocity: 36.1 ft/sec

Na Temperature: 750°F - 1300°F

(Losses are in percentage of energy incident on receiver.)

Na TEMP: 750° → 1300°F

WIND:
16.28 m/s = 53.4 ft/sec = 36.4 mph

A-41

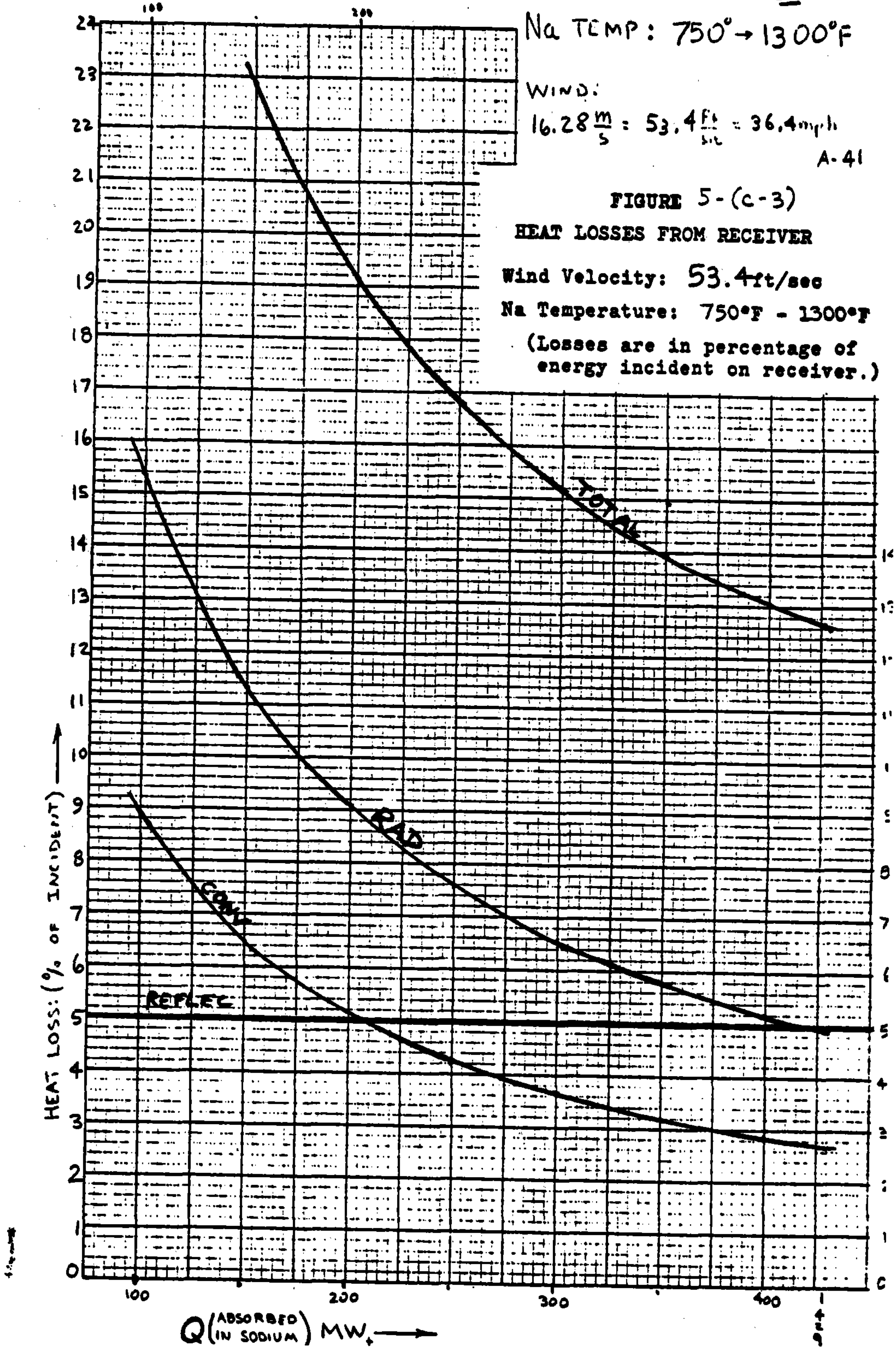

FIGURE 5-(c-3)

HEAT LOSSES FROM RECEIVER

Wind Velocity: 53.4 ft/sec

Na Temperature: 750°F - 1300°F

(Losses are in percentage of energy incident on receiver.)

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Na TEMP: 850° → 1400°F

WIND:
5.7 m/s = 18.7 ft/sec = 12.75 mph

A-42

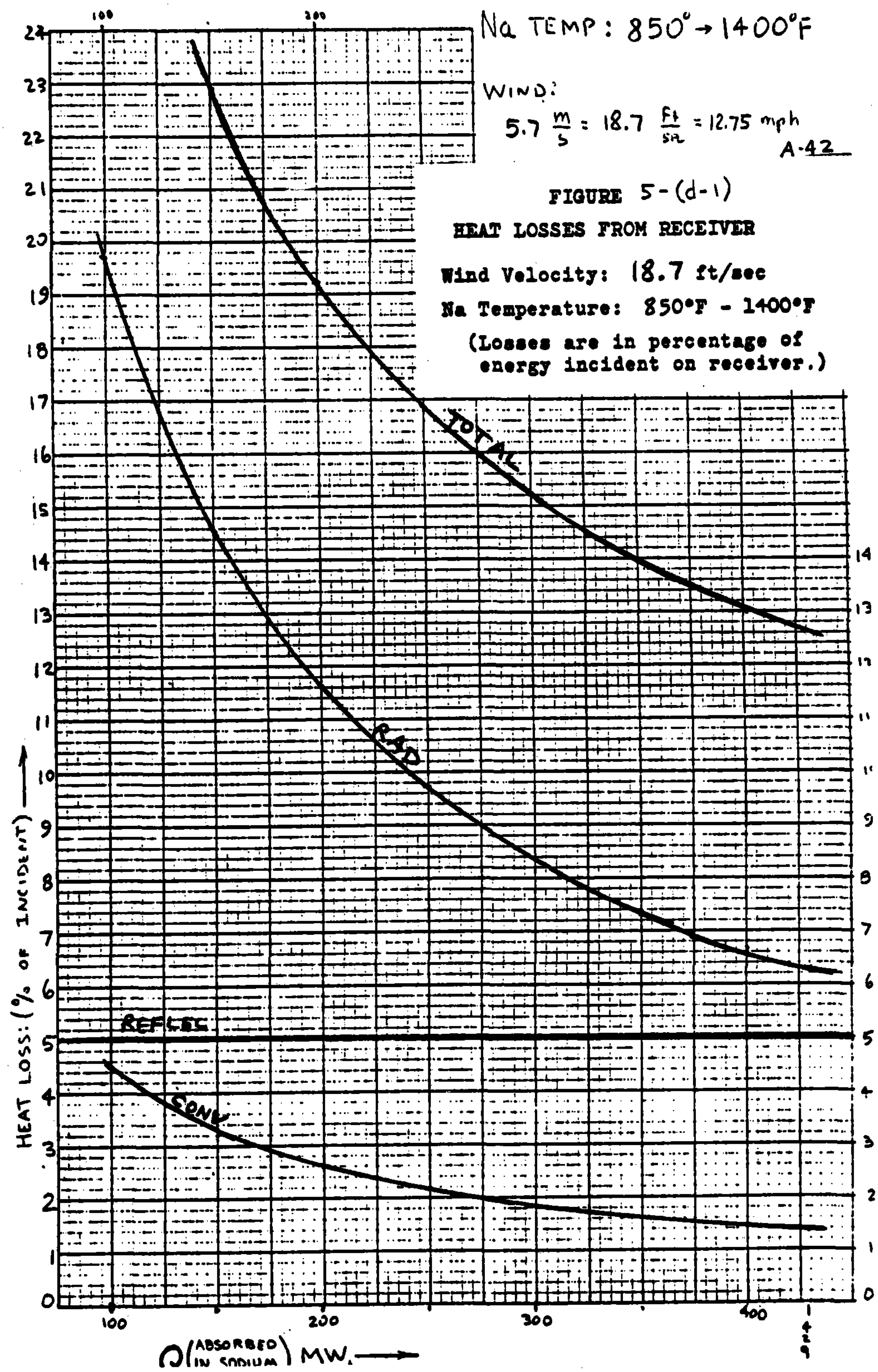

FIGURE 5-(d-1)

HEAT LOSSES FROM RECEIVER

Wind Velocity: 18.7 ft/sec

Na Temperature: 850°F - 1400°F

(Losses are in percentage of energy incident on receiver.)

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Na TEMP: 850° → 1400°F

WIND:
$11.0 \frac{m}{s} = 36.1 \frac{ft}{sec} = 24.6 mph$

A-43

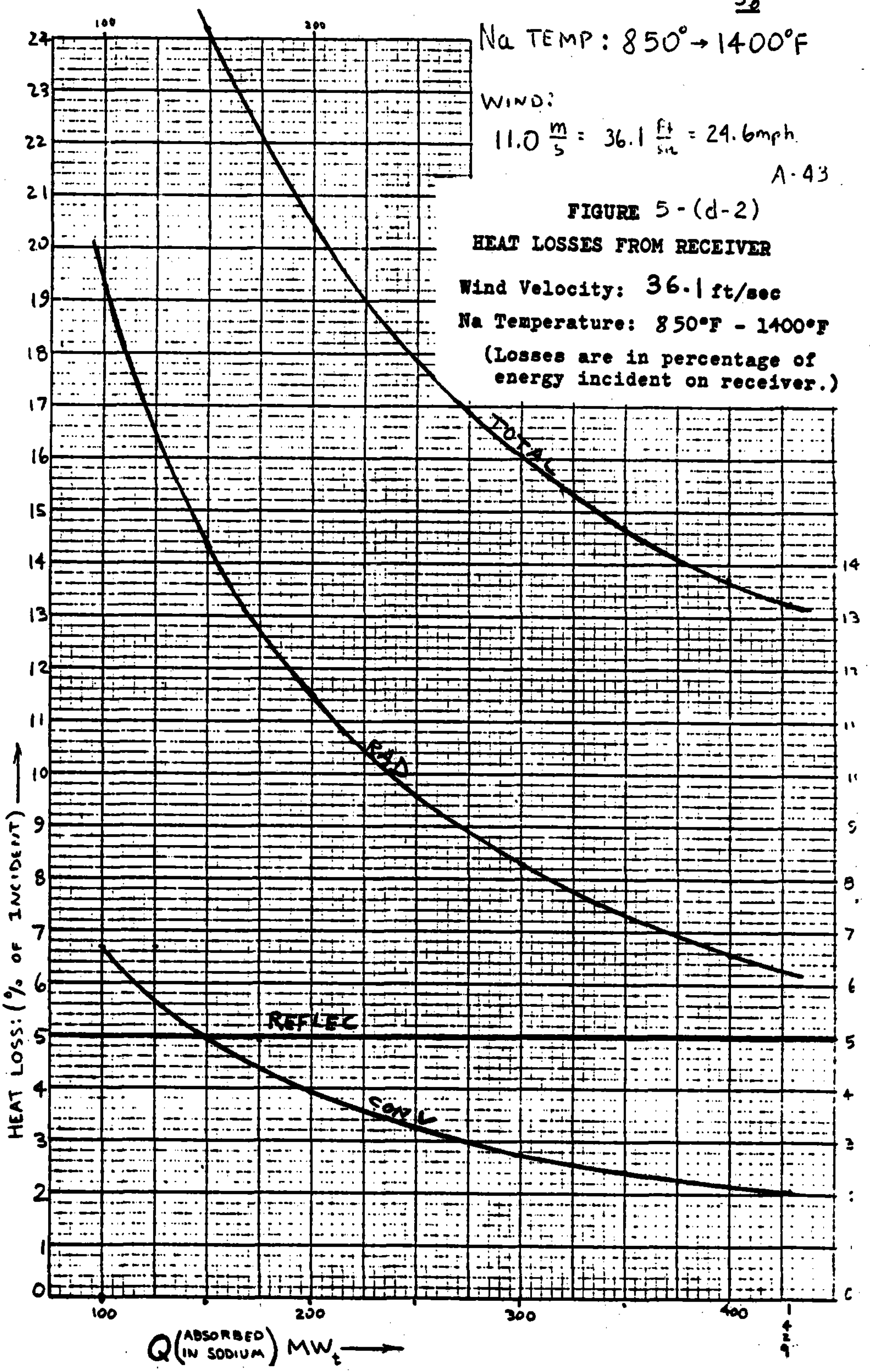

FIGURE 5-(d-2)
HEAT LOSSES FROM RECEIVER
Wind Velocity: 36.1 ft/sec
Na Temperature: 850°F - 1400°F
(Losses are in percentage of energy incident on receiver.)

Na TEMP: 850° → 1400°F

WIND:
16.28 $\frac{m}{s}$ = 53.4 $\frac{ft}{sec}$ = 36.4 mph
A-44

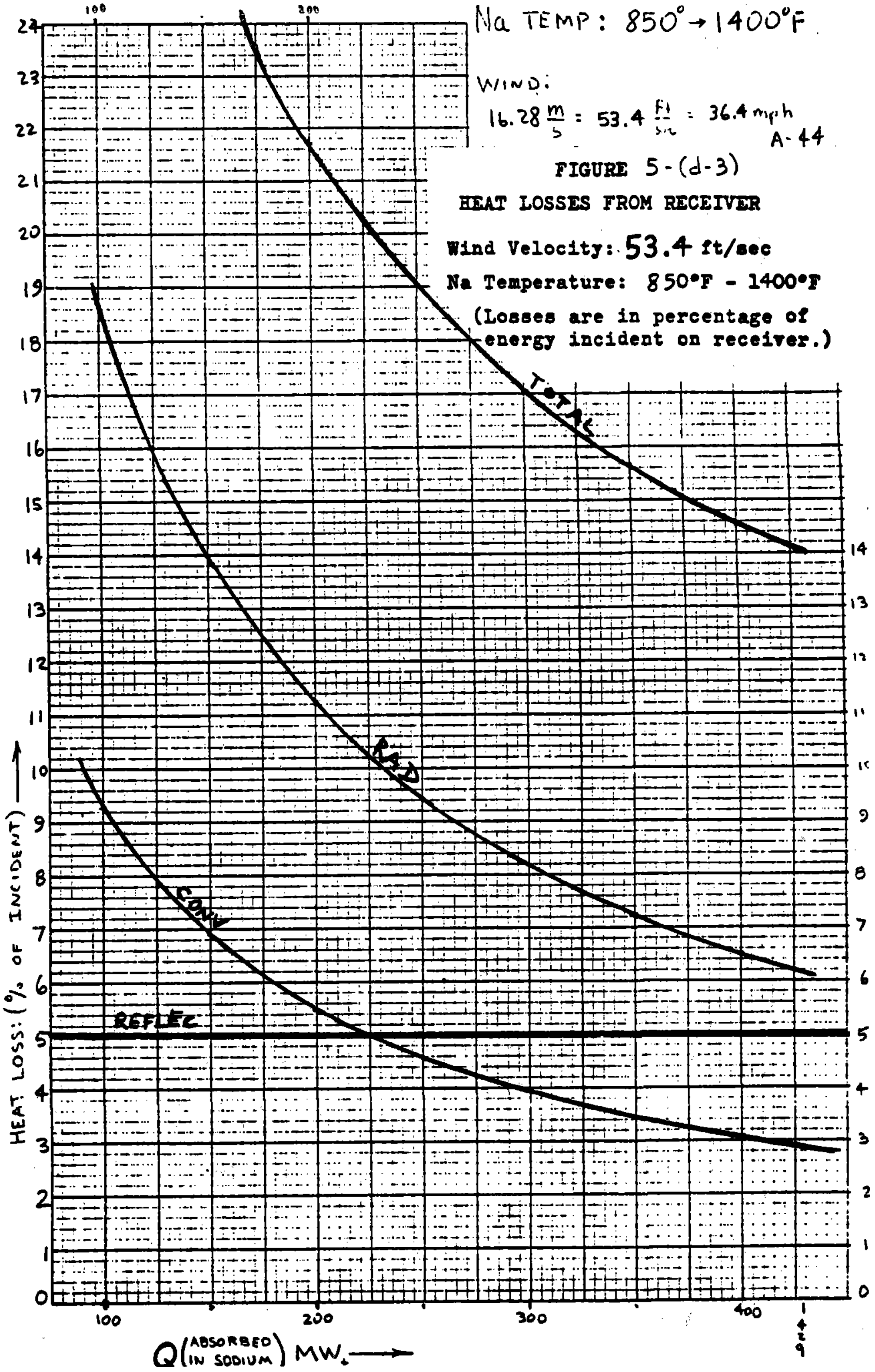

FIGURE 5-(d-3)

HEAT LOSSES FROM RECEIVER

Wind Velocity: 53.4 ft/sec

Na Temperature: 850°F - 1400°F

(Losses are in percentage of energy incident on receiver.)

550°F → 1100°F

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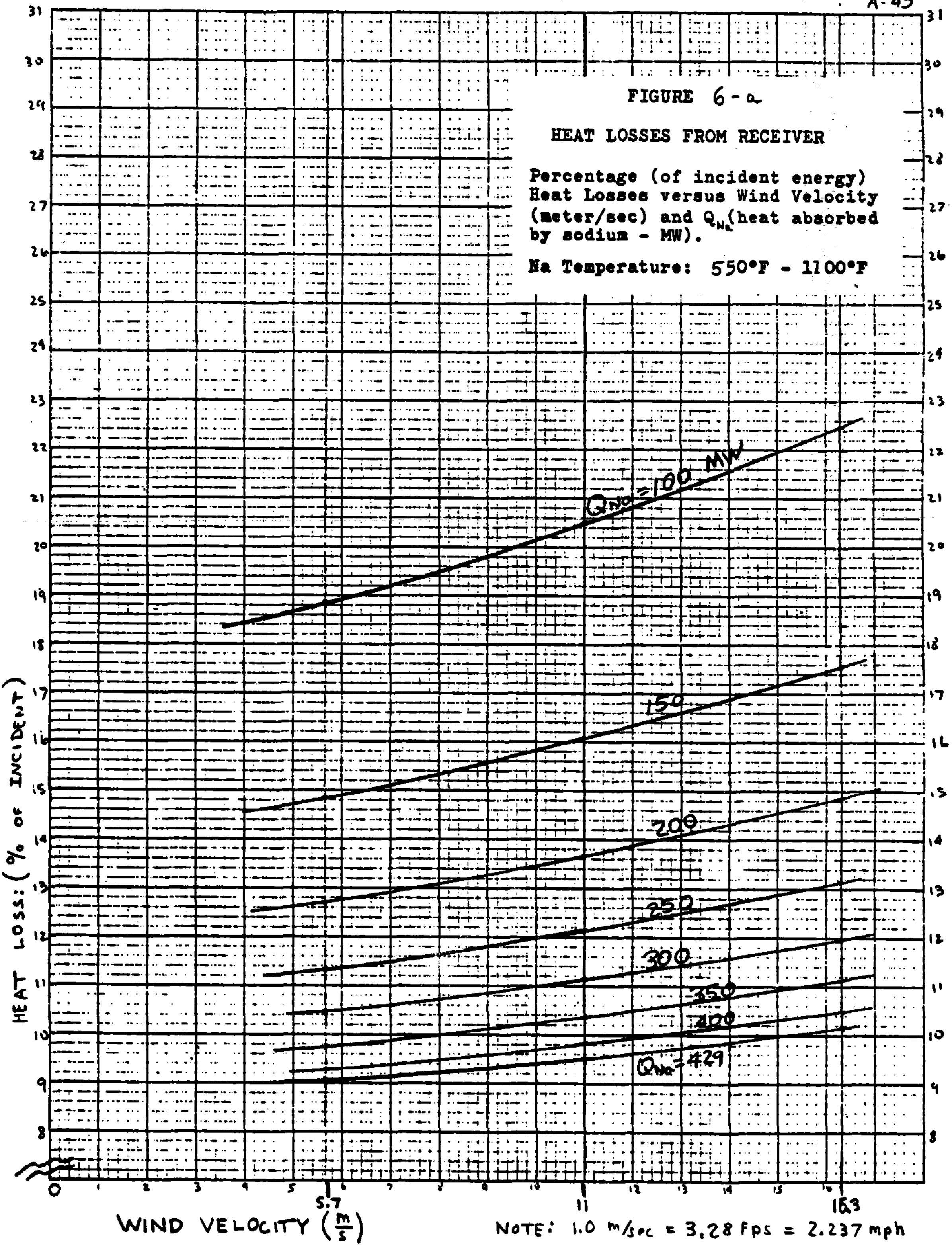

FIGURE 6-a

HEAT LOSSES FROM RECEIVER

Percentage (of incident energy) Heat Losses versus Wind Velocity (meter/sec) and Q_{Na} (heat absorbed by sodium - MW).

Na Temperature: 550°F - 1100°F

650°F → 1200°F

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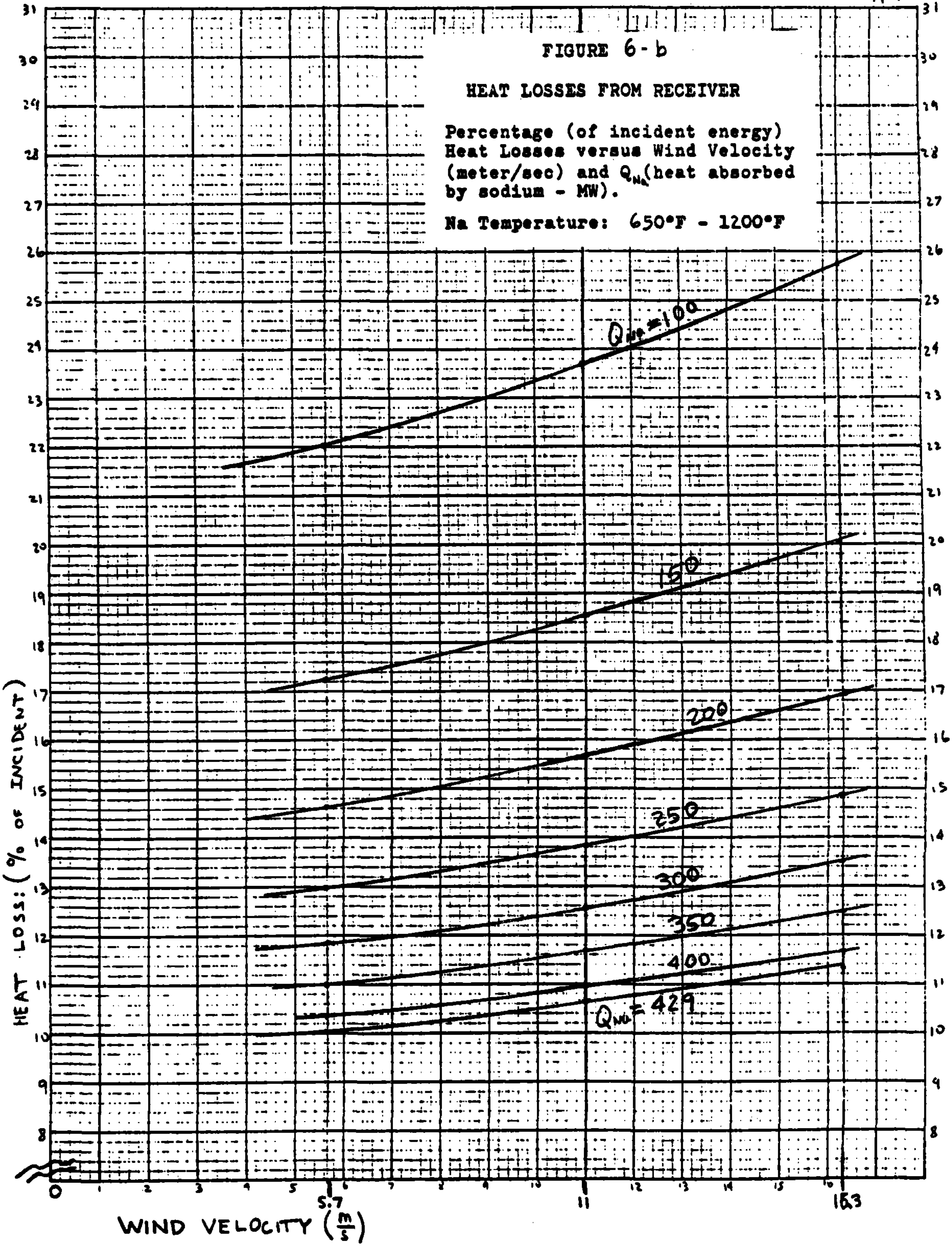

FIGURE 6-b

HEAT LOSSES FROM RECEIVER

Percentage (of incident energy) Heat Losses versus Wind Velocity (meter/sec) and Q_{Na}(heat absorbed by sodium - MW).

Na Temperature: 650°F - 1200°F

750°F → 1300°F

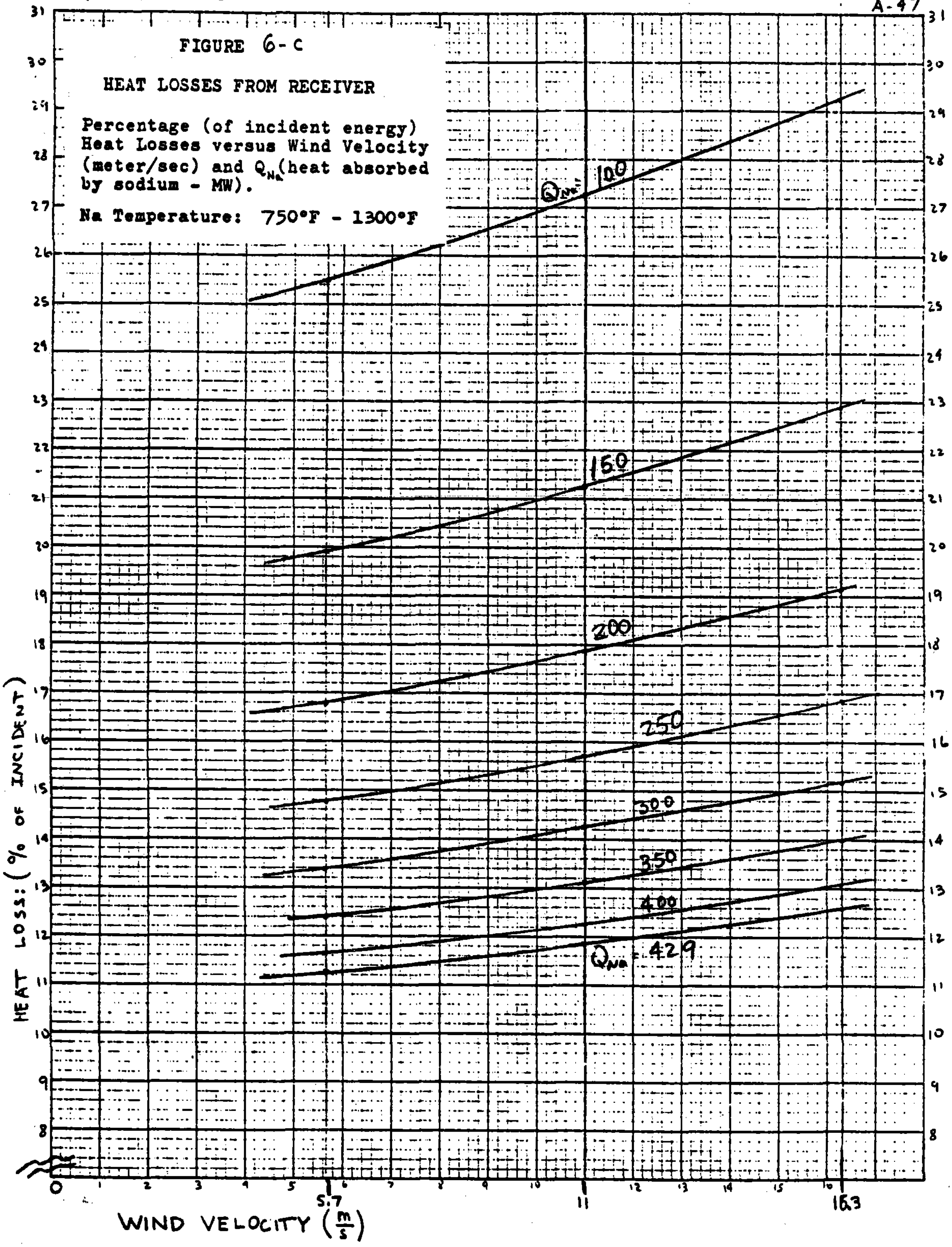

FIGURE 6-C

HEAT LOSSES FROM RECEIVER

Percentage (of incident energy) Heat Losses versus Wind Velocity (meter/sec) and Q_{Na} (heat absorbed by sodium - MW).

Na Temperature: 750°F - 1300°F

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A-48

850°F → 1400°F

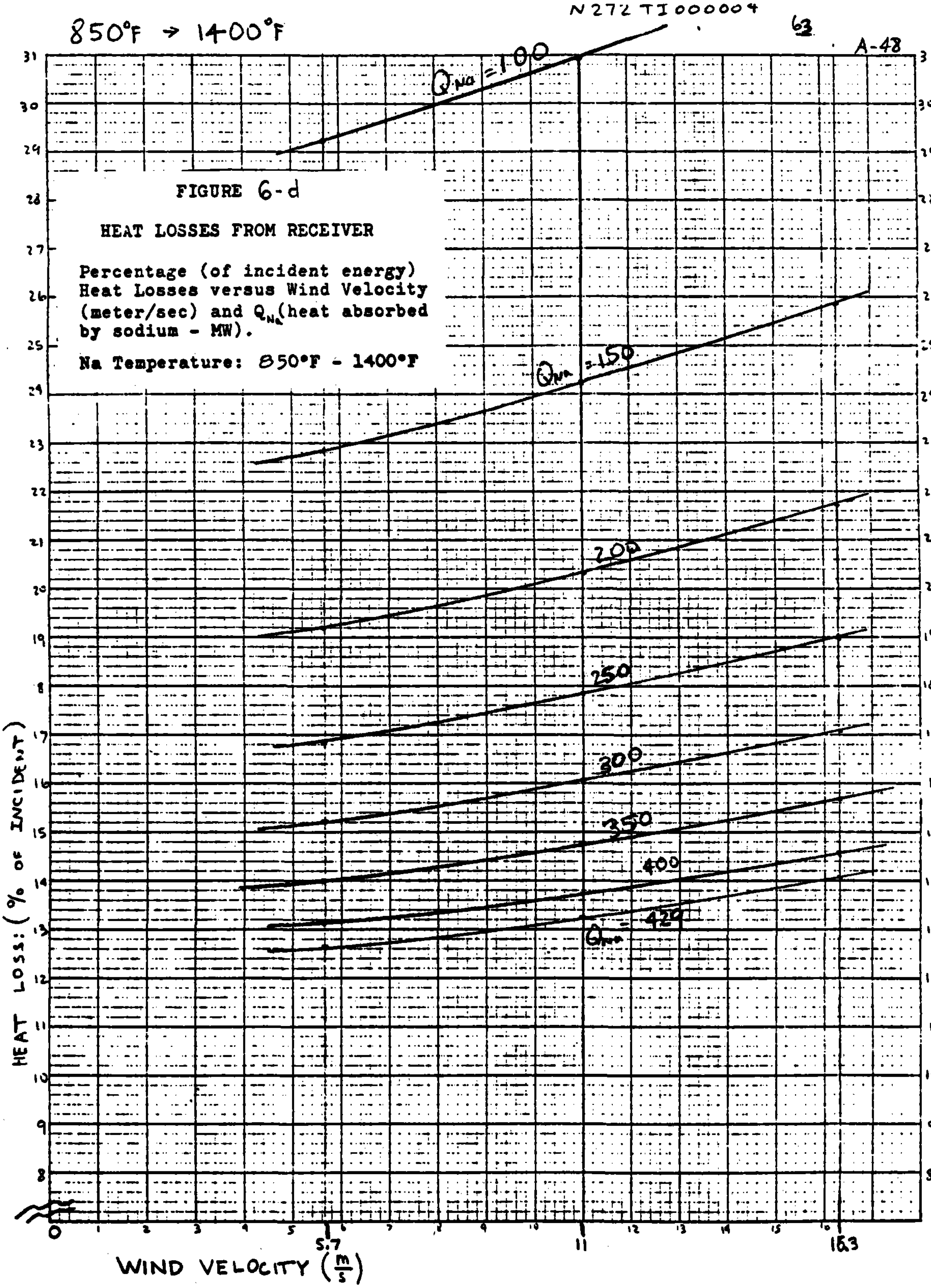


FIGURE 6-d

HEAT LOSSES FROM RECEIVER

Percentage (of incident energy) Heat Losses versus Wind Velocity (meter/sec) and Q_{Na}(heat absorbed by sodium - MW).

Na Temperature: 850°F - 1400°F

HEAT LOSS % vs. OPER. TEMP.

WIND:

5.7 $\frac{m}{s}$ = 18.7 FPS = 12.75 mph.

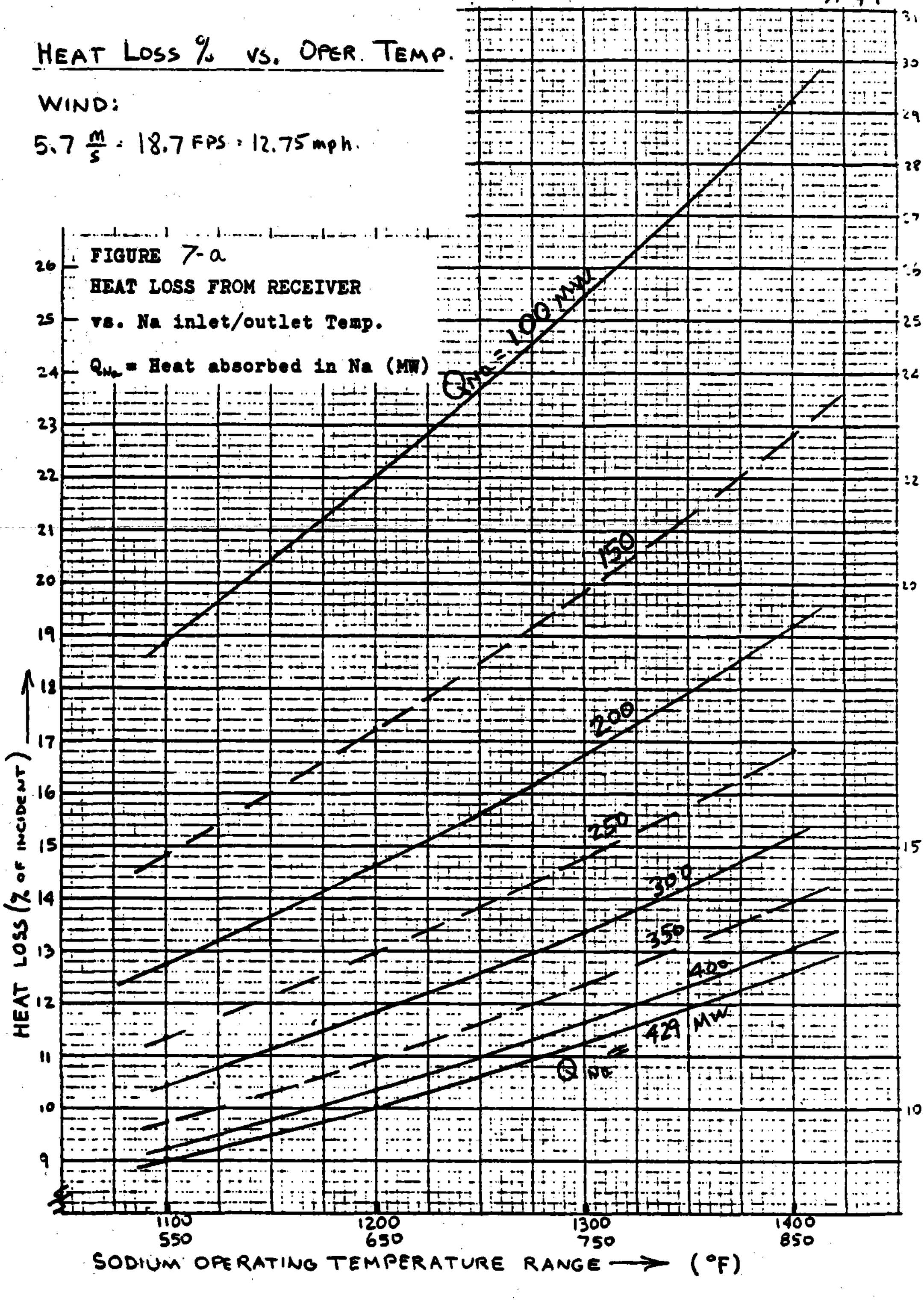
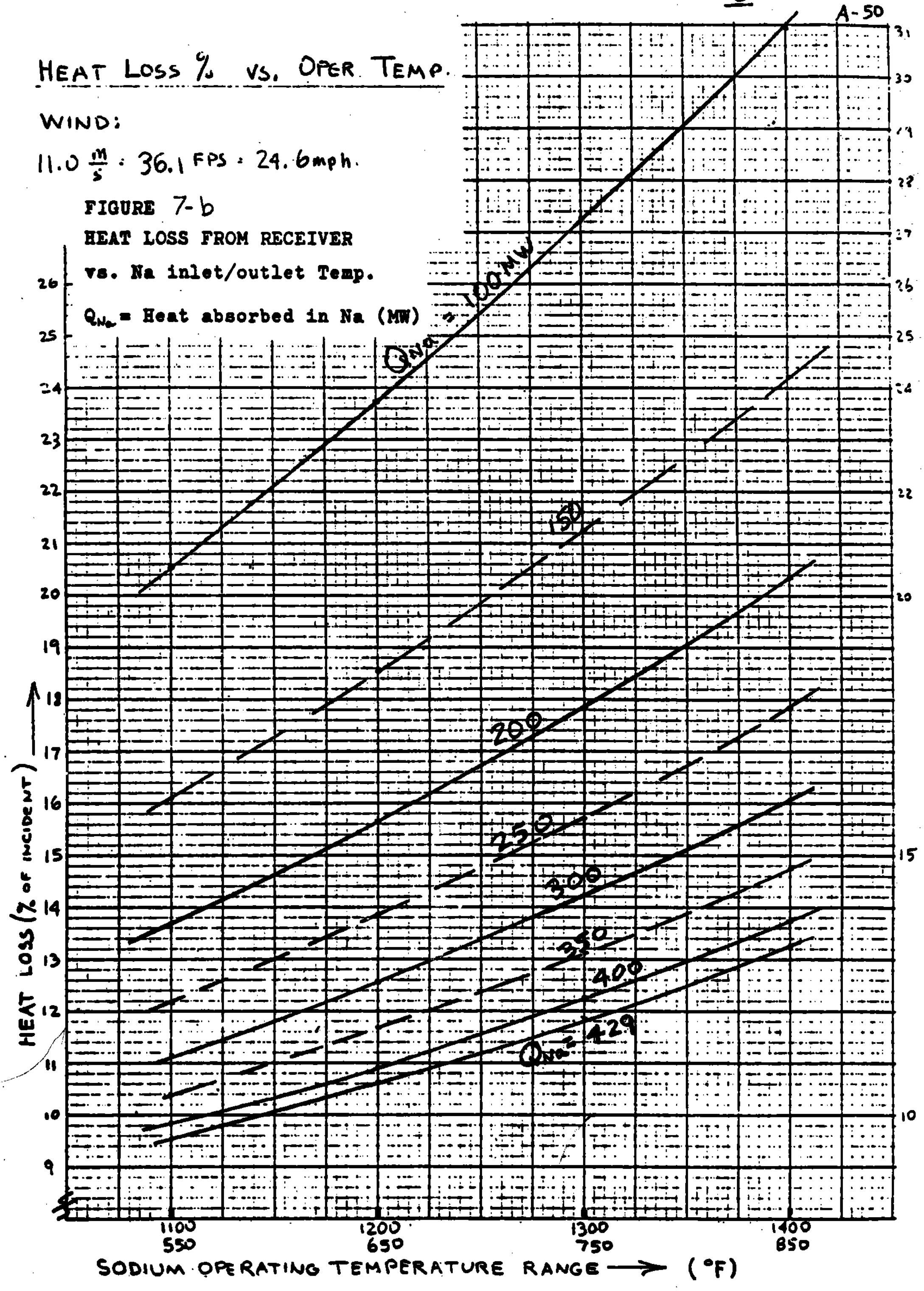


FIGURE 7-a

HEAT LOSS FROM RECEIVER

vs. Na inlet/outlet Temp.

Q_{Na} = Heat absorbed in Na (MW)



HEAT LOSS % vs. OPER TEMP.

WIND:

11.0 $\frac{m}{s}$ = 36.1 FPS = 24.6 mph.

FIGURE 7-b

HEAT LOSS FROM RECEIVER

vs. Na inlet/outlet Temp.

Q_{Na} = Heat absorbed in Na (MW)

HEAT LOSS % vs. OPER. TEMP.

WIND:

16.28 $\frac{m}{s}$ = 53.4 FPS = 36.4 mph.

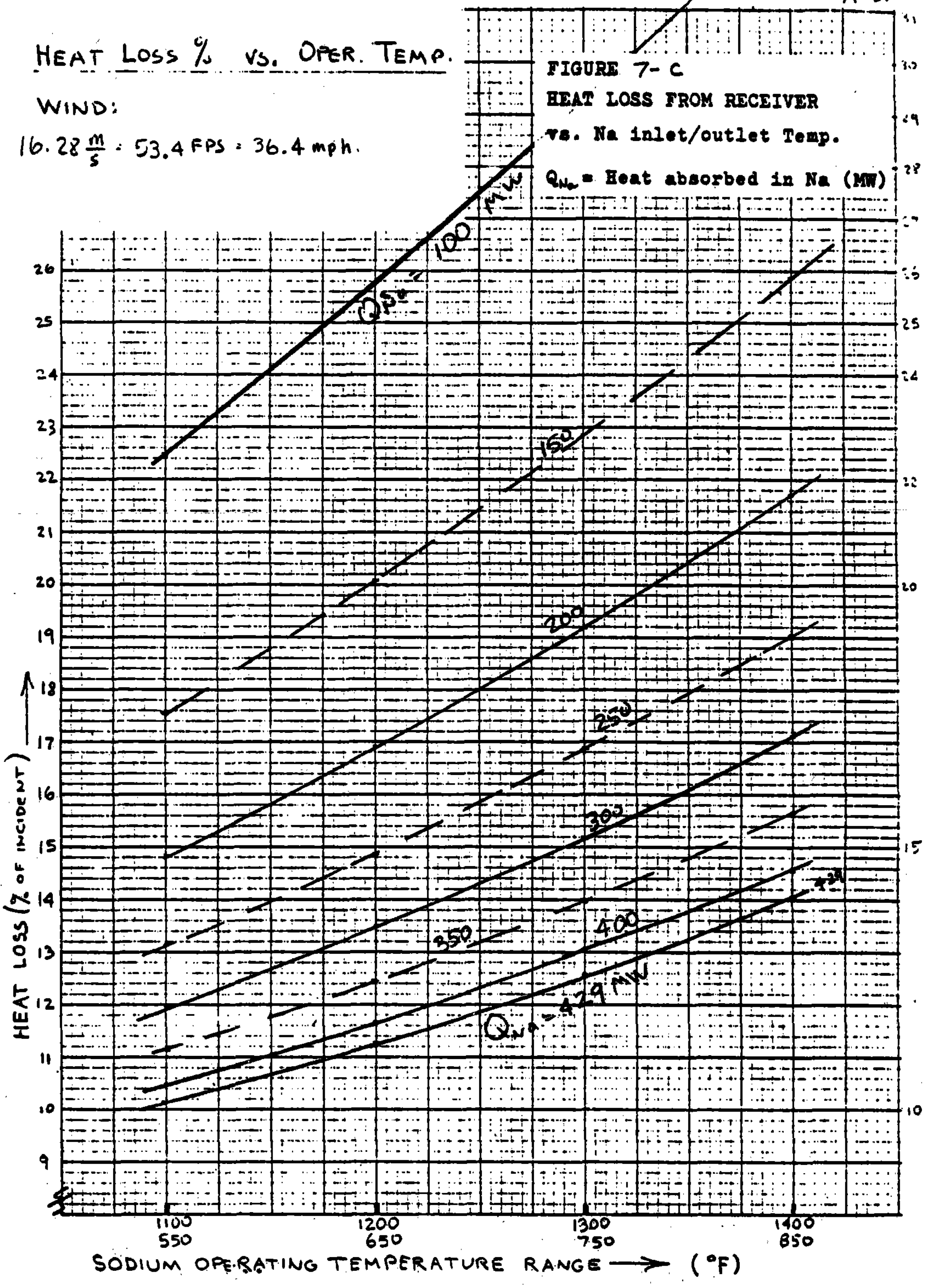


FIGURE 7- C

HEAT LOSS FROM RECEIVER

vs. Na inlet/outlet Temp.

Q_{Na} = Heat absorbed in Na (MW)

APPENDIX G

HEAT TRANSFER AND PRESSURE DROP FOR ROCK BED THERMAL STORAGE

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Document N272TI000003

650-78-094

Rockwell International
Atomics International Division

SUPPORTING DOCUMENT

NUMBER N272TI000003

REV LTR/CHG NO. SEE SUMMARY OF CHG

DOCUMENT TYPE Technical Information

KEY NOUNS Thermal Storage, Solar Power, Pebble Bed

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DOCUMENT TITLE
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ABSTRACT

Heat transfer and pressure drop correlations for air flow through a "fixed pebble bed" are investigated and presented. This is part of the study of a rock-air thermal storage system under investigation for possible use in a central receiver solar power system.

Equations and a time-share computer program have been set up to determine the heat transfer parameter (UA), pressure drop (Δp), and fan electric power (P), for a variety of bed capacities, thermal power rates, bed sizes and porosities, particle diameters, and sphericities, etc.

Calculations have been made for several cases, yielding air flowrates and velocities, bed dimensions and areas, and other parameters in addition to UA, Δp, and P(fan).

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FORM 734-C REV. 11-77

CONTENTS

APPENDICES

I. INTRODUCTION

A pebble bed thermal storage device has been proposed for possible use in a central receiver solar power system. The device is to be composed of a bed of rock pebbles, each of diameter d. The bed configuration is a right circular cylinder of diameter D, and vertical height L. The heat transport medium is air at atmospheric pressure. The air flow is downward through the bed during the charging process (heating rocks: hot air in, cool air out), and upward during discharge (cooling rocks and heating air; cool air in, hot air out).

In this report, correlations are selected and calculational method established to determine a pebble bed's heat transfer (UA), pressure drop (Δp), and fan (blower) electrical power parameters. The pebble diameter and sphericity, pebble matrix porosity (void fraction), bed theoretical energy content, thermal power rate (of energy removal or insertion), pebble bed diameter, rock and air properties, and the operating temperature range are among the system parameters taken into consideration.

The variables to be determined include the bed height, mass, and total surface area; air flow rate, velocity, transit time, Reynolds number and pressure drop; fan (blower) electrical power; heat transfer coefficients h and U, and bed UA (U times total pebble surface area).

A number of correlations for a fixed pebble bed pressure drop and heat transfer coefficient were investigated and are discussed. The correlations and basic equations employed are shown, as well as logic and listing of the time share computer program set up, and a summary of results from several cases run.

II. HEAT TRANSFER CORRELATIONS

A number of heat transfer correlations for gas flow through a fixed pebble bed have been considered for use in this analysis. These correlations are shown in Appendix A in the form that they are presented in the referenced documents. Also shown in Appendix A are the algebraic steps taken to try to reduce all the correlations to the same form: $Nu = \alpha Re^{B}$.

In Appendix A, as well as in Table I, a summary of these heat transfer correlations is shown. Unfortunately, there appears to be some disagreement among them, particularly with respect to the influence on heat transfer coefficient of particle sphericity and particle diameter. Note that heat transfer coefficient (h) varies with the (+0.6), (-0.5), (-0.31), (+0.3), (+0.08), and (-.41) power of particle diameter, depending on the equation used. As far as bed porosity (ϵ) and particle sphericity (ϕ) are concerned, the several correlations show h increasing, decreasing, or unaffected by increasing ϵ and ϕ.

In the experiments from which some of the correlations were derived, only one value of particle diameter was employed. Furthermore, in some of the cases, ϵ and ϕ were not even considered as parameters, but they appear when the equations were manipulated in Appendix A in order to put them, as much as possible, into the same form for comparison.

In attempting to arrive at a compromise correlation, the possible' effect of ϵ and ϕ on heat transfer correlation was omitted because of the contradictions among the several correlations. Close scrutiny of the correlations suggested the selection of an h varying with the -0.3 power of particle diameter as a reasonable compromise. Thus, as shown in Table I and Appendix A, the heat transfer correlation used in this analysis is:

TABLE I

HEAT TRANSFER CORRELATIONS

KUNII & LEVENSPIEL	$Re < 100 \quad Nu \cong 0.0114\, Re^{1.6}$ $Re > 100 \quad Nu \cong 2 + 1.6\, Re^{0.5}$ No ϵ or ϕ dependence.	$h \propto d^{.6}$; $h \downarrow$ as $T \uparrow$ $h \propto d^{-.5}$; $h \uparrow$ as $T \uparrow$
KAYS & LONDON	$Nu \cong .238 \left(\frac{1}{\phi}\right)^{.31} \frac{(1-\epsilon)^{.31}}{\epsilon} Re^{0.69}$ $20 < Re < 600$	$h \propto d^{-.31}$, $h \downarrow$ as $\epsilon \uparrow$ $h \propto \phi^{-.31}$, $h \uparrow$ as $T \uparrow$
LOF & HAWLEY	$Nu \cong .276 \left(\frac{\phi}{1-\epsilon}\right) d_{INCH}^{0.6}\, Re^{0.7}$ $25 < Re < 500$	$h \propto d^{+.3}$ $h \propto \phi$ $h \uparrow$ as $\epsilon \uparrow$; $h \uparrow$ as $T \uparrow$
"ARGENTINE"	$Nu \cong .131 \left(\frac{\phi}{1-\epsilon}\right) d_{INCH}^{0.16}\, Re^{0.92}$ $25 < Re < 200$	$h \propto d^{+0.08}$ $h \propto \phi$ $h \uparrow$ as $\epsilon \uparrow$, $h \uparrow$ as $T \uparrow$
McADAMS Pg 295	$Nu \cong 0.941\, Re^{0.59}$ $350 < Re < 4000$	$h \propto d^{-.41}$ $h \uparrow$ as $T \uparrow$
USED IN ANALYSIS	$Nu = 0.5\, Re^{0.7}$	$h \propto d^{-.3}$ $h \uparrow$ as $T \uparrow$

$$Re = \left(\frac{\dot{W}}{A_{GROSS}} \frac{d_{PARTICLE}}{\mu} \right) \qquad Nu = \frac{h d_{PARTICLE}}{k_{AIR}}$$

d : Particle Diameter

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$$Nu = 0.5\ Re^{.7} \qquad (2a)$$

$$h = 0.5\ \frac{k}{d}\ (\frac{\dot{W}}{A}\frac{d}{\mu})^{0.7} = 0.5\ k\ (\frac{\dot{W}}{A\mu})^{0.7}\ d^{-0.3} \qquad (2b)$$

Figure 1 shows a comparison of the correlations for the case where $d = 1.0"$, $\epsilon = 0.39$, and $\phi = 0.80$.

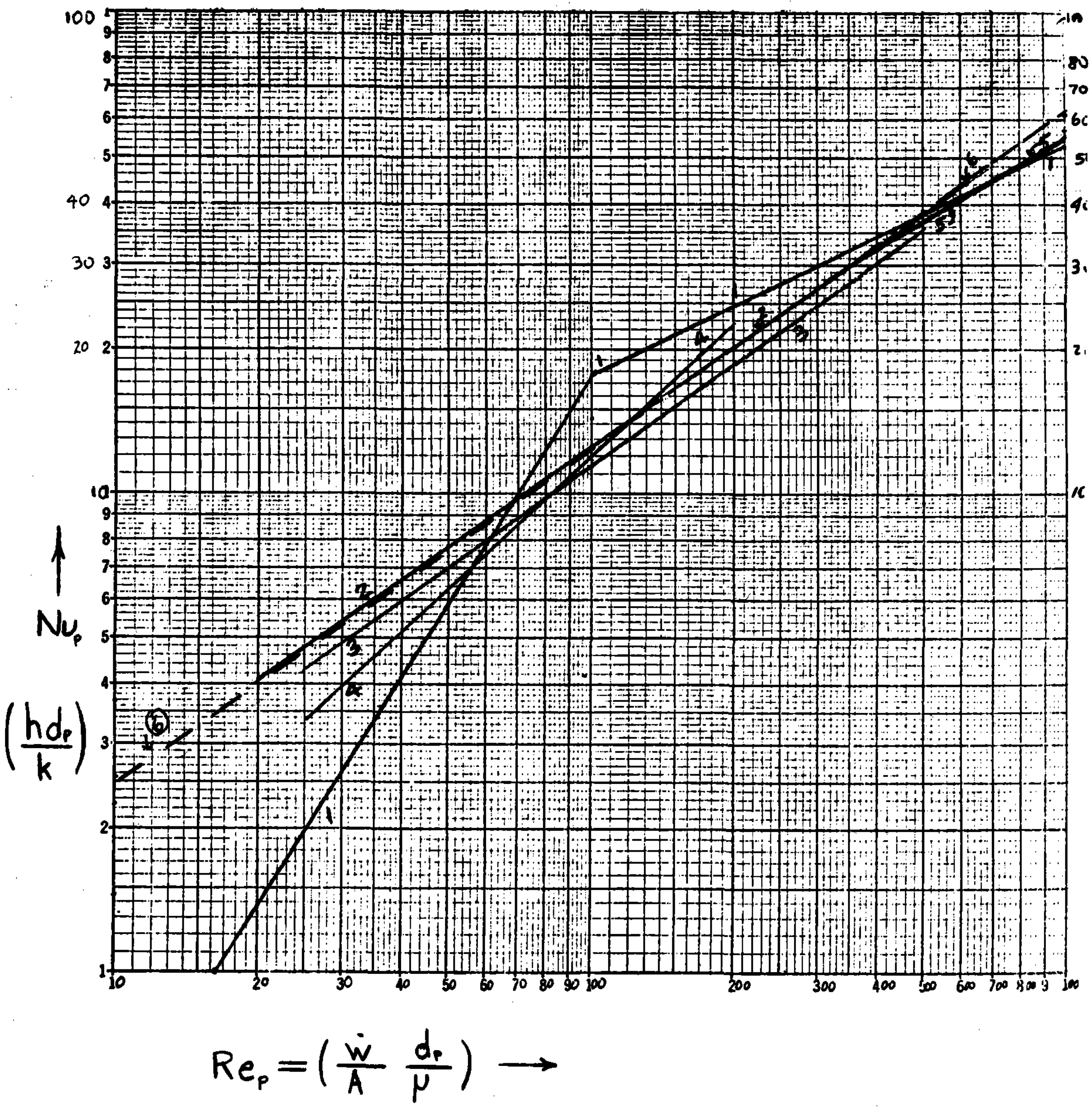
The correlations discussed are based on having a bed composed entirely of a single pebble size. The correlation does not consider any influence of sphericity, ϕ, (see Appendix B) on the heat transfer coefficient. However, sphericity does affect the total surface area, such that UA_{sur} is affected by the value of ϕ.

FIGURE 1

COMPARISON OF HEAT TRANSFER CORRELATIONS

$d_p = 1.0''$
$\epsilon = 0.39$
$\phi = 0.8$

Kunni & Leven	1
Kays & London	2
Lof & Hawley	3
"Argentine"	4
Gamson (McAdams)	5
Used in this analysis.	6 — — —



III. PRESSURE DROP AND FAN POWER CORRELATIONS

Pressure drop correlations are shown in Appendix C. There are two correlations shown, which turn out to be basically in agreement with one another, though presented in different forms. The correlation employed in this analysis is:

$$\Delta p = 200 \frac{L}{g_c} \frac{(1-\epsilon)^2}{\epsilon^3 \phi^2} \frac{\mu Vo}{d^2} + 2.33 \frac{L}{g_c} \frac{(1-\epsilon)}{\epsilon 3 \phi} \frac{\rho Vo^2}{d} \qquad (3)$$

where Vo = superficial air velocity.

The first term is referred to as the "laminar" term as it dominates at low velocities (Reynolds number). The second term is referred to as the "turbulent" term as it dominates at high velocities (Reynolds number).

The "laminar" and "turbulent" terms correspond to $f = 100/Re$ and $f = 1.165$, respectively, as shown in Appendix C.

The fan (blower) electrical power is determined by the expression:

$$P_{fan} = \frac{\Delta p \dot{W}}{\rho_{air} (eff)}.$$

This fan power is determined in kWe for both the upper and lower limit air temperatures.

IV. ANALYSIS

Based on the heat transfer and pressure drop correlations presented, calculations have been set up to determine heat transfer and air flow parameters of the pebble bed. Of particular interest are the heat transfer parameter, UA_{sur} (Btu/hr^{o}F), air pressure drop, Δp (lbF/ft^{2}), and fan power, P_{fan} (kWe).

A time-share computer program has been set up to determine these quantities. In Appendix D, the analysis procedure is shown. The input information includes the pebble bed maximum theoretical energy, the system operating power level, the upper and lower temperature limits, bed diameter, particle diameter, pebble sphericity, bed porosity, and material properties.

Among the calculated parameters are the pebble bed mass, volume and height; air flow rate, velocities, and transit time; total heat transfer surface area; Reynolds and Nusselt numbers; film and overall heat transfer coefficients, h and U; heat transfer coefficient correction due to conduction into pebble (see Appendix E); system hA_{sur}, UA_{sur}, and NTU; and air flow pressure drop and fan power. Part a of Appendix D shows the equations used to determine these parameters. A time-share program has been set up to carry out these calculations, and a listing is shown in Appendix F.

In Part b of Appendix D, expressions are developed showing the influence of the various input variables (system power, bed energy capacity, bed diameter, particle diameter, system ΔT, sphericity, porosity, fan efficiency, and material properties) on the system parameters hA, Δp, and P_{fan}. These expressions are useful in making a judgement as to what influence on system behavior will result from a proposed change in one or more of the bed characteristics. For a summary, see Sheet 9 of Appendix D.

V. CALCULATIONAL RESULTS

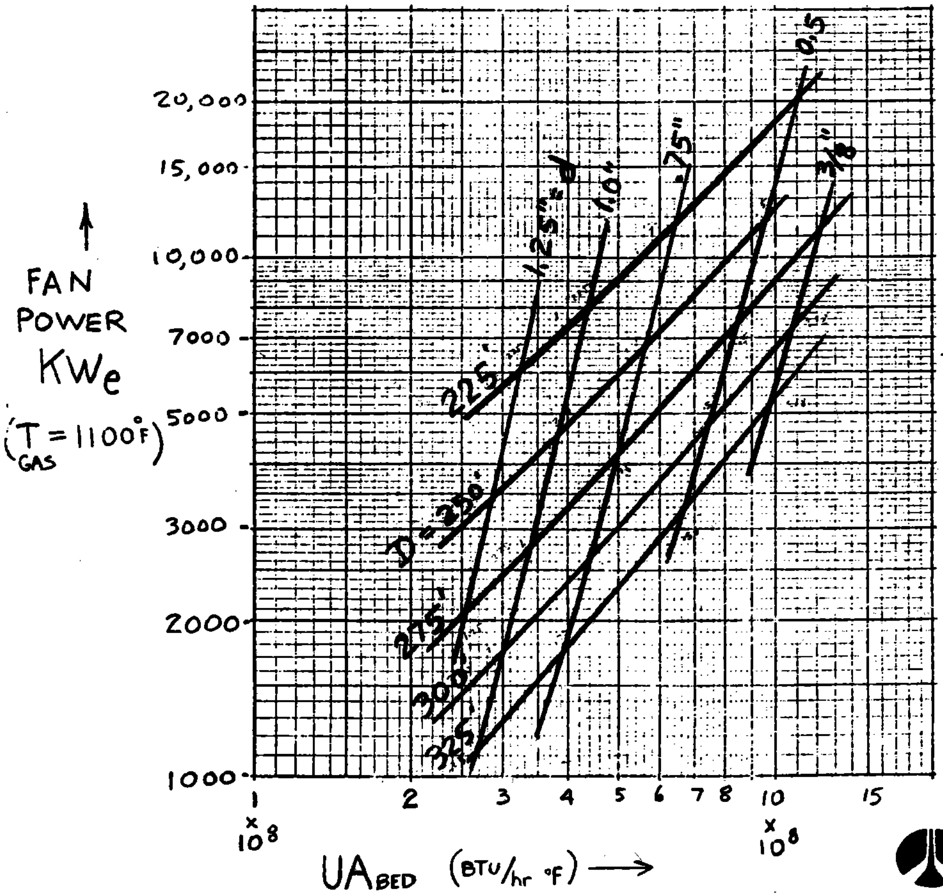
On the basis of the analysis procedure set up, calculations have been made for four cases: (1) ENG = 190 MW days, POW = 286 MWt; (2) ENG = 150 MW days, POW = 286 MWt; (3) ENG = 450 MW days, POW = 286 MWt; (4) ENG = 550 MW days, POW = 250 MWt. All four cases have $\epsilon = 0.39$, $\phi = 0.80$, $T_{hot} = 1100^{o}F$, and $T_{cold} = 600^{o}F$ where ENG denotes the system maximum theoretical energy and POW denotes the system operating power.

Of course, there are just a few of the wide variety of possible cases. Plots of fan electric power (kWe) vs bed UA (Btu/hr^{o}F) are shown in Figures 2a through 2d. The plots shown are an extract from a considerable amount of data calculated. For the reference case (ENG = 190 MW-days, POW = 286 Mwt), the calculated output is shown in Appendix G for all the bed diameter and particle diameter combinations. All the system parameters calculated are shown. Appendix G also serves as an example output for the computer program of Appendix F.

The material properties used for air and rock are shown in Appendix H.

FIGURE 2a

FAN POWER VS. BED UA



ENG(Theo) = 190 MW Days

POWER = 286 MWt

ϵ = 0.39 ϕ = 0.80

T(hot), T(cold) = 1100°, 600°F

BED VOLUME = 1.237×10^6 ft^3

BED MASS = 62,253 Tons

D(ft)	L(ft)
225	31.1
250	25.2
275	20.8
300	17.5
325	14.9

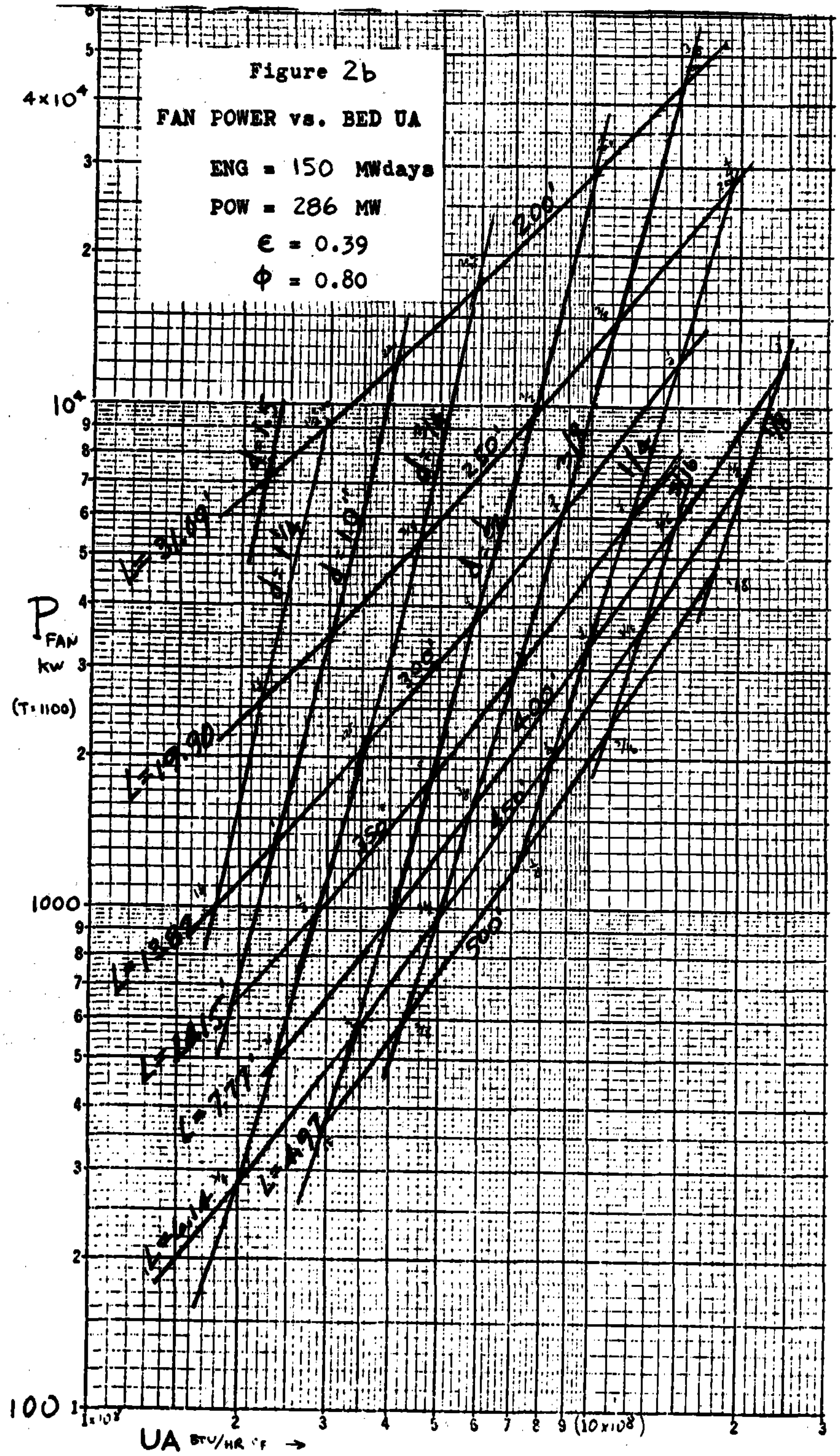


Figure 2b

FAN POWER vs. BED UA

ENG = 150 MWdays

POW = 286 MW

ϵ = 0.39

ϕ = 0.80

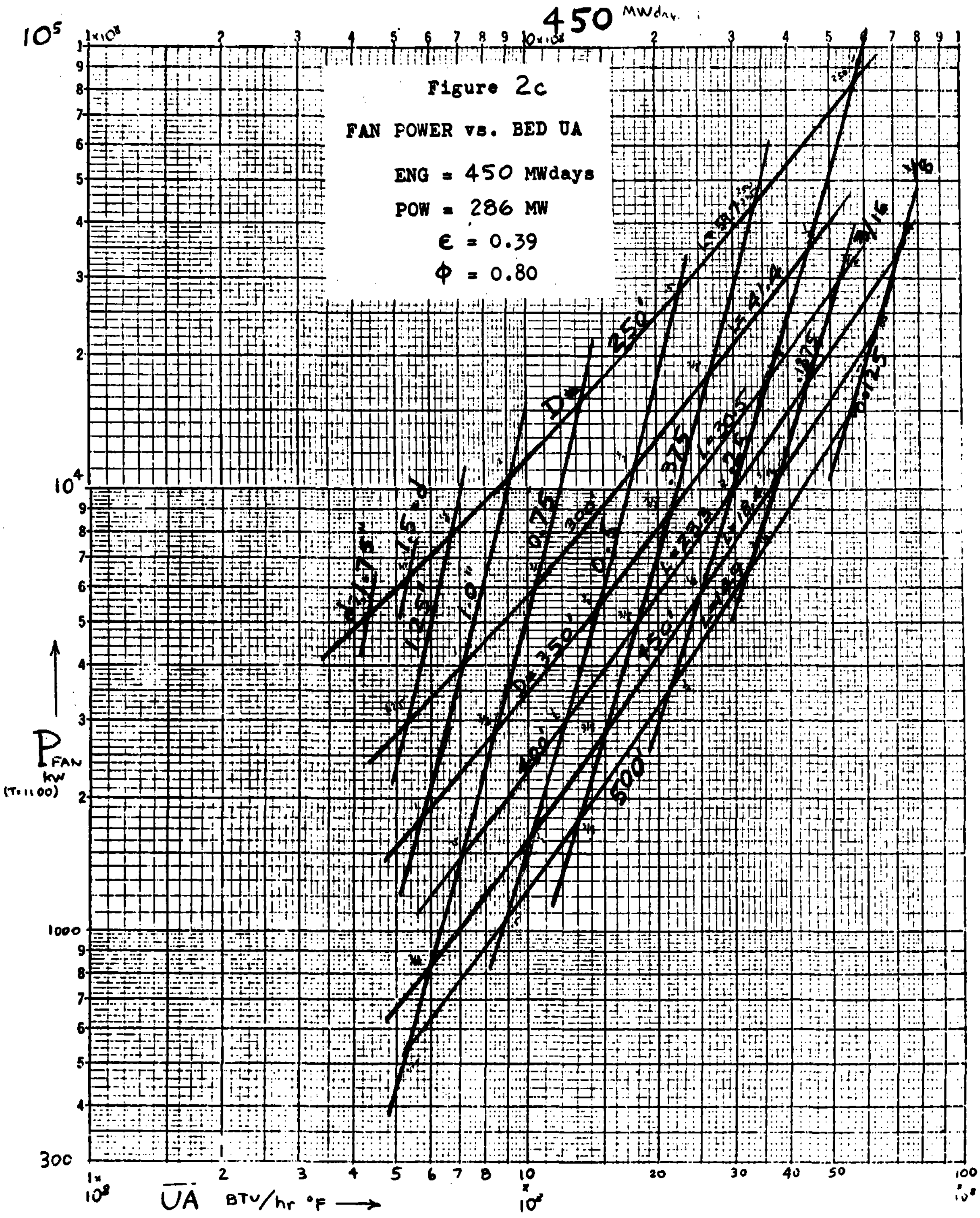


Figure 2c

FAN POWER vs. BED UA

ENG = 450 MWdays

POW = 286 MW

ϵ = 0.39

ϕ = 0.80

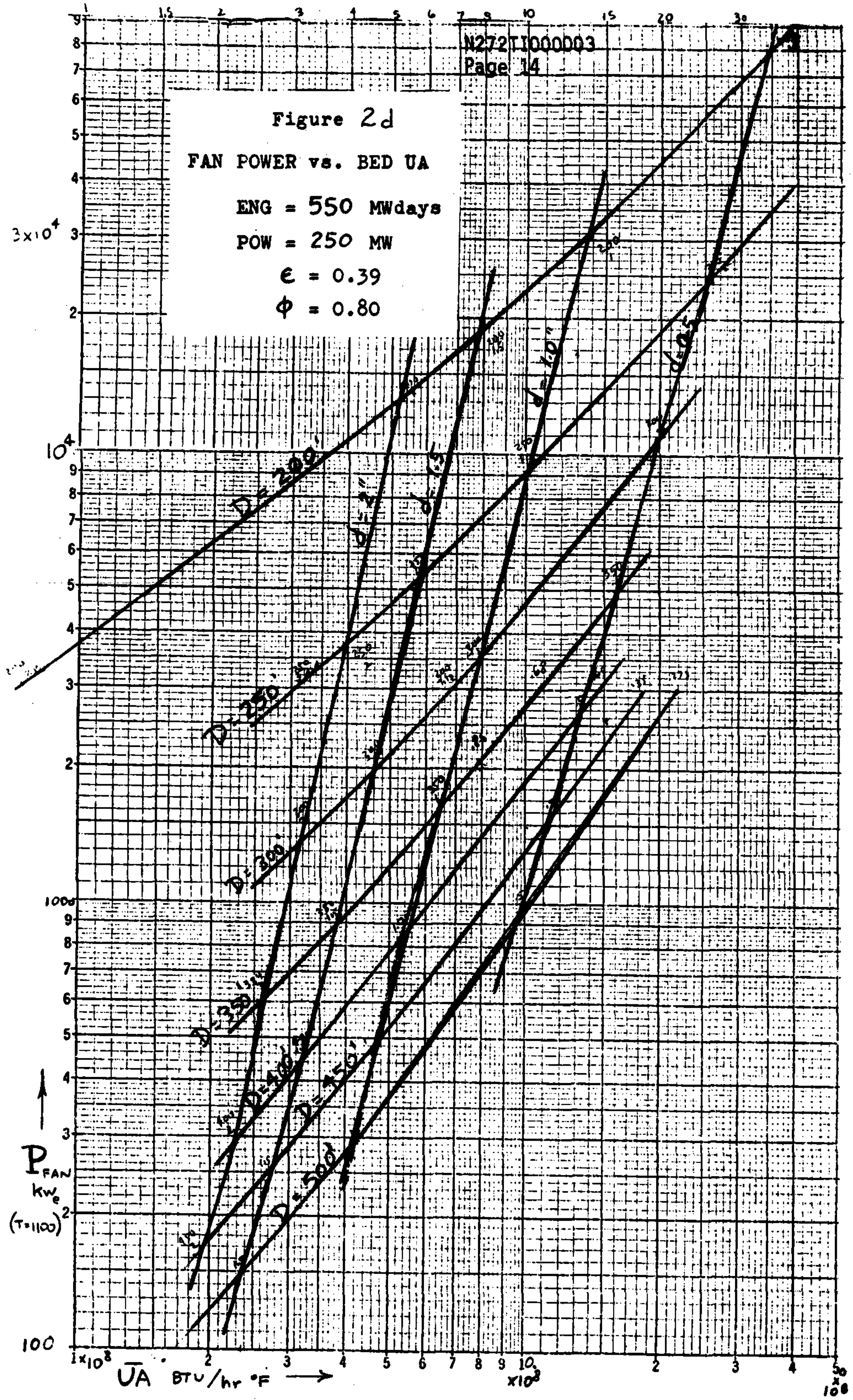


Figure 2d

FAN POWER vs. BED UA

ENG = 550 MWdays

POW = 250 MW

ϵ = 0.39

ϕ = 0.80

VI. NOMENCLATURE

A_{GROSS}	Gross Flow Area Through Bed; $A_{GROSS} = \frac{\pi D^2}{4}$	ft^2
A_{NET}, A_{FREE}	Net Flow Area Through Bed; $A_{NET} = \epsilon A_{GROSS}$	ft^2
A_{SUR}	Total Surface Area of All Particles in Bed.	ft^2
α	Numerical Constant	
B, b	Numerical Constant	
C_p	Specific Heat; air or rock.	$BTU/lb_m\ °F$
D	Bed Diameter	feet
d, d_p	Particle Diameter	inch or Feet
ENG	Maximum Theoretical Energy Capacity of Bed. $ENG = M_{BED}\ C_{p\,ROCK}\ (T_{HOT} - T_{COLD})$	BTU, MW-day:
eff	Fan Efficiency	
f	Flow Friction Factor (See Appendix C)	

G, G_o	Superficial Mass Velocity $G = \frac{\dot{W}}{A_{GROSS}} = \rho_{air} V_o$	$lb_m / hr\ ft^2$
g_c	Gravitational Constant, 32.1739×3600^2	$\frac{ft\ lb_m}{lb_f\ hr^2}$
h	Air-to-Pebble Heat Transfer Coefficient	$BTU / hr\ ft^2\ °F$
hA	Heat Transfer Parameter	$BTU / hr\ °F$
h_v	Volumetric Heat Transfer Coefficient, $h_v = h \times \frac{VOL}{AREA_{sur}} = \frac{h}{\alpha}$	$BTU / hr\ ft^3\ °F$ $watts / sec\ m^3\ °F$
k	Thermal Conductivity; air or rock.	$BTU / hr\ ft\ °F$
L	Bed Height	ft
M	Mass of Bed	lb_m, tons
m	Mass of One Pebble	lb_m
N	Number of Pebbles in Bed	
n	Numerical Constant	

NTU	Heat Transfer Units, $NTU = \frac{UA}{(\dot{w}c_p)_{air}}$	
Nu, Nu_p	Nusselt Number Based on Particle Diameter; $Nu = \frac{h d_p}{k_{air}}$	
$P_{(FAN)}$	Fan Power	kwe
$\Delta p, \Sigma\Delta p$	Air Flow Pressure Drop Through Bed	lb_F/ft^2
Δp_{LAM}	Component of Air Flow Pressure Drop for $\Delta p \propto W^1$	lb_F/ft^2
Δp_{TURB}	Component of Air Flow Pressure Drop for $\Delta p \propto W^2$	lb_F/ft^2
POW	System Operating Power, $POW = \dot{w}_{air} \, c_{p\,air} (T_{HOT} - T_{COLD})$	MW_t
Pr	Prandtl Number, air $Pr = \frac{\mu c_p}{k}$	
Q	Operating Thermal Power $Q = POW = \dot{w}_{air} \, c_{p\,air} (T_{HOT} - T_{COLD})$	BTU/hr
Re	Reynolds Number Based on Particle Diameter and Gross Bed Cross-Sectional Area, $Re = \frac{\dot{w}}{A_{GRS}} \frac{d_p}{\mu}$	

Re_{KL}	Reynolds Number from Kays & London Correlation; $Re = \frac{\dot{W}}{A_{GRS}} \frac{d_p}{\mu} \left[\frac{2\Phi}{3(1-\epsilon)}\right]$, See App. A	
St	Stanton Number $St = \frac{h}{C_p G}$	
T	Temperature	°F
T_{HOT}, T_{COLD}	Maximum and Minimum System Temperatures	°F
ΔT	Maximum Temperature Difference $\Delta T = (T_{HOT} - T_{COLD})$	°F
U	Overall Heat Transfer Coefficient (includes effect of film resistance and conduction into pebble).	$BTU/hr\ ft^2\ °F$
UA, UA_{SUR} UA_{BED}	Total Heat Transfer Parameter for Bed.	BTU/hr °F
V, VOL	Bed Volume	ft^3
V_o	Air Superficial Velocity $V_o = \frac{\dot{W}_{air}}{\rho_{air} A_{cross}}$	ft/sec

V_{NET}, V_{AVG}	Average Air Velocity $V = \frac{\dot{W}_{air}}{\rho_{air} A_{net}}$	ft/sec
$\dot{W}$	Air Mass Flow Rate	lb_m/hr
Y	Thermal Conductance $Y = \frac{kA}{\Delta x}$ or hA	BTU/hr °F
Z	$Z = \frac{(Mc_p)_{ROCK}}{(\dot{w} c_p)_{AIR}}$	hr, sec
Z1, Z2	Calculational Parameters in Pressure Drop Expression	
α	Surface Area per Unit Volume $\alpha = \frac{\text{Surface Area}}{\text{Volume}} = \frac{A_{sur}}{VOL} = \frac{6(1-\epsilon)}{d_p \phi}$	ft^{-1}
ϵ	Bed Porosity (Void Fraction)	
μ	Air Viscosity	$lb_m/hr\ ft$
ρ	Density; Air or Rock	lb_m/ft^3
τ	Air Flow Transit Time, $\tau = \frac{L}{V_{net}} = \frac{L \rho_{air} A_{net}}{\dot{W}}$	sec
ϕ	Particle Sphericity $\phi = \left(\frac{\text{Surface Area of Sphere}}{\text{Actual Surface Area of Particle of same Volume}}\right)$ See App. B	

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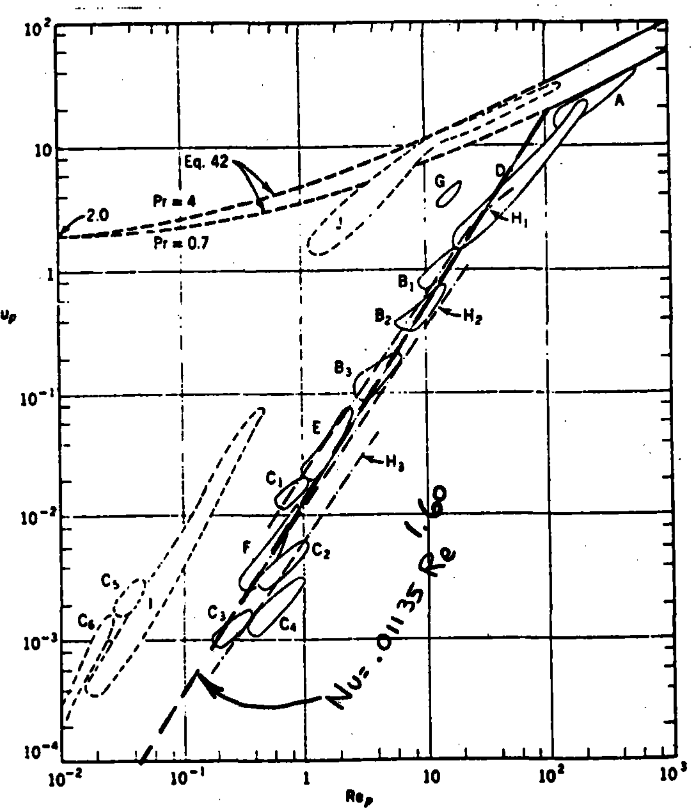
APPENDIX A
HEAT TRANSFER CORRELATIONS

KUNII & LEVENSPIEL
(Ref. 1) Pg. 210-212

For Re > 100, $Nu = 2 + 1.8 Pr^{1/3} Re^{1/2}$

$$Nu \cong 2.0 + 1.6 Re^{0.5} \quad \text{for } Pr \cong 0.7$$

For Re < 100, $Nu \cong 0.01135 Re^{1.60}$
curve drawn through data below:



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KAYS & LONDON:
(Ref. 2) Pg. 123 Fig. 113

Given volume: VOL

Particle diameter. d_p

Volume of one particle: $\frac{\pi}{6} d_p^3$

Surface area, one particle $= \frac{\pi d_p^2}{\Phi}$

Number of particles in volume, $N = \frac{VOL(1-\epsilon)}{\frac{\pi}{6} d_p^3}$

Total surface area, $A_{TOT} = NA_1 = \frac{VOL(1-\epsilon)}{\frac{\pi}{6} d_p^3} \frac{\pi d_p^2}{\Phi} = \frac{VOL(1-\epsilon)\,6}{d_p \Phi}$

Volume/Surface Ratio $= \frac{d_p \Phi}{6(1-\epsilon)}$

Hydraulic Diameter: $4r_h = \frac{4A_{FREE}L}{A_{sur}} = \frac{4\overset{\epsilon\, VOL}{A_{GR}\epsilon L}}{A_{sur}} = 4\epsilon \frac{VOL}{SUR}$

$$4r_h = \frac{2}{3}\frac{\epsilon}{(1-\epsilon)} d_p \Phi$$

$G_{KL} = \frac{\dot{W}}{A_{Free}} = \frac{\dot{W}}{A_{GR}\epsilon}$ $\qquad G_{KL} = G\left(\frac{1}{\epsilon}\right)$

$$Re_{KL} = \frac{4r_h G_{KL}}{\mu} = \frac{2}{3}\frac{\epsilon}{1-\epsilon} d_p \Phi \frac{\dot{W}}{A_{Gr}\epsilon\mu} = \frac{2}{3}\frac{\Phi}{1-\epsilon}\frac{\dot{W}}{A_{Gr}}\frac{d_p}{\mu}$$

$Re = \frac{\dot{W}}{A_{GR}}\frac{d_p}{\mu}$ $\qquad \left(Re_{KL} = \frac{2}{3}\frac{\Phi}{(1-\epsilon)} Re\right)$

$$St = \frac{h}{c_p G_{KL}} = \frac{h\epsilon}{c_p \frac{\dot{W}}{A_{GR}}}$$

$$Pr = \frac{\mu c_p}{k}$$

$$Nu = \frac{h d_p}{k}$$

$$St \; Pr = 0.21 \; Re_{KL}^{-.31} \qquad 20 < Re_{KL} < 600$$

$$\frac{h\,\epsilon}{c_p \frac{\dot{W}}{A_{Gr}}} \; \frac{\mu c_p}{k} = 0.21 \left(\frac{2}{3} \frac{\Phi}{(1-\epsilon)}\right)^{-.31} Re^{-.31}$$

$$\frac{h d_p}{k} = 0.21\left(\frac{3}{2}\right)^{0.31} \left[\frac{1}{\epsilon}\left(\frac{1-\epsilon}{\phi}\right)^{0.31}\right] \left(\frac{\dot{W}}{A_{GR}} \frac{d_p}{\mu}\right)^{.69}$$

$$\boxed{Nu = 0.23813 \left[\frac{1}{\epsilon}\left(\frac{1-\epsilon}{\phi}\right)^{0.31}\right] Re^{0.69}}$$

$20 < Re < 600$ KAYS & LONDON

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LÖF & HAWLEY
(Ref. 3)

$$h_v = 0.79\left(\frac{G}{d_p}\right)^{0.7}$$

h_v = BTU/hr ft^3 °F

G = lb$_m$/hr ft^2 of bed cross-section

d_p = Particle Equivalent Diameter (feet)

$$0.79\ \frac{BTU}{°F\ lb_m^{.7}\ hr^{.3}\ ft^{.9}}$$

$$h = h_v\left(\frac{1}{\alpha}\right) \quad \text{where} \quad \alpha = \frac{AREA}{VOL} = \frac{6(1-\epsilon)}{d_p\,\Phi}$$

$$\underset{Nu}{\frac{h\,d_p}{k}} = \frac{d_p}{k}\,\frac{1}{\alpha}\,0.79\left(\underbrace{\frac{\dot{W}}{A_{GR}\,\dot{d}}\,d\,d}_{Re}\right)^{0.7}\frac{\mu^{0.7}}{d^{1.4}}$$

$$Nu = Re^{0.7}\,d_{FT}^{0.6}\,\frac{\Phi}{6(1-\epsilon)}\,\frac{\mu^{.7}}{k}\,(.79)$$

For air at 100°F ⟶ 250°F ($\bar{T}$=175°F)

μ = .050607 lb$_m$/ft hr

k = .0168437 BTU/hr ft °F

$$\frac{\mu^{.7}}{k} = 7.35377$$

$$Nu = Re^{.7}\left(\frac{d_{INCH}}{12}\right)^{0.6}\frac{\Phi}{6(1-\epsilon)}\,(7.35377)(0.79)$$

$$\boxed{Nu \cong 0.276\,\frac{\Phi}{(1-\epsilon)}\left(d_{INCH}\right)^{0.6} Re^{0.7}}$$ LOF & HAWLEY

$$25 < Re < 500$$

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"ARGENTINE"

ALANIS, SARAVIA & ROVETTA

(Ref. 4)

$$h_v = a\left(\frac{G}{d}\right)^b \qquad a = 824\ \frac{\text{watt}\ \ \text{sec}^{0.92}}{\text{m}^{0.24}\ {}^\circ\text{K}\ \ \text{kg}_m^{0.92}}$$

$b = 0.92$

$$h_v = h\,\frac{\text{VOL}}{\text{AREA}} = h\left(\frac{1}{\alpha}\right)$$

$$\alpha = \frac{\text{AREA}}{\text{VOL}} = \frac{6(1-\epsilon)}{d_p\ \phi}$$

h_v = Volumetric Coeff.

$$a = 824\ \frac{\text{watt}\ \ \text{sec}^{0.92}}{\text{meter}^{.24}\ {}^\circ\text{K}\ \ \text{kg}^{0.92}}$$

$1\ \text{watt} = 3.41276\ \frac{\text{BTU}}{\text{hr}}$

$1\ \text{sec} = \frac{1}{3600}\ \text{hr}$

$1\ {}^\circ\text{K} = 1.8\ {}^\circ\text{R}$

$1\ \text{kg}_m = 2.2046225\ \text{lb}_m$

$1\ \text{meter} = \frac{1}{.3048}\ \text{ft}$

$$a = 824\ \frac{\text{watt}\ \ \text{sec}^{.92}}{\text{m}^{.24}\ \text{K}\ \ \text{kg}^{.92}}\ \ 3.41276\,\frac{\text{BTU}}{\text{hr w}}\ \left(\frac{1}{3600}\right)^{.92}\left(\frac{\text{hr}}{\text{sec}}\right)^{.92}(.3048)^{.24}\left(\frac{\text{m}}{\text{ft}}\right)^{.24}\ \frac{\text{K}}{1.8\,\text{R}}\ \frac{\quad}{2.2046225}\left(\frac{\text{kg}}{\text{lb}_m}\right)^{.92}$$

$$a = 0.3035696\ \frac{\text{BTU}}{\text{hr}^{0.08}\ \text{ft}^{.24}\ {}^\circ\text{R}\ \ \text{lb}_m^{.92}}$$

$T = 18\,^\circ\text{C} \longrightarrow 67\,^\circ\text{C}$

$64.4\,^\circ\text{F} \longrightarrow 152.6\,^\circ\text{F}$

(Test data Range)

$\bar{T} = 108.5\ {}^\circ\text{F}$

$\mu = .046665\ \frac{\text{lb}_m}{\text{ft hr}} \qquad \mu^{.92} = .05963103$

$k = 0.0155116$

$$\frac{\mu^{0.92}}{k} = 3.8443\ \frac{\text{lb}_m^{0.92}\ \text{hr}^{0.08}\ \text{ft}^{0.08}\ {}^\circ\text{F}}{\text{BTU}}$$

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$$h_v = a\left(\frac{G}{d_p}\right)^b$$

$$h = h_v\left(\frac{1}{\alpha}\right) = \frac{1}{\alpha}\, a\left(\frac{G}{d_p}\right)^b$$

$$\underbrace{\frac{h d_p}{k}}_{Nu_p} = \frac{d_p}{k}\,\frac{a}{\alpha}\Big(\underbrace{\frac{G}{d_p}\,\frac{d_p d_o}{\mu}}_{Re_p}\Big)^b\,\frac{\mu^b}{d^{2b}}$$

$$Nu = \frac{d_o}{k}\,\frac{a\, d_p\, \Phi}{6(1-\epsilon)}\, Re^b\, \frac{\mu^b}{D^{2b}}$$

$$Nu = Re^b\, \frac{a}{6}\,\frac{\Phi}{1-\epsilon}\, d^{2(1-b)}\, \frac{\mu^b}{k}$$

$$b = 0.92 \qquad a = .30357 \qquad \frac{\mu^{.92}}{k} = 3.8443$$

$$Nu = Re^{.92}\,\frac{\Phi}{1-\epsilon}\,\frac{d_{INCH}^{0.16}}{12^{0.16}}\,\frac{.30357}{6}\; 3.8443$$

$$\boxed{Nu = 0.1307\left(d_{INCH}\right)^{0.16}\left(\frac{\Phi}{1-\epsilon}\right) Re^{0.92}}$$

"ARGENTINE" $25 < Re < 200$

GAMSON
McADAMS
(Ref 5) Pg. 295

$$j = \frac{h}{c_p G}\left(\frac{c_p \mu}{k}\right)^{2/3} = 1.06\left(\frac{d_p G}{\mu}\right)^{-0.41}$$

$$G = \frac{\dot{w}}{A_{GR}}$$

$$\frac{h\ d_p}{k} = 1.06\ (Re)^{-0.41}\ c_p G\ P_r^{-2/3}\ \frac{d_p}{k}\ \frac{\mu}{\mu}$$

$$\underbrace{\frac{h d_p}{k}}_{Nu} = 1.06\ Re^{-.41}\ P_r^{-.23}\ \underbrace{\frac{G d_p}{\mu}}_{Re}\ \underbrace{\frac{c_p \mu}{k}}_{P_r}$$

$$Nu = 1.06\ P_r^{1/3}\ Re^{0.59}$$

For $P_r \approxeq 0.72$

$$\boxed{Nu = 0.94\ Re^{0.59}}$$ GAMSON (McAdams)

$$350 < Re < 4000$$

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SUMMARY OF HEAT TRANSFER CORRELATIONS

KUNII & LEVENSPIEL	$Re < 100$; $Nu = 0.01135\ Re^{1.6}$ $Re > 100$; $Nu = 2 + 1.6\ Re^{0.5}$ No ϵ or ϕ dependence	$h \propto d^{+.6}$ h↓ as T↑ $h \propto d^{-.5}$ h↑ as T↑
KAYS & LONDON	$Nu = 0.238 \left(\frac{1}{\phi}\right)^{.31} \frac{(1-\epsilon)^{.31}}{\epsilon} Re^{0.69}$ $20 < Re < 600$	$h \propto d^{-.31}$ $h \propto \phi^{-.31}$ h↓ as ϵ↑ h↑ as T↑
LÖF & HAWLEY	$Nu = 0.276 \frac{\phi}{(1-\epsilon)} \left(d_{INCH}\right)^{0.6} Re^{0.7}$ $25 < Re < 500$	$h \propto d^{+.3}$ $h \propto \phi$ h↑ as ϵ↑ h↑ as T↑
"ARGENTINE" Alanis, Saravia, Rovetta	$Nu = 0.131 \frac{\phi}{(1-\epsilon)} \left(d_{INCH}\right)^{0.16} Re^{0.92}$ $25 < Re < 200$	$h \propto d^{+0.08}$ $h \propto \phi$ h↑ as ϵ↑ h↑ as T↑
GAMSON (McAdams)	$Nu = 0.94\ Re^{0.59}$ $350 < Re < 4000$	$h \propto d^{-.41}$ h↑ as T↑ No ϵ or ϕ dependence.
CORRELATION USED IN ANALYSIS.	$Nu = 0.5\ Re^{0.7}$	$h \propto d^{-.3}$ h↑ as T↑ No ϵ or ϕ dependence.

CORRELATION USED IN ANALYSIS:

In comparing the several heat transfer correlations, some areas of agreement and disagreement were found.

POROSITY, (VOID FRACTION), ϵ: One correlation shows h decreasing with ϵ, two correlations show h increasing with ϵ, and two correlations show no effect.

THUS, NO CONCLUSIVE INDICATION.

SPHERICITY, ϕ: One correlation shows h decreasing with ϕ, two correlations show h increasing with ϕ, and two correlations show no effect.

THUS, NO CONCLUSIVE INDICATION.

PARTICLE DIAMETER, d_p: Correlations show h varying with the -0.5 to the $+0.6$ power. However, most show $h \propto d^{-.3}$

To approximate the several heat transfer correlations, the following expression is used:

$$Nu_p = 0.5\, Re_p^{0.7}$$

where:

$$\begin{cases} Nu = \dfrac{h\, d_p}{k} \\ Re = \dfrac{\dot{w}\, d_p}{A_{GR}\, \mu} \end{cases}$$

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APPENDIX B

SPHERICITY = Φ_s

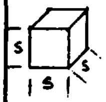
$$\Phi_s = \left(\frac{\text{Surface Area of Sphere}}{\text{Surface Area of Particle}} \right)_{\substack{\text{Both of} \\ \text{Same Volume}}}$$

$$V = \frac{\pi}{6} d^3 \qquad \bar{d} = \left(\frac{6}{\pi} V \right)^{1/3}$$

$$A \left(\begin{matrix}\text{Surface Area} \\ \text{of sphere with} \\ \text{Volume } V\end{matrix} \right) = \pi \bar{d}^2 = \left(36 \pi V^2 \right)^{1/3}$$

$$\boxed{\Phi_s = \frac{(36\pi V^2)^{1/3}}{A_{\substack{\text{Actual} \\ \text{Surface}}}} = \frac{\pi \bar{d}^2}{A_{\substack{\text{Act} \\ \text{Surf.}}}}}$$ SPHERICITY

CUBE:



$$V = S^3$$

$$A_{Act} = 6S^2$$

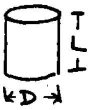
$$\bar{d} = \left(\frac{6}{\pi} V \right)^{1/3} = \left(\frac{6}{\pi} \right)^{1/3} S$$

$$\bar{d} = 1.2407 \, S$$

$$\Phi_s = \frac{\pi \bar{d}^2}{A_{Act}} = \frac{\pi \left(\frac{6}{\pi} \right)^{2/3} S^2}{6 S^2}$$

$$\boxed{\Phi_{s_{\text{CUBE}}} = \left(\frac{\pi}{6} \right)^{1/3} = 0.806}$$

CYLINDER:



Say $f = \frac{L}{D}$ $(L = fD)$

$$V = \frac{\pi}{4} D^2 L = \frac{\pi}{4} f D^3$$

$$A_{Act} = 2 \frac{\pi}{4} D^2 + \pi D L = D^2 \pi \left(f + \tfrac{1}{2} \right)$$

$$\bar{d} = \left(\frac{6}{\pi} V \right)^{1/3} = D \left(1.5 f \right)^{1/3}$$

$$A_{\substack{\text{SURFACE} \\ \text{SPHERE}}} = \pi \bar{d}^2 = \pi D^2 \left(2.25 f^2 \right)^{1/3}$$

$$\Phi_s = \frac{A_{\text{sur sphere}}}{A_{act}} = \frac{(2.25 f^2)^{1/3}}{(f + \frac{1}{2})}$$

$f = \frac{L}{D}$	Φ_s
$f \to 0$	$\Phi \to 2.621 f^{2/3}$
0.5	.8255
0.75	.8655
1.0	.87358 (MAX. VALUE)
1.25	.8689
1.50	.8585
2.0	.832
$f \to \infty$	$\frac{1.3104}{f^{1/3}}$

RIGHT
CIRCULAR
CYLINDERS

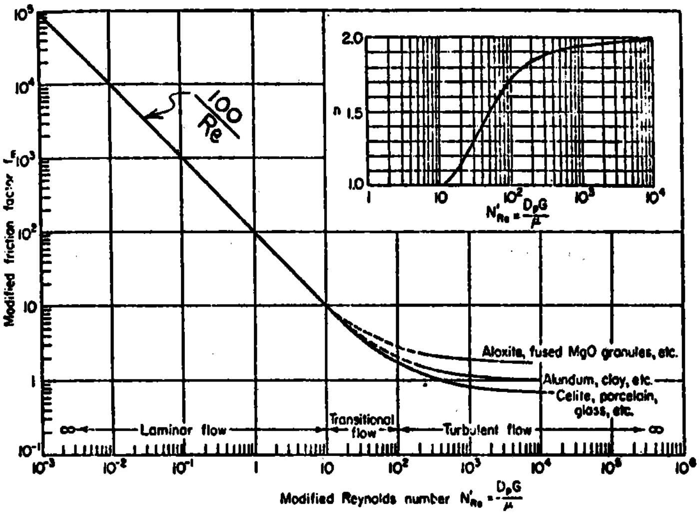
APPENDIX C

PRESSURE DROP & FAN POWER CORRELATIONS

LEVA:
Perry
(Ref. 6) Pg. 5.49 - 5.53

$$\Delta p = \frac{2 f_m G^2 L (1-\epsilon)^{3-n}}{d_p g_c \rho \Phi^{3-n} \epsilon^3}$$

$$N_{Re}' = \frac{d_p G_{GR}}{\mu}$$



Friction factor for beds of solids. [*Leva, "Fluidisation," p. 49, McGraw-Hill, New York*, 1959.]

At low Reynolds Number; (Re < 10)

$$f_m = \frac{100}{Re} = \frac{100\,\mu}{d_p G} \qquad n = 1.0$$

$$\Delta p = \frac{2 f_m G^2 L (1-\epsilon)^{3-n}}{d_p g_c \rho \phi^{3-n} \epsilon^3} = 2 \frac{100\,\mu}{d_p G} \frac{G^2 L (1-\epsilon)^{3-1}}{d_p g_c \rho \phi^{3-1} \epsilon^3}$$

$$\Delta p = \frac{L}{g_c} (200) \frac{\mu V_o}{d_p^2} \frac{(1-\epsilon)^2}{\epsilon^3 \phi^2} \qquad \text{At Low Re.}$$

At high Reynolds Number; (Re > 1000)

$$\text{Say } f_m \cong 1.165 \qquad n = 2.0$$

$$\Delta p = \frac{2 f_m G^2 L (1-\epsilon)^{3-n}}{d_p g_c \rho \phi^{3-n} \epsilon^3} = \frac{2(1.165)\rho^2 V_o^2 L (1-\epsilon)^1}{d_p g_c \rho \phi \epsilon^3}$$

$$\Delta p = \frac{L}{g_c} (2.33) \frac{\rho V_o^2}{d_p} \frac{(1-\epsilon)}{\epsilon^3 \phi} \qquad \text{At High Re.}$$

At intermediate values of Reynolds Number; (10 < Re < 1000)

Requires reading f_m and n values from plot on previous page.

(Ergun)
KUNNI & LEVENSPIEL
(Ref. 1) Pg. 66

Streeter
(Ref. 7) Pg. 17.33

$$\Delta p = \frac{L}{g_c}\left\{150 \frac{(1-\epsilon)^2}{\epsilon^3 \phi^2} \frac{\mu V_0}{d_p^2} + 1.75 \frac{(1-\epsilon)}{\epsilon^3 \phi} \frac{\rho V_0^2}{d_p}\right\}$$

ERGUN CORRELATION

Kunni & Levenspiel suggest using a pressure drop expression made up of the sum of two terms. At low flow velocity, the first term predominates; at high velocity the second term predominates.

At intermediate flow velocities (i.e., Reynolds Numbers), both term contribute, making it unnecessary to determine a friction factor from a plot.

CORRELATION USED IN ANALYSIS:

The Leva correlation matches the Kunni & Levenspiel (Ergun) Equation at the Reynolds Number limits (i.e., for Re < 10 and Re > 1000), except for the numerical value of the constant. The K & L correlation has the calculational advantage of not requiring plot look-ups for f_m and n, as Leva does.

Therefore; the Ergun form for pressure drop is used in the analysis, with the modification that the numerical constants have been increased by a factor of 4/3, to match the more conservative Leva values.

PRESSURE DROP:

$$\Delta p = \frac{L}{g_c}\left\{200\,\frac{(1-\epsilon)^2}{\epsilon^3\phi^2}\,\frac{\mu V_o}{d_p^2} + 2.33\,\frac{(1-\epsilon)}{\epsilon^3\phi}\,\frac{\rho V_o^2}{d_p}\right\}$$

FOR FAN POWER:

$$P_{FAN} = \frac{\Delta p\ \dot{W}}{\rho_{air}\ (eff)}$$

APPENDIX D

ANALYSIS PROCEDURE

Part a: Program Logic

INPUT:

Material Properties: Air, Rock.

Φ = Sphericity of Pebble.

ϵ = Bed Porosity (Void Fraction)

Temperature Limits, T_{HOT}, T_{COLD}

ENG = SYSTEM MAXIMUM THEORETICAL ENERGY, MW-days

POW = SYSTEM OPERATING POWER, MW_t

BED DIAMETER, ft. D_{Bed}

PARTICLE DIAMETER, inch d

CALCULATE:

$\Delta T = T_{HOT} - T_{COLD}$ °F

$\rho(BED) = \rho(Rock) \times (1-\epsilon)$ lbm/ft^3

$ENG(BTU) = 24 \times 3.416 \times 10^6 \times ENG(MW days)$

$Mass\ Bed = M(Bed) = ENG / (C_{P_{Rock}}\ \Delta T)$

$Volume\ Bed = Vol(Bed) = M(Bed) / \rho(Bed)$

D-a-2

$$Q\left(\begin{matrix}\text{Heat Rate}\\ \text{(AIR)}\end{matrix}\right) \frac{\text{BTU}}{\text{hr}} = \text{POW}(\text{MW}) * 3.413 \times 10^{6}$$

$$\dot{W}\left(\begin{matrix}\text{air Mass}\\ \text{FLOW}\end{matrix}\right) \frac{\text{lbm}}{\text{hr}} = Q(\text{air}) \Big/ \left(\bar{C}_{p_{\text{air}}} \; \Delta T\right)$$

$$Z = \frac{(MC_p)_{\text{ROCK BED}}}{(\dot{W}\bar{C}_p)_{\text{AIR}}}$$

$$L(\text{Bed}) = \text{BED HEIGHT} = \left(\frac{4}{\pi}\right) \frac{\text{VOL (Bed)}}{(D_{\text{Bed}})^2} \qquad \text{ft}$$

$$A\left(\begin{matrix}\text{Gross}\\ \text{Cross-Sect}\end{matrix}\right) \text{ft}^2 = \frac{\pi}{4}\left(D_{\text{Bed}}\right)^2$$

$$\alpha = \frac{\text{Surface Area}}{\text{Unit Volume}} = \frac{6(1-\epsilon)}{d}$$

See App. A
Sheet 2

$$\text{MASS}\left(\begin{matrix}\text{One}\\ \text{Rock}\end{matrix}\right) = m(\text{lbm}) = \frac{\pi}{6} d^3 \rho_{\text{ROCK}} \qquad (d = \text{ft})$$

$$N\left(\begin{matrix}\text{Number}\\ \text{of Rocks}\end{matrix}\right) = \frac{M(\text{Bed})}{m(1\ \text{Rock})}$$

$$A\left(\begin{matrix}\text{Surface Area,}\\ \text{1 Rock}\end{matrix}\right) \text{ft}^2 = \pi d^2 \left(\frac{1}{\Phi}\right) \qquad (d = \text{ft})$$

$$A_{\substack{\text{TOT}\\ \text{SUR}}}\left(\begin{matrix}\text{TOTAL}\\ \text{SURFACE}\end{matrix}\right) = N\left(\begin{matrix}\text{Number}\\ \text{Rocks}\end{matrix}\right) * A\left(\begin{matrix}\text{Surface}\\ \text{One Rock}\end{matrix}\right) \qquad \text{ft}^2$$

$$A\left(\begin{matrix}\text{Gross}\\ \text{Flow}\end{matrix}\right) = \frac{\pi}{4} D_{\text{Bed}}^2$$

$$A\left(\begin{matrix}\text{Net}\\ \text{Flow}\end{matrix}\right) = \frac{\pi}{4} D_{\text{Bed}}^2 * \epsilon$$

$$GO\left(\begin{matrix}\text{Superficial}\\ \text{Mass Velocity}\end{matrix}\right) = G_o = \frac{\dot{W}(\text{air})}{A_{\substack{\text{Gross}\\ \text{Flow}}}}$$

$$KDX = (k)_{\text{Rock}} / (\Delta x) = 7.7 * \frac{k_{\text{ROCK}}}{d}$$

See Appendix E

$$Vo\left(\begin{matrix}\text{Superficial}\\ \text{Velocity}\end{matrix}\right) = \frac{G_o(\text{Gross})}{\rho_{\text{air}}} = \frac{\dot{W}}{A_{\text{GRS}}\, \rho_{\text{air}}}$$

$$V\left(\begin{matrix}\text{Net Average}\\ \text{Velocity}\end{matrix}\right) = \frac{G_o}{\rho_{\text{air}} * \epsilon} = \frac{\dot{W}}{A_{\text{Net}}\, \rho_{\text{air}}}$$

$$\text{TRANSIT TIME (Air flow)} = \frac{L(\text{Bed})}{V\left(\begin{matrix}\text{Net}\\ \text{Avg}\end{matrix}\right)} = \frac{L\, \rho_{\text{air}}\, A_{\text{Net}}}{\dot{W}}$$

Fig 37

D-a-3

$$Z1 = (\text{Pressure Drop Factor; LAM}) = \frac{L}{g_c}\, 200\, \frac{(1-\epsilon)^2}{\epsilon^3}$$

$$Z2 = (\text{Pressure Drop Factor; TURB}) = \frac{L}{g_c}\, 2.33\, \frac{(1-\epsilon)}{\epsilon^3}$$

$$\Delta p_{LAM} = Z1 * \mu \frac{V_0}{\phi^2 d^2}$$

$$\Delta p_{TURB} = Z2 * \frac{\rho V_0^2}{\phi d}$$

$$\Sigma \Delta p = \Delta p_{LAM} + \Delta p_{TURB}$$

$$Re\,(\text{Reynolds}) = \frac{d G_0}{\mu}$$

$$Nu\,(\text{Nusselt}) = 0.5\, Re^{0.7}$$

$$h = \frac{Nu \times k_{air}}{d}$$

$$hA = h * A\left(\substack{\text{TOTAL}\\\text{SURFACE}}\right)$$

$$\frac{1}{U} = \frac{1}{h} + \frac{1}{k\,dx}$$

$$UA = U * A\left(\substack{\text{TOTAL}\\\text{SURFACE}}\right)$$

$$P\left(\substack{\text{FAN}\\\text{POWER}}, kw_e\right) = \frac{\Sigma \Delta p \cdot \dot{W}_{air}}{\rho_{air}\ (\text{eff})}$$

$$\overline{UA}\left(\substack{\text{Average}\\UA}\right) = \frac{1}{2}\left(UA_{T=HOT} + UA_{T=COLD}\right)$$

$$NTU = \frac{\overline{UA}}{(\dot{w}\,\bar{c}_p)_{AIR}}$$

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Part b: Influence of Input Variables:

BED hA_{SUR}:

ENG (Theoretical Bed Energy Capacity, BTU or MWdays)

$$ENG = M C_{p_{ROCK}} \Delta T$$

$$M \text{ (Rock Mass)} = \frac{ENG}{C_{p_{ROCK}} \Delta T}$$

$$VOL \text{ (Gross Bed Volume)} = \frac{M}{\bar{\rho}_{BED}} = \frac{M}{\rho_{ROCK}(1-\epsilon)}$$

$$\frac{A_{SUR}}{VOL_{BED}} = \frac{6(1-\epsilon)}{d\,\phi} = \alpha$$

$$A_{SUR} = \alpha(VOL) = \frac{6(1-\epsilon)}{d\,\phi} \frac{M}{\rho_{ROCK}(1-\epsilon)} = \frac{6}{d\,\phi} \frac{ENG}{\rho_{ROCK}\, C_{p_{ROCK}} \Delta T}$$

$$A_{SUR} = \frac{6\, ENG}{d.\,\phi\,(\rho C_p)_{ROCK}\, \Delta T}$$

POW (Power Rate, MW_t or BTU/hr)

$$POW = \dot{w}\,\bar{C}_p\,\Delta T \qquad \dot{w} = \frac{POW}{C_{p_{AIR}} \Delta T}$$

$$A_{GRS} \text{ (Gross Bed Cross-Section)} = \frac{\pi}{4} D^2$$

Say: $Nu = a\,Re^B$

$$\frac{hd}{k} = a\left(\frac{\dot{w}}{A_{GRS}}\right)^B \left(\frac{d}{\mu}\right)^B$$

$$hA_{sur} = \frac{k}{d}\, a \left(\frac{POW}{\bar{C}_{p_{AIR}} \Delta T}\right)^B \left(\frac{4}{\pi D^2}\right)^B \left(\frac{d}{\mu}\right)^B \frac{6\, ENG}{d\phi \quad (\rho C_p)_{ROCK}\, \Delta T}$$

$$hA_{SUR} = \left[6a\left(\frac{4}{\pi}\right)^B\right]\left[(POW)^B (ENG)\right]\left(\frac{k_{air}}{\mu_{air}^B\, \bar{C}_{p_{air}}^B \quad \rho C_{p_{Rock}}}\right)\left(\frac{1}{D^{2B}}\right)\left(\frac{1}{d^{2-B}}\right)\left(\frac{1}{\phi}\right)\left(\frac{1}{\Delta T^{1+B}}\right)$$

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FOR: $Nu = 0.5\, Re^{0.7}$ $\qquad a = 0.5$, $B = 0.7$

$$\left[6a\left(\frac{4}{\pi}\right)^{B}\right] = (6)(.5)\left(\frac{4}{\pi}\right)^{0.7} = 3.55270$$

$$(POW)^{B} = (POW)^{.7} = \left[POW(MW)\right]^{0.7}\left(\left(3.413\times10^{6}\right)^{0.7}\left(\frac{BTU}{hr\ MW}\right)^{0.7}\right) = 37427.90\left(\underset{MW}{POW}^{.7}\right)\left(\frac{BTU}{hr\ MW}^{.7}\right)$$

$$(ENG) = \left[ENG\ (MW\text{-}day)\right]\left(3.413\times10^{6}\ \frac{BTU}{hr\ MW}\times 24\ \frac{hr}{day}\right) = 8.1912\times10^{7}\left(\underset{MW\cdot day}{ENG}\right)\frac{BTU}{MW\cdot day}$$

$$\frac{k_{air}}{\underset{air}{\mu^{0.7}}\ \underset{air}{C_p^{0.7}}\ \underset{ROCK}{(\rho C_P)}} = \left(\frac{{}^{\circ}F^{\,0.7}\ ft^{2.7}}{hr^{0.3}\ BTU^{0.7}}\right)$$

$$D^{1.4} = (DIAM: BED)^{1.4} = ft^{1.4}$$

$$d^{1.3} = \left(d_{inch}\right)^{1.3}\left(\frac{ft}{12\ inch}\right)^{1.3} = \left[.03954252\left(\frac{ft}{inch}\right)^{1.3}\right]\left[\underset{INCH}{d}^{1.3}\right]$$

$$\Delta T^{-1.7} = \left(\frac{1}{{}^{\circ}F}\right)^{-1.7}$$

$$\underset{SUR}{hA} = (3.55270)\left(\underset{MW}{POW}\right)^{0.7}\left(37427.9\left(\frac{BTU}{hr\ MW}\right)^{.7}\right)\underset{MW\text{-}day}{\left[ENG\right]}\left(8.1912\times10^{7}\ \frac{BTU}{MW\ day}\right)\left(\frac{k_{air}}{\mu_{air}^{.7}\ \bar{C}_{p\,air}^{.7}}\right)$$

$$\left(\frac{1}{\underset{ROCK}{\rho C_P}}\right)\left(\frac{{}^{\circ}F^{.7}\ ft^{2.7}}{hr^{0.3}\ BTU^{0.7}}\right)\left(\frac{1}{D_{FT}}\right)^{1.4}\left(\frac{1}{d_{INCH}}\right)^{1.3}\left(\frac{1}{.03954252}\right)\left(\frac{inch}{ft}\right)^{1.3}\frac{1}{\phi}\left(\frac{1}{\Delta T^{1.7}}\right)\frac{1}{{}^{\circ}F^{1.7}}$$

$$\boxed{\underset{SUR}{hA} = \left(2.7545\times10^{14}\right)\left[\underset{MW}{POW}\right]^{0.7}\left[\underset{MW\text{-}day}{ENG}\right]^{1.0}\left(\underset{AIR}{\frac{k}{\mu^{.7}\,\bar{C}_p^{.7}}}\right)\left(\underset{ROCK}{\frac{1}{\rho C_p}}\right)\left(\underset{FT}{\frac{1}{D}}\right)^{1.4}\left(\underset{INCH}{\frac{1}{d}}\right)^{1.3}\left(\frac{1}{\phi}\right)\left(\frac{1}{\Delta T^{1.7}}\right)}$$

$$\frac{BTU}{hr\ {}^{\circ}F}$$

N 152.8.2 REV. 2-76

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BED Δp and FAN POWER

$$\Delta p = \underset{(\text{"LAM"})}{200} \frac{L}{g_c} \frac{(1-\epsilon)^2}{\epsilon^3 \Phi^2} \frac{\mu V_0}{d_p^2} + \underset{(\text{"TURB"})}{2.33} \frac{L}{g_c} \frac{(1-\epsilon)}{\epsilon^3 \Phi} \frac{\rho_g V_0^2}{d_p}$$

$$\underset{\substack{\text{FAN}\\\text{POWER}}}{P} = \frac{\Delta p \ \dot{W}}{\rho_{air} \ (eff)}$$

$$\underset{lb_m/hr}{\dot{W}} = \frac{POW}{\underset{AIR}{\bar{C}_p} \ \Delta T} = \frac{[POW\text{-}MW] \ 3.413 \times 10^6 \ \frac{BTU}{hr \ MW}}{\underset{air}{\bar{C}_p} \ \Delta T \ \frac{BTU}{lb_m \ {}^\circ F} \ {}^\circ F}$$

$$\underset{FAN}{P} \left(\frac{lb_F \ ft}{hr} \right) = \frac{\Delta p \ {}^{lb_F/ft^2} \ \dot{w} \ {}^{lb_m/hr}}{\rho_{air} \ \frac{lb_m}{ft^3} \ (eff)}$$

$$\underset{FAN}{P} = \frac{\Delta p \ {}^{lb_F/ft^2}}{\underset{air}{\rho} \frac{lb_m}{ft^3} \ (eff)} \ \frac{[POW \ (MW)] \ \ 3.413 \times 10^6 \ \frac{BTU}{hr \ MW}}{\underset{AIR}{\bar{C}_p} \ \frac{BTU}{lb_m \ {}^\circ F} \ \Delta T \ {}^\circ F} \ \frac{BTU}{778.16 \ ft \ lb_F} \ \frac{hr \ \ kW_e}{3.413 \times 10^3 \ BTU}$$

$$\boxed{\underset{KWe}{P_{FAN}} = \frac{\Delta p \ \frac{lb_F}{ft^2} \ [POW\text{-}MW]}{\underset{air}{\rho} \ (eff) \ \underset{air}{\bar{C}_p} \ \Delta T} \ (1.2851)}$$

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$$\Delta p_{LAM} = 200 \frac{L}{g_c} \frac{(1-\epsilon)^2}{\epsilon^3} \frac{\mu V_o}{\phi^2 d^2}$$

$$V_o = \frac{\dot{W}}{A_{GRS}\, \rho_{air}} \qquad \dot{W} = \frac{POW}{\bar{C}_{p\,AIR}\, \Delta T} \qquad A_{GRS} = \frac{\pi}{4} D^2$$

$$V_o = \frac{4}{\pi} \frac{POW}{\bar{C}_{p\,AIR}\, \Delta T} \frac{1}{\rho_{air} D^2}$$

$$VOL = A_{GRS} L = \frac{M}{\rho_{ROCK} (1-\epsilon)} \qquad M = \frac{ENG}{C_{p\,ROCK}\, \Delta T}$$

$$L = \frac{VOL}{A_{GRS}} = \left(\frac{4}{\pi} \frac{1}{(1-\epsilon)} \frac{1}{(\rho C_p)_{ROCK}} \frac{ENG}{\Delta T\ D^2} \right)$$

$$\Delta p_{LAM} = \frac{L}{g_c} 200 \frac{(1-\epsilon)^2}{\epsilon^3} \frac{\mu V_o}{\phi^2 d^2} = \left[\left(\frac{4}{\pi}\right)^2 (200)\right] \left(\frac{1}{g_c}\right) \left[\frac{(1-\epsilon)}{\epsilon^3} \frac{1}{\phi^2}\right] \left[(ENG)(POW)\right] \left(\frac{1}{\Delta T^2}\right) \left(\frac{1}{D^4}\right) \left(\frac{1}{d^2}\right) \left(\frac{\mu}{\rho \bar{C}_p}\right)_{AIR} \left(\frac{1}{\rho C_p}\right)_{ROCK}$$

$$(ENG)(POW) = (ENG\ MW\text{-}day)(POW\ MW) \underbrace{\left[(3.413 \times 10^6)^2 \left(\frac{BTU}{hr\ MW}\right)^2 24 \frac{hr}{day}\right]}_{2.79566 \times 10^{14} \frac{BTU^2}{hr\ MW^2\ day}}$$

$$\frac{1}{d^2} = \frac{1}{d^2_{INCH}} \ 144 \frac{in^2}{ft^2}$$

$$g_c = \left(32.1739 \frac{ft\ lb_F}{lb_m\ sec^2}\right)\left(3600^2 \frac{sec^2}{hr^2}\right) = 4.16974 \times 10^8 \ \frac{ft\ lb_F}{lb_m\ hr^2}$$

$$\boxed{\underset{\frac{lb_F}{ft^2}}{\Delta p_{LAM}} = \left(3.1303 \times 10^{10}\right) \frac{(1-\epsilon)}{\epsilon^3} \frac{1}{\phi^2} \left[(ENG)_{MW\ day}(POW)_{MV}\right] \left(\frac{1}{D^4}\right) \left(\frac{1}{\Delta T^2}\right) \left(\frac{1}{d^2}\right)_{INCH} \left(\frac{\mu}{\rho \bar{C}_p}\right)_{AIR} \left(\frac{1}{\rho C_p}\right)_{ROCK}}$$

$$\boxed{\underset{\underset{LAM}{KW_e}}{P_{FAN}} = \left(4.0227 \times 10^{10}\right) \frac{(1-\epsilon)}{\epsilon^3 \phi^2} \left[(ENG)(POW^2)\right] \left(\frac{1}{D^4}\right) \left(\frac{1}{\Delta T^3}\right) \left(\frac{1}{d^2}\right)_{INCH} \left(\frac{\mu}{\rho^2 \bar{C}_p^2}\right)_{AIR} \left(\frac{1}{\rho C_p}\right)_{Rock} \left(\frac{1}{eff}\right)}$$

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$$\underset{TURB}{\Delta p} = 2.33 \frac{L}{g_c} \frac{1-\epsilon}{\epsilon^3} \frac{\rho V_0^2}{\phi d}$$

$$V_0 = \frac{4}{\pi} \frac{Pow}{\underset{AIR}{\bar{c}_p} \Delta T} \frac{1}{\underset{air}{\rho} D^2} \qquad L = \frac{4}{\pi(1-\epsilon)} \frac{1}{\underset{Rock}{(\rho C_p)}} \frac{ENG}{D^2 \Delta T}$$

$$\underset{TURB}{\Delta p} = 2.33 \frac{4}{\pi(1-\epsilon)} \frac{1}{\underset{ROCK}{\rho C_p}} \frac{ENG}{D^2 \Delta T} \frac{1}{g_c} \frac{1-\epsilon}{\epsilon^3} \frac{\rho}{\phi d} \left(\frac{4}{\pi}\right)^2 \frac{(Pow)^2}{\underset{AIR}{(\bar{C}_p)^2} (\Delta T)^2} \frac{1}{\underset{air}{\rho^2} D^4}$$

$$\boxed{\underset{TURB}{\Delta p} = \left[\left(\frac{4}{\pi}\right)^3 (2.33)\right]\left(\frac{1}{g_c}\right)\left[\frac{1}{\epsilon^3} \frac{1}{\Phi}\right]\left[(ENG)(POW)^2\right]\left(\frac{1}{\Delta T^3}\right)\left(\frac{1}{D^6}\right)\left(\frac{1}{d}\right)\underset{air}{\left(\frac{1}{\rho \bar{C}_p^2}\right)}\underset{Rock}{\left(\frac{1}{\rho C_p}\right)}}$$

$$(ENG)(POW^2) = [ENG \ mw \cdot day][POW \ mw^2]\left(3.413 \times 10^6 \frac{BTU}{hr \ Mw}\right)^3 \left(24 \frac{hr}{day}\right)$$

$$9.54156 \times 10^{20}$$

$$\frac{1}{d} = \underset{INCH}{\left(\frac{1}{d}\right)}\left(12 \frac{inch}{ft}\right) \qquad g_c = 4.16974 \times 10^8 \ \frac{ft \ lb_F}{lb_m \ hr^2}$$

$$\boxed{\underset{\substack{TURB \\ lb_F/ft^2}}{\Delta p} = \left(1.3206 \times 10^{14}\right)\left[\frac{1}{\epsilon^3} \frac{1}{\Phi}\right]\left[\underset{\substack{MW \\ day}}{(ENG)} \underset{MW}{(POW)^2}\right]\left(\frac{1}{\Delta T^3}\right)\underset{FT}{\left(\frac{1}{D^6}\right)}\underset{INCH}{\left(\frac{1}{d}\right)}\underset{AIR}{\left(\frac{1}{\rho \bar{C}_p^2}\right)}\underset{ROCK}{\left(\frac{1}{\rho C_p}\right)}}$$

$$\boxed{\underset{\substack{KWe \\ TURB}}{P_{FAN}} = \left(1.6971 \times 10^{14}\right)\left[\frac{1}{\epsilon^3 \phi}\right]\left[\underset{\substack{MW \\ day}}{(ENG)} \underset{MW}{(POW)^3}\right]\left(\frac{1}{\Delta T^4}\right)\underset{FT}{\left(\frac{1}{D^6}\right)}\underset{INCH}{\left(\frac{1}{d}\right)}\underset{AIR}{\left(\frac{1}{\rho^2 \bar{C}_p^3}\right)}\underset{ROCK}{\left(\frac{1}{\rho C_p}\right)}\left(\frac{1}{eff}\right)}$$

EFFECT OF BED PARAMETERS ON hA, Δp and P_{FAN}.

	$hA_{SUR.}$	Δp LAM TURB	P_{FAN} LAM
POROSITY (ϵ)	—	$\Delta p \propto \left(\frac{1-\epsilon}{\epsilon^3}\right)$ OR $\left(\frac{1}{\epsilon^3}\right)$	$P \propto \left(\frac{1-\epsilon}{\epsilon^3}\right)$ OR $\left(\frac{1-\epsilon}{\epsilon^3}\right)$
SPHERICITY (Φ)	$hA \propto \frac{1}{\Phi}$	$\Delta p \propto \frac{1}{\Phi^2}$ OR $\frac{1}{\Phi}$	$P \propto \frac{1}{\Phi^2}$ OR $\frac{1}{\Phi}$
THEORETICAL MAX ENERGY CONTENT (ENG) $ENG = (\rho C_p)_{Rock} \Delta T$	$hA \propto [ENG]$	$\Delta p \propto [ENG]^{1.0}$ OR $[ENG]^{1.0}$	$P \propto [ENG]^{1.0}$ OR $[ENG]^{1.0}$
POWER RATE (POW) $POW = \dot{w}\, C_{p\,AIR} \Delta T$	$hA \propto [POW]^{0.7}$	$\Delta p \propto [POW]$ OR $[POW]^2$	$P \propto [POW]^2$ OR $[POW]^3$
BED DIAMETER, D	$hA \propto \left(\frac{1}{D}\right)^{1.4}$	$\Delta p \propto \left(\frac{1}{D}\right)^4$ OR $\left(\frac{1}{D}\right)^6$	$P \propto \left(\frac{1}{D}\right)^4$ OR $\left(\frac{1}{D}\right)^6$
PARTICLE DIAMETER, d	$hA \propto \left(\frac{1}{d}\right)^{1.3}$	$\Delta p \propto \left(\frac{1}{d}\right)^2$ OR $\left(\frac{1}{d}\right)^1$	$P \propto \left(\frac{1}{d}\right)^2$ OR $\left(\frac{1}{d}\right)^1$
AIR PROPERTIES	$hA \propto \left(\frac{k}{\mu^{.7}\bar{C}_p^{.7}}\right)_{air}$	$\Delta p \propto \left(\frac{\mu}{\rho\bar{C}_p}\right)_{air}$ OR $\left(\frac{1}{\rho\bar{C}_p^2}\right)_{air}$	$P \propto \left(\frac{\mu}{\rho^2\bar{C}_p^2}\right)_{air}$ OR $\left(\frac{1}{\rho^2\bar{C}_p^3}\right)_{air}$
ROCK PROPERTIES	$hA \propto \left(\frac{1}{\rho C_p}\right)_{Rock}$	$\Delta p \propto \left(\frac{1}{\rho C_p}\right)_{Rock}$ OR $\left(\frac{1}{\rho C_p}\right)_{Rock}$	$P \propto \left(\frac{1}{\rho C_p}\right)_{Rock}$ OR $\left(\frac{1}{\rho C_p}\right)_{Rock}$
TEMPERATURE DIFFERENCE (ΔT)	$hA \propto \left(\frac{1}{\Delta T^{1.7}}\right)$	$\Delta p \propto \left(\frac{1}{\Delta T}\right)^2$ OR $\left(\frac{1}{\Delta T}\right)^3$	$P \propto \left(\frac{1}{\Delta T}\right)^3$ OR $\left(\frac{1}{\Delta T}\right)^4$
FAN EFFIENCY (eff)	-	- -	$P \propto \left(\frac{1}{eff}\right)$ OR $\left(\frac{1}{eff}\right)$

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Part c: Partial Numerical Evaluation

$$ENG = M\, C_p\, \Delta T$$

$$M = (VOL)\,\bar{\rho} = (VOL)\,\rho(1-\epsilon)$$

$$VOL = \frac{\pi}{4} D^2 L$$

$$ENG = (VOL)(\rho)(1-\epsilon)(c_p)\,\Delta T$$

$$L_{ft} = \frac{ENG}{\rho(1-\epsilon)(c_{p_{Rock}})(\Delta T)\frac{\pi}{4}D^2} = \frac{(ENG\text{-}MWday)\ 3.413\times10^6 \frac{BTU}{hr\ MW}\ 24\frac{hr}{day}}{(165)(1-.39)\frac{lb_m}{ft^3}\left(.25\frac{BTU}{lb_m{}^\circ F}\right)(500^\circ F)\frac{\pi}{4}D^2\ ft^2}$$

$$\boxed{L_{FT} = \frac{ENG(MW\cdot day)}{D^2_{FT}}\ (8289.605)} \leftarrow \left\{\begin{array}{ll} \epsilon = .39 & \Delta T = 500 \\ \rho = 165 & C_{p_{Rock}} = .25 \end{array}\right.$$

$$M = \frac{ENG}{C_p\,\Delta T} = \frac{(ENG\ MW\cdot day)\left(3.413\times10^6\frac{BTU}{hr\ MW}\times 24\frac{hr}{day}\right)}{\left(.25\frac{BTU}{lb_m{}^\circ F}\right)(500\ ^\circ F)\ \left(2000\frac{lb_m}{TON}\right)}$$

$$\boxed{M_{TON} = ENG(MW\cdot day)\ \ (327.648)}$$

$$VOL = \frac{M}{\bar{\rho}} = \frac{327.648\ ENG}{100.65}$$

$$\boxed{VOL_{ft^3} = ENG(MW\cdot day)\ \ (6510.641)}$$

$$POW = \dot{w}\, C_{p_{air}}\, \Delta T$$

$$\dot{w} = \frac{POW}{\bar{C}_{p_{air}}\,\Delta T} = \frac{(POW\text{-}MW)\left(3.413\times10^6\frac{BTU}{hr\ MW}\right)}{\left(.257057\frac{BTU}{lb_m{}^\circ F}\right)(500\ ^\circ F)}$$

$$\boxed{\dot{W}_{air\ lb_m/hr} = POW(MW)\ \ (26554.422)} \leftarrow \left\{\begin{array}{l} \Delta T = 500 \\ \bar{C}_{p_{air}} = .257057\frac{BTU}{lb_m{}^\circ F} \end{array}\right.$$

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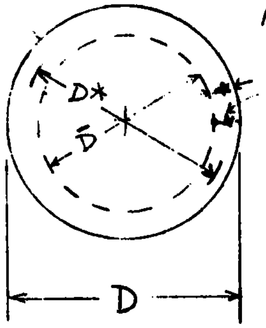
APPENDIX E

CONDUCTION THROUGH UPPER LAYER OF ROCK.

Assume Spherical Pebble.



Represents Thermal Resistance of Upper Layer of Rock.

Assume thermal capacitance of pebble is concentrated at "mid-volume" location.

$$V = \frac{\pi}{6} D^3 \qquad V_{\frac{1}{2}} = \frac{\pi}{6} \bar{D}^3 = 0.5\,V$$

$$\frac{0.5}{1.0} = \left(\frac{\bar{D}}{D}\right)^3$$

$$\bar{D} = (.5)^{1/3} = 0.7937$$

$$\Delta X = \tfrac{1}{2}(1 - .7937)D = 0.10315\,D$$

$$D^* = \sqrt{D \times \bar{D}} = D\sqrt{.7937} = 0.8909\,D$$

$$\bar{A}_{COND} = \pi D^{*2} = 0.7937\,\pi D^2$$

$$Y_{COND} = \frac{kA}{\Delta x} = k\,\frac{.7937\pi D^2}{.10315\,D} = \frac{\overset{A_{sur}}{\pi D^2}(7.69462)\,k}{D}$$

$$A_{sur} = \pi D^2$$

$$Y_{COND} = \frac{7.7\,k_{ROCK}\,A_{sur}}{D}$$

$$\frac{1}{UA} = \frac{1}{Y_{CONV}} + \frac{1}{Y_{COND}}$$

$$\frac{1}{UA} = \frac{1}{hA} + \frac{D_{PARTICLE}}{7.7\,k\,A_{sur}}$$

$$\boxed{\text{"KDX"} = \frac{7.7\,k_{ROCK}}{D_{PARTICLE}}}$$

APPENDIX F

TIME SHARE PROGRAM

```
FMM003

100C   F M MOURADIAN   EXT 2409
150C         FMM003
200C    F       8440     R388
500C   PRESSURE DROP AND HEAT TRANSFER COEFFICIENT
510C   IN THERMAL STORAGE ROCK BED.
1000C
2100C      PRESSURE DROP:    KUNII & LEVENSPIEL   *   4/3
2200C      HEAT TRANS COEFF:       NU = 0.5*RE**.7
1010 DIMENSION T(2), CP(2), MU(2), K(2), RHO(2), PR(2), PR3(2)
1030 DIMENSION DELP(2), DELPL(2), DELPT(2)
1040 DIMENSION UO(2),UOS(2),US(2), RE(2)
1050 DIMENSION NUHIR(2), NULOR(2), NU(2), H(2), HA(2)
1060 DIMENSION  PFN(2), PFHP(2), PFKW(2)
1070 DIMENSION  TTRANS(2), U(2), UR(2), UA(2)
1510 REAL NU, K, MU
1520 REAL MBED, MIRK, NRK, LBED
1530 REAL KRK, KDX, NTU, NNDAYS
2000C       - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
2003 CPRK = 0.25
2004 RHORK = 165.0
2005 KRK = 1.0
2101 EFF = 0.75
2201 PI = 3.141592653
2202 GC = 32.1739*3600.**2
2301 EFFPCT = 100.*EFF
10000C      - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
10010C  I=1, HOT AIR.        I=2, COOL AIR.
10110C  AIRK = SURFACE AREA OF ONE PARTICLE,    FT2
10111C     AIRK CONSIDERS INCREASE IN AREA:SURF DUE TO SPHRCTY
10120C  ASTOT = TOTAL SURFACE AREA IN BED,    FT2
10132C  AGRFL = GROSS (SUPERFICIAL) FLOW AREA,    FT2
10133C  ACRE = LAND AREA OF BED,  ACRES
10134C  ANTFL = NET FLOW AREA (GROSS*POROSITY),    FT2
10170C  ALPHA = SURFACE AREA PER UNIT VOLUME,    FT2/FT3
10310C  CP(I) = AIR SPECIFIC HEAT    BTU/LBM F
10315C  CPRP = AVERAGE AIR SPECIFIC HEAT,    BTU/LBM F
10340C  CPRK = SPECIFIC HEAT OF ROCK     BTU/LBM F
10410C  DTAIR = DELTA TEMP OF SYSTEM,    F
10431C  DELPL(I) = PRESSURE DROP, "LAMINAR TERM" PSF
10432C  DELPT(I) = PRESSURE DROP, "TURBULENT TERM"  PSF
10433C  DELP(I) = TOTAL AIR FLOW PRESSURE DROP   PSF
10470C  DBED = BED DIAMETER.   FT
10482C  DPIN = PARTICLE DIAMETER,    INCH
10484C  DP   = PARTICLE DIAMETER,    FEET
10510C  E = POROSITY OF ROCK BED
10511C     E(REF) = 0.39
10520C  ENG = TOTAL ENERGY STORAGE CAPACITY, ~~10% MARGIN~~, BTU
10530C  EFF = FAN (BLOWER) EFFICIENCY
10531C  EFFPCT = FANEFFICIENCY, PERCENT
10710C  GO = SUPERFICIAL MASS VELOCITY,  LBM/FT2 HR
```

EMM003 CONTINUED

```
10730C  GC = GRAVITATIONAL CONSTANT   FT LBM/LBF HR2
10910C  H(I) = HEAT TRANSFER COEFFICIENT,   BTU/HR FT2 F
10920C  HA(I) = TOTAL HA FOR BED,   BTU/HR F
11110C  K(I) = AIR THERMAL CONDUCTIVITY   BTU/HR FT F
11120C  KRK = ROCK THERMAL CONDUCTIVITY, BTU/HR FT F
11140C  KDX(I) = K/DX (EFF): ROCK    BTU/HR FT2 F
11210C  LBED = LENGTH (HEIGHT) OF BED,   FT
11710C  MU(I) = AIR VISCOSITY   LBM/FT HR
11330C  MBED = TOTAL MASS OF BED,   LBM
11331C  MBEDTN = TOTAL MASS OF BED,   TONS
11340C  M1RK = MASS OF ONE ROCK,   LBM
11350C  MWDAYS = THEORETICAL MAXIMUM BED ENERGY CAPACITY, MW-DAYS
11436C  NU(I) = NUSSELT NO. MINIMUM NU.  VALUE TO USE.
11440C  NRK = NUMBER OF ROCKS
11450C  NTU = HT TRANS UNITS:  (UA:BAR)/(WAIR*CP)
11510C  OS = SPHERICITY
11511C     OS(REF) = 0.80
11610C  PR(I) = AIR PRANDTL NUMBER
11611C  PR3(I) = PR**(1/3)
11622C  PFN(I)  = FAN (BLOWER) POWER, FT LBF/HR
11624C  PFHP(I) = FAN (BLOWER) POWER,  HP
11626C  PFKW(I) = FAN (BLOWER) POWER,  KW
11670C  PI = 3.141592653
11670C  POPER = STORAGE BED OPERATING POWER RATE, MWT
11710C  QAIR = HEAT RATE,   BTU/HR
11810C  RE(I) = REYNOLDS NUMBER
11840C  RHO(I) = AIR DENSITY AT 1 ATM   LBM/FT3
11850C  RHORK = DENSITY OF SOLID ROCK   LBM/FT3
11855C  RHOBED = AVERAGE DENSITY OF BED,  LBM/FT3
12010C  T(I) = AIR TEMPERATURE, F
12020C  T1,T2 = TEMP HOT, COLD
12030C  TTRANS(I) = FLOW TRANSIT TIME,  SECONDS
12110C  U(I) = EFFECTIVE OVERALL HEAT TRANSFER COEFFICIENT
12120C  UA(I) = TOTAL UA FOR BED,  BTU/HR F
12130C  UABR = UA:AVG BETWEEN HOT & COLD
12221C  V0(I) = SUPERFICIAL VELOCITY   FT/HR
12222C  V0S(I) = SUPERFICIAL VELOCITY  FT/SEC
12223C  VS(I) = AVERAGE ACTUAL VELOCITY  FT/SEC
12240C  VOLBED = VOLUME OF BED,   FT3
12310C  WAIR = AIR FLOW RATE,  LBM/HR
12610C  Z1,Z2 = PARAM IN Δ P CALC,  LBF HR2/LBM
12620C  ZPER = Z*PERIOD = (MCP:ROCK)/(WAIR*CP:AIR)  HRS
12700C
19000C      - - - - - - - - - - - - - - - - - - - - - - - - - - -
20080 PRINT.
20081 PRINT.
20082 PRINT.
20083 PRINT.
20090 PRINT, "POROSITY E,  SPHERICITY OS ?"
20091 READ, E, OS
```

EMM003 CONTINUED

```
20100 PRINT, "T(HOT), T(COLD) =?"
20101 READ, T(1), T(2)
20200 DO 100 I=1,2
20210 CP(I) = .239 + .90E-05*T(I) + .14E-07*T(I)**2
20220 MU(I) = .03996 + .6336E-04*T(I) - .144E-07*T(I)**2
20230 K(I) = .0133 + .206E-04*T(I) - .2E-08*T(I)**2
20240 RHO(I) = 39.65874/(T(I)+459.69)
20250 PR(I) = MU(I)*CP(I)/K(I)
20260 PR3(I) = PR(I)**(1./3.)
20350 100 CONTINUE
20511 T1 = T(1)
20512 T2 = T(2)
20520 DTAIR = T1-T2
20530 CPBR = .239 + (.9E-05/2.)*(T1+T2)
20531 CPBR = CPBR + (.14E-07/3.)*(T1**2+T1*T2+T2**2)
21510 PRINT.
21511 PRINT.
21512 PRINT, " - - - - - - - - - - - - - - - - - - - - - - - - - -"
21513 PRINT.
21514 PRINT.
21515 PRINT 701, T(1), T(2)
21516 701 FORMAT (" T:HOT =",F9.1,"     T:COLD =",F9.1,"  F")
21518 PRINT 702, DTAIR
21519 702 FORMAT ("  DEL TEMP =",F9.1,"  F")
21600 PRINT.
22110 PRINT. "  AIR PROPERTIES:"
22200 PRINT. "          HOT           COLD"
22210 PRINT 511, T(1), T(2)
22211 511 FORMAT (F13.1, F13.1, "  TEMP: AIR,   F")
22220 PRINT 512, CP(1), CP(2)
22221 512 FORMAT (F13.6,F13.6,"  CP:AIR   BTU/LBM F")
22230 PRINT 513, MU(1), MU(2)
22231 513 FORMAT (F13.6,F13.6,"  VISCOSITY:AIR  LBM/HR FT")
22240 PRINT 514, RHO(1),RHO(2)
22241 514 FORMAT (F13.6,F13.6,"  DENSITY:AIR   LBM/FT3")
22250 PRINT 515, PR(1), PR(2)
22251 515 FORMAT (F13.6,F13.6,"  PRANDTL:AIR")
22260 PRINT 516, PR3(1),PR3(2)
22261 516 FORMAT (F13.6,F13.6,"  PR**1/3")
22270 PRINT 517, K(1), K(2)
22271 517 FORMAT (F13.6,F13.6,"  CONDUCTIVITY:AIR BTU/HR FT F")
22300 PRINT 518, CPBR
22301 518 FORMAT ("AVG AIR CP =",F9.6," BTU/LBM F")
22509 PRINT.
22510 PRINT. "  ROCK PROPERTIES:"
22530 RHOBED = (1.-F)*RHORK
22610 PRINT 521, CPRK
22611 521 FORMAT (F8.4, "  CP(ROCK)   BTU/LBM F")
22620 PRINT 522, RHORK
22621 522 FORMAT (F8.3,"  DENSITY OF SOLID ROCK,  LBM/FT3")
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EMM003 CONTINUED

```
22630 PRINT 523, RHOBED
22631 523 FORMAT (F8.3,"  MEAN BED DENSITY,  LBM/FT3")
22640 PRINT 524, E
22641 524 FORMAT (F8.3,"  POROSITY")
22650 PRINT 525, OS
22651 525 FORMAT (F8.3,"  SPHERICITY")
22660 PRINT 526, KRK
22661 526 FORMAT (F8.3,"  CONDUCTIVITY:ROCK   BTU/HR FT F")
25000 25 CONTINUE
25011 PRINT,
25012 PRINT,
25015 PRINT, " - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
25021 PRINT,
25022 PRINT,
25109 PRINT,
25110 PRINT, "PLANT MW-DAYS,(THEO):  OPERATING MWT?"
25111 READ,  MWDAYS, POPER
25153 IF (POPER.LE.0.0) GO TO 64
25210 ENG = MWDAYS * 24.0 * 3.413E+06
25211 IF (ENG.LE.0.0) GO TO 64
25220 MBED = ENG/(CPRK*DTAIR)
25225 MBEDTN = MBED/2000.
25230 RHOBED = (1.-E)*RHORK
25240 VOLBED = MBED/RHOBED
25310 QAIR = 3.413E+06*POPER
25320 WAIR = QAIR/(CPBR*DTAIR)
25330 ZPER = (MBED*CPRK)/(WAIR*CPBR)
27060 PRINT 531, MWDAYS
27061 531 FORMAT ("STORAGE FOR",F8.2," MW-DAYS, THEO ")
27080 PRINT 532, POPER
27081 532 fORMAT (F8.2, " MWT BED POWER RATE")
27110 PRINT 541, ENG
27111 541 FORMAT (1PE13.6, "  THEO ENERGY STOR CAP,  BTU")
27120 PRINT 542, MBED
27121 542 FORMAT (1PE13.6,"  MASS OF BED,  LBM")
27125 PRINT 545, MBEDTN
27126 545 FORMAT (F13.2,"  MASS OF BED,  TONS")
27130 PRINT 543, RHOBED
27131 543 FORMAT (F13.5, "  MEAN BED DENSITY,  LBM/FT3")
27140 PRINT 544, VOLBED
27141 544 FORMAT (1PE13.6, "  BED VOLUME,  FT3")
27210 PRINT 551, QAIR
27211 551 FORMAT (1PE13.6,"  HEAT RATE,  BTU/HR")
27220 PRINT 552, WAIR
27221 552 FORMAT (1PE13.6,"  AIR FLOW RATE,  LBM/HR")
27230 PRINT 553, ZPER
27231 553 FORMAT (F13.5,"  Z*PERIOD = MCP:RK/WCP:AIR  HRS")
29500 30 CONTINUE
29980 PRINT,
29981 PRINT,
```

EMM003 CONTINUED

```
29982 PRINT,
29983 PRINT,
29985 PRINT, " = = = = = = = = = = = = = = = = = = = = = = = = = = ="
29986 PRINT, " - - - - - - - - - - - - - - - - - - - - - - - - - - -"
29989 PRINT,
29990 PRINT,
29991 PRINT,
30109 PRINT,
30110 PRINT, "BED DIAM (FT)?"
30111 READ, DBED
30130 IF (DBED.LE.0.0) GO TO 63
30160 LBED = (4./PI)*(VOLBED/DBED**2)
30210 PRINT 535,  DBED,LBED, VOLBED
30211 535 FORMAT ("BED:  D=",F7.1," FT   L=",F9.4,"   VOL=",1PE13.6," FT
30300 ACRE = (PI/4.)*(DBED**2)/43560.
30400 PRINT 536,ACRE
30401 536 FORMAT (F13.5," ACRES OF LAND AREA")
33000 33 CONTINUE
33109 PRINT,
33110 PRINT, "PARTICLE DIAM, INCH ?"
33111 READ, DPIN
33130 IF (DPIN.LE.0.0) GO TO 62
33150 DP = DPIN/12.
33210 ALPHA = 6.*(1.-E)/DP
33220 M1RK = (PI/6.)*(DP**3)*(RHORK)
33230 NRK = MBED/M1RK
33240 A1RK = PI*(DP**2)
33241 A1RK = A1RK/OS
33250 ASTOT = NRK*A1RK
33260 AGRFL = (PI/4.)*(DBED**2)
33270 ANTFL = AGRFL*E
33280 GO = WAIR/AGRFL
33510 PRINT 561, DPIN
33511 561 FORMAT ("ROCK SIZE =",F12.6," INCH")
33513 PRINT,
33515 PRINT 570, M1RK, A1RK, OS
33516 570 FORMAT ("ONE ROCK: MS=",F9.7," LBM   A=",F9.7," FT2 FOR OS=",F
                                                                      F6.
33520 PRINT 562, ALPHA
33521 562 FORMAT (F13.5,"  ALPHA = A:SURF/VOL   FT2/FT3")
33530 PRINT 563, NRK
33531 563 FORMAT (1PE13.6,"  NUMBER OF ROCKS")
33540 PRINT 564, ASTOT
33541 564 FORMAT (1PE13.6,"  TOTAL SURFACE AREA,  FT2")
33550 PRINT 565, AGRFL
33551 565 FORMAT (1PE13.6,"  SUPERFICIAL FLOW AREA, FT2")
33560 PRINT 566, ANTFL
33561 566 FORMAT (1PE13.6."  NET FLOW AREA,  FT2")
33570 PRINT 567, GO
33571 567 FORMAT (F13.5,"  W/A SUPERFICIAL,   LBM/HR FT2")
39000C     - - - - - - - - - - - - - - - - - - - - - - - - -
```

EMM003 CONTINUED

```
39210 KDX = 7.7*KRK/DP
40110 DO 200 I = 1,2
41120 VO(I) = GO/RHO(I)
41130 VOS(I) = VO(I)/3600.
41135 VS(I) = VOS(I)/E
41150 TTRANS(I) = LBED/VS(I)
43111 Z1 = (LBED/GC)*(200.*(1.-E)**2)/(E**3)
43121 Z2 = (LBED/GC)*(2.33*(1.-E))/(E**3)
43210 DELPL(I) = Z1*MU(I)*VO(I)/((DS*DP)**2)
43220 DELPT(I) = Z2*RHO(I)*(VO(I)**2)/(DS*DP)
43310 DELP(I) = DELPL(I) + DELPT(I)
45140 RE(I) = DP*GO/MU(I)
45151 NU(I) = 0.5*(RE(I)**.7)
45180 H(I) = NU(I)*K(I)/DP
45190 HA(I) = H(I)*ASTOT
45510 UR(I) = (1./H(I)) + (1./KDX)
45520 U(I) = 1./UR(I)
45530 UA(I) = U(I)*ASTOT
46110 PFN(I) = DELP(I)*WAIR/(RHO(I)*EFF)
46120 PFHP(I) = PFN(I)/(550.*3600.)
46130 PFKW(I) = PFN(I)/(778.16*3413.)
48999 200 CONTINUE
49110 UABR = (UA(1)+UA(2))/2.
49150 NTU = UABR/(WAIR*CPBR)
50101 PRINT,
50110 PRINT, "           HOT              COLD"
50120 PRINT 511, T(1), T(2)
50140 PRINT 584, VOS(1); VOS(2)
50141 584 FORMAT (F13.6,F13.6,"  SUPERFICIAL VELOCITY,  FT/SEC")
50150 PRINT 585, VS(1), VS(2)
50151 585 FORMAT (F13.6,F13.6,"  AVERAGE VELOCITY,  FT/SEC")
50160 PRINT 586, TTRANS(1), TTRANS(2)
50161 586 FORMAT (F13.3,F13.3,"  FLOW TRANSIT TIME, SEC")
50210 PRINT 601, RE(1), RE(2)
50211 601 FORMAT (F13.4,F13.4,"  REYNOLDS NO.")
50240 PRINT 604, NU(1), NU(2)
50241 604 FORMAT (F13.4,F13.4, " NUSSELT,  NU = .5*RE**.7")
50250 PRINT 605, H(1), H(2)
50251 605 FORMAT (F13.4,F13.4,"  H:  HT TRANS COEFF, BTU/HR FT2 F")
50260 PRINT 621, KDX, KDX
50261 621 FORMAT (F13.4,F13.4,"  K/DX EFF OF ROCK, BTU/HR FT2 F")
50270 PRINT 622, U(1), U(2)
50271 622 FORMAT(F13.4,F13.4,"  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F")
50280 PRINT 623, HA(1), HA(2)
50281 623 FORMAT (1PE13.6,1PE13.6, "  HA:BED   BTU/HR F")
50290 PRINT 624, UA(1), UA(2)
50291 624 FORMAT (1PE13.6,1PE13.6, "  UA:BED   BTU/HR F")
50295 PRINT 625, UABR
50296 625 FORMAT ("    ",1PE13.6,"  UA:AVG,   BTU/HR F")
50300 PRINT 626, NTU
```

EMM003 CONTINUED

```
50301 626 FORMAT ("    ",F13.4,"  NTU")
50310 PRINT 611, DELPL(1), DELPL(2)
50311 611 FORMAT (F13.5,F13.5,"  DEL P:   LAMIN   PSF")
50320 PRINT 612, DELPT(1), DELPT(2)
50321 612 FORMAT (F13.5,F13.5,"  DEL P:   TURBT   PSF")
50330 PRINT 613, DELP(1),  DELP(2)
50331 613 FORMAT (F13.5,F13.5,"  TOTAL DELTA PRESS   PSF")
50360 PRINT 616, PFKW(1), PFKW(2)
50361 616 FORMAT (F13.3,F13.3,"  FAN POWER,   KW")
50400 PRINT 619, EFFPCT
50401 619 FORMAT (" FAN EFF =",F5.1," %")
59990C   - - - - - - - - - - - - - - - - - - - - - - - -
60100 61 GO To 33
60200 62 GO TO 30
60300 63 GO TO 25
60400 64 CONTINUE
99999 END
```

Pg 53

APP[redacted]X G

CALCULATIONAL
OUTPUT

G-1

```
EMM003    15:53  RI T/S FEB 06, 1978



PORDSITY E,  SPHERICITY OS ?
INPUT:20091

 ? .39,    .8

T(HOT), T(COLD) =?
INPUT:20101
 ? 1100,  600


 - - - - - - - - - - - - - - - - - - - - - - -


 T:HOT =    1100.0      T:COLD =     600.0  F
  DEL TEMP =     500.0  F

  AIR PROPERTIES:
        HOT            COLD
       1100.0          600.0  TEMP: AIR,    F
     0.265840       0.249440  CP:AIR   BTU/LBM F
     0.092232       0.072792  VISCOSITY:AIR  LBM/HR FT
     0.025427       0.037425  DENSITY:AIR   LBM/FT3
     0.731036       0.728037  PRANDTL:AIR
     0.900837       0.899603  PR**1/3
     0.033540       0.024940  CONDUCTIVITY:AIR BTU/HR FT F
AVG AIR CP = 0.257057 BTU/LBM F

v  ROCK PROPERTIES:
  0.2500  CP(ROCK)   BTU/LBM F
 165.000  DENSITY OF SOLID ROCK,  LBM/FT3
 100.650  MEAN BED DENSITY,  LBM/FT3
   0.390  POROSITY
   0.800  SPHERICITY
   1.000  CONDUCTIVITY:ROCK   BTU/HR FT F


 - - - - - - - - - - - - - - - - - - - - - - - - - - -


PLANT MW-DAYS,(THEO);  OPERATING MWT?
INPUT:25111
 ?     190,      286

STORAGE FOR  190.00 MW-DAYS, THEO
  286.00 MWT BED POWER RATE
  1.556328E+10  THEO ENERGY STOR CAP,  BTU
  1.245062E+08  MASS OF BED,  LBM
     62253.00  MASS OF BED,  TONS
    100.65000  MEAN BED DENSITY,  LBM/FT3
  1.237021E+06  BED VOLUME,  FT3
  9.761180E+08  HEAT RATE,  BTU/HR
  7.594574E+06  AIR FLOW RATE,  LBM/HR
     15.94406  Z*PERIOD = MCP:RK/WCP:AIR  HRS



 = = = = = = = = = = = = = = = = = = = = = = = = = =
 - - - - - - - - - - - - - - - - - - - - - - - - -
```

ENG = 190 MW days

POW = 286 MW$_t$

$\epsilon = 0.39$

$\phi = 0.80$

Pg 54

```
INPUT:30111
 ? 225

BED:   D=  225.0 FT    L=  31.1116    VOL=  1.237021E+06 FT3
       0.91278 ACRES OF LAND AREA
```

D=225'

D=225'

G-2

```
PARTICLE DIAM, INCH ?
INPUT:33111
 ? 1
```

d = 1.0"

```
ROCK SIZE =     1.000000 INCH

ONE ROCK: MS=0.0499964 LBM    A=0.0272708 FT2 FOR DS= 0.800
      43.92000  ALPHA = A:SURF/VOL    FT2/FT3
  2.490304E+09  NUMBER OF ROCKS
  6.791249E+07  TOTAL SURFACE AREA,  FT2
  3.976078E+04  SUPERFICIAL FLOW AREA, FT2
  1.550670E+04  NET FLOW AREA,  FT2
     191.00667  W/A SUPERFICIAL,   LBM/HR FT2

        HOT              COLD
       1100.0            600.0  TEMP: AIR,    F
     2.086630         1.417705  SUPERFICIAL VELOCITY,  FT/SEC
     5.350333         3.635142  AVERAGE VELOCITY,  FT/SEC
        5.815            8.559  FLOW TRANSIT TIME, SEC
     172.5781         218.6672  REYNOLDS NO.
      18.4018          21.7179 NUSSELT,  NU = .5*RE**.7
       7.4064           6.4997  H:  HT TRANS COEFF, BTU/HR FT2 F
      92.4000          92.4000  K/DX EFF OF ROCK, BTU/HR FT2 F
       6.8567           6.0726  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
 5.029837E+08  4.414138E+08  HA:BED    BTU/HR F
 4.656587E+08  4.124039E+08  UA:BED    BTU/HR F
    4.390313E+08  UA:AVG,   BTU/HR F
       224.8864  NTU
     14.59223          7.82464  DEL P:    LAMIN    PSF
     39.47630         26.14170  DEL P:    TURBT    PSF
     53.06853         33.96634  TOTAL DELTA PRESS    PSF
     7957.441         3460.395  FAN POWER,    KW
 FAN EFF = 75.0 %

PARTICLE DIAM, INCH ?
INPUT:33111
 ? .75

ROCK SIZE =     0.750000 INCH
```

d = 0.75"

```
ONE ROCK: MS=0.0210922 LBM    A=0.0153398 FT2 FOR DS= 0.800
      58.56000  ALPHA = A:SURF/VOL    FT2/FT3
  5.902942E+09  NUMBER OF ROCKS
  9.054999E+07  TOTAL SURFACE AREA,  FT2
  3.976078E+04  SUPERFICIAL FLOW AREA, FT2
  1.550670E+04  NET FLOW AREA,  FT2
     191.00667  W/A SUPERFICIAL,   LBM/HR FT2

        HOT              COLD
       1100.0            600.0  TEMP: AIR,    F
     2.086630         1.417705  SUPERFICIAL VELOCITY,  FT/SEC
     5.350333         3.635142  AVERAGE VELOCITY,  FT/SEC
        5.815            8.559  FLOW TRANSIT TIME, SEC
     129.4336         164.0004  REYNOLDS NO.
      15.0454          17.7567 NUSSELT,  NU = .5*RE**.7
       8.0739           7.0856  H:  HT TRANS COEFF, BTU/HR FT2 F
     123.2000         123.2000  K/DX EFF OF ROCK, BTU/HR FT2 F
       7.5774           6.7003  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
 7.310958E+08  6.416028E+08  HA:BED    BTU/HR F
 6.861301E+08  6.067091E+08  UA:BED    BTU/HR F
    6.464196E+08  UA:AVG,   ,BTU/HR F
       331.1175  NTU
     25.94174         13.91047  DEL P:    LAMIN    PSF
     51.30174         34.85560  DEL P:    TURBT    PSF
     77.24348         48.76607  TOTAL DELTA PRESS    PSF
    11592.390         4968.150  FAN POWER,    KW
```

Pg 55

```
PARTICLE DIAM, INCH ?
INPUT:33111
 ? .5

ROCK SIZE =     0.500000 INCH        d=0.5"

ONE ROCK: MS=0.0062496 LBM   A=0.0068177 FT2 FOR DS= 0.800
     87.84000  ALPHA = A:SURF/VOL   FT2/FT3                  D=225'
  1.992243E+10  NUMBER OF ROCKS
  1.358250E+08  TOTAL SURFACE AREA,  FT2
  3.976078E+04  SUPERFICIAL FLOW AREA, FT2
  1.550670E+04  NET FLOW AREA,  FT2                                      G-3
    191.00667  W/A SUPERFICIAL,   LBM/HR FT2

        HOT             COLD
      1100.0            600.0  TEMP: AIR,    F
     2.086630        1.417705  SUPERFICIAL VELOCITY,  FT/SEC
     5.350333        3.635142  AVERAGE VELOCITY,  FT/SEC
        5.815           8.559  FLOW TRANSIT TIME, SEC
      86.2890        109.3336  REYNOLDS NO.
      11.3276         13.3690 NUSSELT,  NU = .5*RE**.7
       9.1183          8.0021  H:  HT TRANS COEFF, BTU/HR FT2 F
     184.8000        184.8000  K/DX EFF OF ROCK, BTU/HR FT2 F
       8.6895          7.6700  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  1.238491E+09  1.086888E+09  HA:BED    BTU/HR F
  1.180255E+09  1.041777E+09  UA:BED    BTU/HR F
     1.111016E+09  UA:AVG,    BTU/HR F
        569.0996  NTU
     58.36891        31.29855  DEL P:   LAMIN   PSF
     76.95261        52.28341  DEL P:   TURBT   PSF
    135.32152        83.58195  TOTAL DELTA PRESS   PSF
    20290.990        8515.094  FAN POWER,   KW
 FAN EFF = 75.0 %

PARTICLE DIAM, INCH ?
INP'-33111
 ? 1.25

ROCK SIZE =     1.250000 INCH      d=1.25"

ONE ROCK: MS=0.0976492 LBM   A=0.0426106 FT2 FOR DS= 0.800
     35.13600  ALPHA = A:SURF/VOL   FT2/FT3
  1.275035E+09  NUMBER OF ROCKS
  5.433000E+07  TOTAL SURFACE AREA,  FT2
  3.976078E+04  SUPERFICIAL FLOW AREA, FT2
  1.550670E+04  NET FLOW AREA,  FT2
    191.00667  W/A SUPERFICIAL,   LBM/HR FT2

        HOT             COLD
      1100.0            600.0  TEMP: AIR,    F
     2.086630        1.417705  SUPERFICIAL VELOCITY,  FT/SEC
     5.350333        3.635142  AVERAGE VELOCITY,  FT/SEC
        5.815           8.559  FLOW TRANSIT TIME, SEC
     215.7226        273.3340  REYNOLDS NO.
      21.5128         25.3896 NUSSELT,  NU = .5*RE**.7
       6.9268          6.0789  H:  HT TRANS COEFF, BTU/HR FT2 F
      73.9200         73.9200  K/DX EFF OF ROCK, BTU/HR FT2 F
       6.3333          5.6170  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  3.763318E+08  3.302653E+08  HA:BED    BTU/HR F
  3.440885E+08  3.051694E+08  UA:BED    BTU/HR F
     3.246290E+08  UA:AVG,    BTU/HR F
        166.2857  NTU
      9.33903         5.00777  DEL P:   LAMIN   PSF
     30.78104        20.91336  DEL P:   TURBT   PSF
     40.12007        25.92113  TOTAL DELTA PRESS   PSF
     6015.864        2640.772  FAN POWER,   KW
 FAN EFF = 75.0 %
```

Pg 56

G-4

BED DIAM

```
 ? 250

BED:  D=  250.0 FT   L=  25.2004   VOL=  1.237021E+06 FT3
      1.12689 ACRES OF LAND AREA

PARTICLE DIAM, INCH ?
INPUT:33111
 ? 1

ROCK SIZE =     1.000000 INCH
```

d = 1.0"

D = 250'

```
ONE ROCK: MS=0.0499964 LBM    A=0.0272708 FT2 FOR OS= 0.800
     43.92000  ALPHA = A:SURF/VOL    FT2/FT3
  2.490304E+09  NUMBER OF ROCKS
  6.791249E+07  TOTAL SURFACE AREA,  FT2
  4.908739E+04  SUPEJFICIAL FLOW AREA, FT2
  1.914408E+04  NET FLOW AREA,  FT2
    154.71540  W/A SUPERFICIAL,   LBM/HR FT2

        HOT             COLD
       1100.0            600.0  TEMP: AIR,   F
     1.690170         1.148341  SUPERFICIAL VELOCITY,  FT/SEC
     4.333770         2.944465  AVERAGE VELOCITY,  FT/SEC
        5.815            8.559  FLOW TRANSIT TIME, SEC
     139.7883         177.1204  REYNOLDS NO.
      15.9781          19.7395 NUSSELT,   NU = .5*RE**.7
       6.3906           5.6084  H:  HT TRANS COEFF, BTU/HR FT2 F
      92.4000          92.4000  K/DX EFF OF ROCK, BTU/HR FT2 F
       5.9772           5.2874  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  4.340037E+08  3.908776E+08  HA:BED    BTU/HR F
  4.059286E+08  3.590825E+08  UA:BED    BTU/HR F
     3.825056E+08  UA:AVG,    BTU/HR F
          195.9320  NTU
      9.57396       5.13374  DEL P:   LAMIN   PSF
     20.44789      13.89277  DEL P:   TURBT   PSF
     30.02185      19.02652  TOTAL DELTA PRESS    PSF
     4501.671      1938.368  FAN POWER,    KW
 AN EFF = 75.0 %

PARTICLE DIAM, INCH ?
INPUT:33111
 ? .75

ROCK SIZE =     0.750000 INCH
```

d = 0.75"

```
ONE ROCK: MS=0.0210922 LBM    A=0.0153398 FT2 FOR OS= 0.800
     59.56000  ALPHA = A:SURF/VOL    FT2/FT3
  5.902942E+09  NUMBER OF ROCKS
  9.054999E+07  TOTAL SURFACE AREA,  FT2
  4.908739E+04  SUPERFICIAL FLOW AREA, FT2
  1.914408E+04  NET FLOW AREA,  FT2
    154.71540  W/A SUPERFICIAL,   LBM/HR FT2

        HOT             COLD
       1100.0            600.0  TEMP: AIR,   F
     1.690170         1.148341  SUPERFICIAL VELOCITY,  FT/SEC
     4.333770         2.944465  AVERAGE VELOCITY,  FT/SEC
        5.815            8.559  FLOW TRANSIT TIME, SEC
     104.8412         132.8403  REYNOLDS NO.
      12.9820          15.3215 NUSSELT,   NU = .5*RE**.7
       6.9667           6.1139  H:  HT TRANS COEFF, BTU/HR FT2 F
     123.2000         123.2000  K/DX EFF OF ROCK, BTU/HR FT2 F
       6.5938           5.8248  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  6.308322E+08  5.536124E+08  HA:BED    BTU/HR F
  5.970693E+08  5.274379E+08  UA:BED    BTU/HR F
     5.622536E+08  UA:AVG,    BTU/HR F
          288.0049  NTU
     17.02037       9.12666  DEL P:   LAMIN   PSF
     27.26385      18.52370  DEL P:   TURBT   PSF
     44.28422      27.65035  TOTAL DELTA PRESS    PSF
```

```
PARTICLE DIAM, INCH ?
INPUT:33111
 ? .5

ROCK SIZE =     0.500000 INCH         d = 0.5"

ONE ROCK: MS=0.0062496 LBM   A=0.0068177 FT2 FOR DS= 0.800
     87.84000  ALPHA = A:SURF/VOL    FT2/FT3
  1.992243E+10  NUMBER OF ROCKS
  1.358250E+08  TOTAL SURFACE AREA,  FT2                 D= 250'
  4.908739E+04  SUPERFICIAL FLOW AREA, FT2
  1.914408E+04  NET FLOW AREA,  FT2
    154.71540  W/A SUPERFICIAL,   LBM/HR FT2                          G.5

         HOT             COLD
        1100.0            600.0  TEMP: AIR,    F
      1.690170         1.148341  SUPERFICIAL VELOCITY,  FT/SEC
      4.333770         2.944465  AVERAGE VELOCITY,  FT/SEC
         5.815            8.559  FLOW TRANSIT TIME, SEC
       69.8941          98.5602  REYNOLDS NO.
        9.7741          11.5355 NUSSELT,  NU = .5*RE**.7
        7.8678           6.9047  H:  HT TRANS COEFF, BTU/HR FT2 F
      184.8000         184.8000  K/DX EFF OF ROCK, BTU/HR FT2 F
        7.5465           6.6560  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  1.068642E+09  9.378307E+08  HA:BED    BTU/HR F
  1.025003E+09  9.040525E+08  UA:BED    BTU/HR F
      9.645279E+08  UA:AVG,    BTU/HR F
         494.0632  NTU
      38.29584       20.53498  DEL P:   LAMIN   PSF
      40.89577       27.78555  DEL P:   TURBT   PSF
      79.19161       48.32052  TOTAL DELTA PRESS   PSF
     11874.506       4922.759  FAN POWER,   KW
 FAN EFF = 75.0 %

PARTICLE DIAM, INCH ?
INPUT:33111
 ? 1.25

ROCK SIZE =     1.250000 INCH        d = 1.25"

ONE ROCK: MS=0.0976492 LBM   A=0.0426106 FT2 FOR DS= 0.800
     35.13600  ALPHA = A:SURF/VOL    FT2/FT3
  1.275035E+09  NUMBER OF ROCKS
  5.433000E+07  TOTAL SURFACE AREA,  FT2
  4.908739E+04  SUPERFICIAL FLOW AREA, FT2
  1.914408E+04  NET FLOW AREA,  FT2
    154.71540  W/A SUPERFICIAL,   LBM/HR FT2

         HOT             COLD
        1100.0            600.0  TEMP: AIR,    F
      1.690170         1.148341  SUPERFICIAL VELOCITY,  FT/SEC
      4.333770         2.944465  AVERAGE VELOCITY,  FT/SEC
         5.815            8.559  FLOW TRANSIT TIME, SEC
      174.7353         221.4005  REYNOLDS NO.
       18.5625          21.9076 NUSSELT,  NU = .5*RE**.7
        5.9768           5.2452  H:  HT TRANS COEFF, BTU/HR FT2 F
       73.9200          73.9200  K/DX EFF OF ROCK, BTU/HR FT2 F
        5.5297           4.8977  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F.
 3.247211E+08  2.849722E+08  HA:BED    BTU/HR F
 3.004297E+08  2.660909E+08  UA:BED    BTU/HR F
     2.832603E+08  UA:AVG,    BTU/HR F
        145.0953  NTU
       6.12733        3.28560  DEL P:   LAMIN   PSF
      16.35831       11.11422  DEL P:   TURBT   PSF
      22.48564       14.39981  TOTAL DELTA PRESS   PSF
      3371.644       1467.013  FAN POWER,   KW
 FAN EFF = 75.0 %
```

Pg. 58

```
INPUT:30111
 ? 275

BED:  D=  275.0 FT   L=  20.8268   VOL=  1.237021E+06 FT3
       1.36354 ACRES OF LAND AREA

PARTICLE DIAM, INCH ?
INPUT:33111
 ? 1

ROCK SIZE =     1.000000 INCH
```

d = 1.0"

D = 275'

G-6

```
ONE ROCK: MS=0.0499964 LBM   A=0.0272708 FT2 FOR DS= 0.800
     43.92000  ALPHA = A:SURF/VOL    FT2/FT3
  2.490304E+09  NUMBER OF ROCKS
  6.791249E+07  TOTAL SURFACE AREA,  FT2
  5.939574E+04  SUPERFICIAL FLOW AREA, FT2
  2.316434E+04  NET FLOW AREA,  FT2
    127.86397  W/A SUPERFICIAL,   LBM/HR FT2

       HOT             COLD
      1100.0            600.0  TEMP: AIR,   F
    1.396835         0.949042  SUPERFICIAL VELOCITY,  FT/SEC
    3.581628         2.433442  AVERAGE VELOCITY,  FT/SEC
       5.815            8.559  FLOW TRANSIT TIME, SEC
    115.5275         146.3805  REYNOLDS NO.
     13.8947          16.3987 NUSSELT,  NU = .5*RE**.7
      5.5923           4.9078  H:  HT TRANS COEFF, BTU/HR FT2 F
     92.4000          92.4000  K/DX EFF OF ROCK, BTU/HR FT2 F
      5.2732           4.6603  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  3.797902E+08  3.333003E+08  HA:BED   BTU/HR F
  3.581159E+08  3.164900E+08  UA:BED   BTU/HR F
     3.373029E+08  UA:AVG,   BTU/HR F
         172.7777  NTU
     6.53914          3.50642  DEL P:   LAMIN   PSF
    11.54230         7.842w11  DEL P:   TURBT   PSF
    18.08144         11.34852  TOTAL DELTA PRESS   PSF
    2711.249         1156.156  FAN POWER,   KW
 FAN EFF = 75.0 %

PARTICLE DIAM, INCH ?
INPUT:33111
 ? .75

ROCK SIZE =     0.750000 INCH
```

d = 0.75"

```
ONE ROCK: MS=0.0210922 LBM   A=0.0153398 FT2 FOR DS= 0.800
     58.56000  ALPHA = A:SURF/VOL    FT2/FT3
  5.902942E+09  NUMBER OF ROCKS
  9.054999E+07  TOTAL SURFACE AREA,  FT2
  5.939574E+04  SUPERFICIAL FLOW AREA, FT2
  2.316434E+04  NET FLOW AREA,  FT2
    127.86397  W/A SUPERFICIAL,   LBM/HR FT2

       HOT             COLD
      1100.0            600.0  TEMP: AIR,   F
    1.396835         0.949042  SUPERFICIAL VELOCITY,  FT/SEC
    3.581628         2.433442  AVERAGE VELOCITY,  FT/SEC
       5.815            8.559  FLOW TRANSIT TIME, SEC
     86.6456         109.7854  REYNOLDS NO.
     11.3604          13.4076 NUSSELT,  NU = .5*RE**.7
      6.0964           5.3502  H:  HT TRANS COEFF, BTU/HR FT2 F
    123.2000         123.2000  K/DX EFF OF ROCK, BTU/HR FT2 F
      5.8090           5.1275  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  5.520318E+08  4.844579E+08  HA:BED   BTU/HR F
  5.260030E+08  4.642951E+08  UA:BED   BTU/HR F
     4.951491E+08  UA:AVG,   BTU/HR F
         253.6318  NTU
    11.62514          6.23363  DEL P:   LAMIN   PSF
    15.38973         10.45614  DEL P:   TURBT   PSF
    27.01488         16.68977  TOTAL DELTA PRESS   PSF
    4050.786         1700.307  FAN POWER,   KW
```

6

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```
PARTICLE DIAM, INCH ?
INPUT:33111
 ? .50

ROCK SIZE =     0.500000 INCH      d = 0.5"

ONE ROCK: MS=0.0062496 LBM   A=0.0068177 FT2 FOR DS= 0.800
     87.84000  ALPHA = A:SURF/VOL   FT2/FT3
  1.992243E+10  NUMBER OF ROCKS
  1.358250E+08  TOTAL SURFACE AREA,  FT2                    D = 275'
  5.939574E+04  SUPERFICIAL FLOW AREA, FT2
  2.316434E+04  NET FLOW AREA,  FT2
     127.86397  W/A SUPERFICIAL,   LBM/HR FT2                           G-7

        HOT             COLD
       1100.0           600.0  TEMP: AIR,   F
     1.396835        0.949042  SUPERFICIAL VELOCITY,  FT/SEC
     3.581628        2.433442  AVERAGE VELOCITY,  FT/SEC
        5.815           8.559  FLOW TRANSIT TIME, SEC
      57.7637         73.1903  REYNOLDS NO.
       8.5532         10.0946 NUSSELT,  NU = .5*RE**.7
       6.8850          6.0422  H:  HT TRANS COEFF, BTU/HR FT2 F
     184.8000        184.8000  K/DX EFF OF ROCK, BTU/HR FT2 F
       6.6377          5.8509  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  9.351531E+08  8.206816E+08  HA:BED   BTU/HR F
  9.015640E+08  7.946982E+08  UA:BED   BTU/HR F
     8.481311E+08  UA:AVG,   BTU/HR F
        434.4409  NTU
     26.15658       14.02567  DEL P:   LAMIN   PSF
     23.08460       15.68422  DEL P:   TURBT   PSF
     49.24117       29.70988  TOTAL DELTA PRESS   PSF
     7383.542       3026.759  FAN POWER,   KW
 FAN EFF = 75.0 %

PARTICLE DIAM, INCH ?
INPUT:33111
 ? 1.25

ROCK SIZE =     1.250000 INCH      d = 1.25"

ONE ROCK: MS=0.0976492 LBM   A=0.0426106 FT2 FOR DS= 0.800
     35.13600  ALPHA = A:SURF/VOL   FT2/FT3
  1.275035E+09  NUMBER OF ROCKS
  5.433000E+07  TOTAL SURFACE AREA,  FT2
  5.939574E+04  SUPERFICIAL FLOW AREA, FT2
  2.316434E+04  NET FLOW AREA,  FT2
     127.86397  W/A SUPERFICIAL,   LBM/HR FT2

        HOT             COLD
       1100.0           600.0  TEMP: AIR,   F
     1.396835        0.949042  SUPERFICIAL VELOCITY,  FT/SEC
     3.581628        2.433442  AVERAGE VELOCITY,  FT/SEC
        5.815           8.559  FLOW TRANSIT TIME, SEC
     144.4094        182.9756  REYNOLDS NO.
      16.2438         19.1710 NUSSELT,  NU = .5*RE**.7
       5.2302          4.5900  H:  HT TRANS COEFF, BTU/HR FT2 F
      73.9200         73.9200  K/DX EFF OF ROCK, BTU/HR FT2 F
       4.8846          4.3217  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  2.841595E+08  2.493749E+08  HA:BED   BTU/HR F
  2.653814E+08  2.347954E+08  UA:BED   BTU/HR F
     2.500884E+08  UA:AVG,   BTU/HR F
        128.1036  NTU
      4.18505        2.24411  DEL P:   LAMIN   PSF
      9.23384        6.27369  DEL P:   TURBT   PSF
     13.41889        8.51779  TOTAL DELTA PRESS   PSF
     2012.116        867.769  FAN POWER,   KW
FAN EFF = 75.0 %
```

```
PARTICLE DIAM, INCH ?
INPUT:33111
 ? .375

ROCK SIZE =      0.375000 INCH      d = 0.375"

ONE ROCK: MS=0.0026365 LBM   A=0.0038350 FT2 FOR DS= 0.800
    117.12000  ALPHA = A:SURF/VOL    FT2/FT3
  4.722353E+10  NUMBER OF ROCKS                                   D = 275'
  1.811000E+08  TOTAL SURFACE AREA,  FT2
  5.939574E+04  SUPERFICIAL FLOW AREA, FT2
  2.316434E+04  NET FLOW AREA,  FT2
    127.86397  W/A SUPERFICIAL,    LBM/HR FT2

        HOT             COLD
       1100.0            600.0  TEMP: AIR,    F
     1.396835         0.949042  SUPERFICIAL VELOCITY,  FT/SEC
     3.581628         2.433442  AVERAGE VELOCITY,  FT/SEC
        5.815            8.559  FLOW TRANSIT TIME, SEC
      43.3228          54.8927  REYNOLDS NO.
       6.9931           8.2533 NUSSELT,  NU = .5*RE**.7
       7.5056           6.5868  H:  HT TRANS COEFF, BTU/HR FT2 F
     246.4000         246.4000  K/DX EFF OF ROCK, BTU/HR FT2 F
       7.2837           6.4153  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  1.359262E+09  1.192875E+09  HA:BED   BTU/HR F
  1.319081E+09  1.161817E+09  UA:BED   BTU/HR F
     1.240449E+09  UA:AVG,   BTU/HR F
        635.3992  NTU
     46.50058         24.93452  DEL P:    LAMIN    PSF
     30.77946         20.91229  DEL P:    TURBT    PSF
     77.28004         45.84680  TOTAL DELTA PRESS    PSF
    11587.873         4670.743  FAN POWER,    KW
FAN EFF = 75.0 %
```

```
INPUT:30111
 ? 300

BED:  D=  300.0 FT   L=  17.5003   VOL=  1.237021E+06 FT3
       1.62272 ACRES OF LAND AREA

PARTICLE DIAM, INCH ?
INPUT:33111
 ? 1

ROCK SIZE =     1.000000 INCH
```

d=1.0"   D = 300'

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```
ONE ROCK: MS=0.0499964 LBM   A=0.0272708 FT2 FOR DS= 0.800
      43.92000  ALPHA = A:SURF/VOL    FT2/FT3
  2.490304E+09  NUMBER OF ROCKS
  6.791249E+07  TOTAL SURFACE AREA,  FT2
  7.068583E+04  SUPERFICIAL FLOW AREA, FT2
  2.756748E+04  NET FLOW AREA,  FT2
     107.44125  W/A SUPERFICIAL,    LBM/HR FT2

         HOT            COLD
        1100.0          600.0   TEMP: AIR,    F
      1.173729       0.797459   SUPERFICIAL VELOCITY,  FT/SEC
      3.009562       2.044767   AVERAGE VELOCITY,  FT/SEC
         5.815          8.559   FLOW TRANSIT TIME, SEC
       97.0752       123.0003   REYNOLDS NO.
       12.3012        14.5179 NUSSELT,   NU = .5*RE**.7
        4.9510         4.3449   H:  HT TRANS COEFF, BTU/HR FT2 F
       92.4000        92.4000   K/DX EFF OF ROCK, BTU/HR FT2 F
        4.6992         4.1498   U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  3.362325E+08  2.950745E+08  HA:BED    BTU/HR F
  3.191328E+08  2.818224E+08  UA:BED    BTU/HR F
      3.004776E+08  UA:AVG,    BTU/HR F
         153.9146  NTU
       4.61707        2.47576   DEL P:    LAMIN    PSF
       6.84796        4.65266   DEL P:    TURBT    PSF
      11.46503        7.12843   TOTAL DELTA PRESS    PSF
      1719.141        726.224   FAN POWER,    KW
 FAN EFF = 75.0 %

PARTICLE DIAM, INCH ?
INPUT:33111
 ? .75

ROCK SIZE =     0.750000 INCH
```

d=0.75"

```
ONE ROCK: MS=0.0210922 LBM   A=0.0153398 FT2 FOR DS= 0.800
      58.56000  ALPHA = A:SURF/VOL    FT2/FT3
  5.902942E+09  NUMBER OF ROCKS
  9.054999E+07  TOTAL SURFACE AREA,  FT2
  7.068583E+04  SUPERFICIAL FLOW AREA, FT2
  2.756748E+04  NET FLOW AREA,  FT2
     107.44125  W/A SUPERFICIAL,    LBM/HR FT2

         HOT            COLD
        1100.0          600.0   TEMP: AIR,    F
      1.173729       0.797459   SUPERFICIAL VELOCITY,  FT/SEC
      3.009562       2.044767   AVERAGE VELOCITY,  FT/SEC
         5.815          8.559   FLOW TRANSIT TIME, SEC
       72.8064        92.2502   REYNOLDS NO.
       10.0575        11.8699 NUSSELT,   NU = .5*RE**.7
        5.3972         4.7366   H:  HT TRANS COEFF, BTU/HR FT2 F
      123.2000       123.2000   K/DX EFF OF ROCK, BTU/HR FT2 F
        5.1707         4.5612   U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  4.887200E+08  4.288961E+08  HA:BED    BTU/HR F
  4.682083E+08  4.130171E+08  UA:BED    BTU/HR F
      4.406127E+08  UA:AVG,    BTU/HR F
         225.6964  NTU
       8.20813        4.40136   DEL P:    LAMIN    PSF
       9.13061        6.20355   DEL P:    TURBT    PSF
      17.33874       10.66491   TOTAL DELTA PRESS    PSF
      2599.883       1080.398   FAN POWER,    KW
```

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```
PARTICLE DIAM, INCH ?
INPUT:33111
 ? .5

ROCK SIZE =     0.500000 INCH
```

d = 0.5"

```
ONE ROCK: MS=0.0062496 LBM   A=0.0068177 FT2 FOR DS= 0.800
      87.84000  ALPHA = A:SURF/VOL   FT2/FT3
  1.992243E+10  NUMBER OF ROCKS
  1.358250E+08  TOTAL SURFACE AREA,  FT2
  7.068583E+04  SUPERFICIAL FLOW AREA, FT2
  2.756748E+04  NET FLOW AREA,  FT2
     107.44125  W/A SUPERFICIAL,   LBM/HR FT2
```

D = 300'

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```
         HOT            COLD
        1100.0           600.0  TEMP: AIR,   F
      1.173729        0.797459  SUPERFICIAL VELOCITY,  FT/SEC
      3.009562        2.044767  AVERAGE VELOCITY,  FT/SEC
         5.815           8.559  FLOW TRANSIT TIME, SEC
       48.5376         61.5001  REYNOLDS NO.
        7.5722          8.9368 NUSSELT,  NU = .5*RE**.7
        6.0954          5.3492  H:  HT TRANS COEFF, BTU/HR FT2 F
      184.8000        184.8000  K/DX EFF OF ROCK, BTU/HR FT2 F
        5.9007          5.1987  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  8.279016E+08  7.265587E+08  HA:BED    BTU/HR F
  8.014664E+08  7.061193E+08  UA:BED    BTU/HR F
     7.537929E+08  UA:AVG,   BTU/HR F
        386.1177  NTU
      18.46829         9.90306  DEL P:   LAMIN   PSF
      13.69591         9.30532  DEL P:   TURBT   PSF
      32.16420        19.20838  TOTAL DELTA PRESS   PSF
      4822.909        1956.895  FAN POWER,   KW
 FAN EFF = 75.0 %

PARTICLE DIAM, INCH ?
INPUT:33111
 ? .375

ROCK SIZE =     0.375000 INCH
```

d = .375"

```
ONE ROCK: MS=0.0026365 LBM   A=0.0038350 FT2 FOR DS= 0.800
     117.12000  ALPHA = A:SURF/VOL   FT2/FT3
  4.722353E+10  NUMBER OF ROCKS
  1.811000E+08  TOTAL SURFACE AREA,  FT2
  7.068583E+04  SUPERFICIAL FLOW AREA, FT2
  2.756748E+04  NET FLOW AREA,  FT2
     107.44125  W/A SUPERFICIAL,   LBM/HR FT2

         HOT            COLD
        1100.0           600.0  TEMP: AIR,   F
      1.173729        0.797459  SUPERFICIAL VELOCITY,  FT/SEC
      3.009562        2.044767  AVERAGE VELOCITY,  FT/SEC
         5.815           8.559  FLOW TRANSIT TIME, SEC
       36.4032         46.1251  REYNOLDS NO.
        6.1911          7.3068 NUSSELT,  NU = .5*RE**.7
        6.6448          5.8314  H:  HT TRANS COEFF, BTU/HR FT2 F
      246.4000        246.4000  K/DX EFF OF ROCK, BTU/HR FT2 F
        6.4703          5.6966  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  1.203369E+09  1.056066E+09  HA:BED    BTU/HR F
  1.171770E+09  1.031650E+09  UA:BED    BTU/HR F
     1.101710E+09  UA:AVG,   BTU/HR F
        564.3325  NTU
      32.83251        17.60543  DEL P:   LAMIN   PSF
      18.26121        12.40710  DEL P:   TURBT   PSF
      51.09373        30.01253  TOTAL DELTA PRESS   PSF
      7661.326        3057.592  FAN POWER,   KW
 FAN EFF = 75.0 %
```

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```
 ? 325  BED DIAM

BED:  D=  325.0 FT   L=  14.9115   VOL=  1.237021E+06 FT3
  '   1.90445 ACRES OF LAND AREA

PARTICLE DIAM, INCH ?
INPUT:33111
 ? 1
```

D = 325'

```
ROCK SIZE =     1.000000 INCH      d = 1.0"

ONE ROCK: MS=0.0499964 LBM   A=0.0272708 FT2 FOR DS= 0.800
      43.92000  ALPHA = A:SURF/VOL    FT2/FT3
  2.490304E+09  NUMBER OF ROCKS
  6.791249E+07  TOTAL SURFACE AREA,  FT2
  8.295768E+04  SUPERFICIAL FLOW AREA, FT2
  3.235350E+04  NET FLOW AREA,  FT2
      91.54757  W/A SUPERFICIAL,   LBM/HR FT2
```

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```
         HOT            COLD
        1100.0          600.0  TEMP: AIR,    F
      1.000101       0.679492  SUPERFICIAL VELOCITY,  FT/SEC
      2.564361       1.742287  AVERAGE VELOCITY,  FT/SEC
         5.815          8.559  FLOW TRANSIT TIME, SEC
       82.7149       104.8050  REYNOLDS NO.
       10.9971        12.9789 NUSSELT,  NU = .5*RE**.7
        4.4261         3.8843  H:  HT TRANS COEFF, BTU/HR FT2 F
       92.4000        92.4000  K/DX EFF OF ROCK, BTU/HR FT2 F
        4.2238         3.7276  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  3.005888E+08   2.637939E+08  HA:BED    BTU/HR F
  2.868493E+08   2.531519E+08  UA:BED    BTU/HR F
      2.700001E+08  UA:AVG,    BTU/HR F
         138.3030  NTU
       3.35211        1.79747  DEL P:    LAMIN    PSF
       4.23632        2.87825  DEL P:    TURBT    PSF
       7.58843        4.67572  TOTAL DELTA PRESS    PSF
      1137.858        476.349  FAN POWER,    KW
 FAN EFF = 75.0 %

PARTICLE DIAM, INCH ?
INPUT:33111
 ? .75

ROCK SIZE =     0.750000 INCH      d = 0.75"

ONE ROCK: MS=0.0210922 LBM   A=0.0153398 FT2 FOR DS= 0.800
      58.56000  ALPHA = A:SURF/VOL    FT2/FT3
  5.902942E+09  NUMBER OF ROCKS
  9.054999E+07  TOTAL SURFACE AREA,  FT2
  8.295768E+04  SUPERFICIAL FLOW AREA, FT2
  3.235350E+04  NET FLOW AREA,  FT2
      91.54757  W/A SUPERFICIAL,   LBM/HR FT2

         HOT            COLD
        1100.0          600.0  TEMP: AIR,    F
      1.000101       0.679492  SUPERFICIAL VELOCITY,  FT/SEC
      2.564361       1.742287  AVERAGE VELOCITY,  FT/SEC
         5.815          8.559  FLOW TRANSIT TIME, SEC
       62.0362        78.6037  REYNOLDS NO.
        8.9913        10.6116 NUSSELT,  NU = .5*RE**.7
        4.8251         4.2344  H:  HT TRANS COEFF, BTU/HR FT2 F
      123.2000       123.2000  K/DX EFF OF ROCK, BTU/HR FT2 F
        4.6432         4.0937  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  4.369112E+08   3.834291E+08  HA:BED    BTU/HR F
  4.204446E+08   3.706884E+08  UA:BED    BTU/HR F
      3.955665E+08  UA:AVG,    BTU/HR F
         202.6223  NTU
       5.95931        3.19550  DEL P:    LAMIN    PSF
       5.64842        3.83767  DEL P:    TURBT    PSF
      11.60773        7.03317  TOTAL DELTA PRESS    PSF
      1740.578        716.519  FAN POWER,    KW
```

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G-12

```
PARTICLE DIAM, INCH ?
INPUT:33111
 ? .5

ROCK SIZE =     0.500000 INCH     d = 0.5"

ONE ROCK: MS=0.0062496 LBM   A=0.0068177 FT2 FOR OS= 0.800
     87.84000  ALPHA = A:SURF/VOL    FT2/FT3
  1.992243E+10  NUMBER OF ROCKS
  1.358250E+08  TOTAL SURFACE AREA,  FT2              D = 325'
  8.295768E+04  SUPERFICIAL FLOW AREA, FT2
  3.235350E+04  NET FLOW AREA,  FT2
      91.54757  W/A SUPERFICIAL,    LBM/HR FT2

       HOT              COLD
      1100.0            600.0  TEMP: AIR,    F
    1.000101         0.679492  SUPERFICIAL VELOCITY,  FT/SEC
    2.564361         1.742287  AVERAGE VELOCITY,  FT/SEC
       5.815            8.559  FLOW TRANSIT TIME, SEC
     41.3575          52.4025  REYNOLDS NO.
      6.7695           7.9894 NUSSELT,  NU = .5*RE**.7
      5.4492           4.7822  H:  HT TRANS COEFF, BTU/HR FT2 F
    184.8000         184.8000  K/DX EFF OF ROCK, BTU/HR FT2 F
      5.2931           4.6615  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  7.401364E+08  6.495368E+08  HA:BED    BTU/HR F
  7.189371E+08  6.331524E+08  UA:BED    BTU/HR F
    6.760447E+08  UA:AVG,   BTU/HR F
       346.2925  NTU
    13.40844         7.18987  DEL P:   LAMIN   PSF
     8.47263         5.75650  DEL P:   TURBT   PSF
    21.88107        12.94637  TOTAL DELTA PRESS   PSF
    3280.990        1318.940  FAN POWER,   KW
 FAN EFF = 75.0 %

PARTICLE DIAM, INCH ?
INPUT:33111
 ? .375

ROCK SIZE =     0.375000 INCH     d = 0.375"

ONE ROCK: MS=0.0026365 LBM   A=0.0038350 FT2 FOR OS= 0.800
     117.12000  ALPHA = A:SURF/VOL    FT2/FT3
  4.722353E+10  NUMBER OF ROCKS
  1.811000E+08  TOTAL SURFACE AREA,  FT2
  8.295768E+04  SUPERFICIAL FLOW AREA, FT2
  3.235350E+04  NET FLOW AREA,  FT2
      91.54757  W/A SUPERFICIAL,    LBM/HR FT2

       HOT              COLD
      1100.0            600.0  TEMP: AIR,    F
    1.000101         0.679492  SUPERFICIAL VELOCITY,  FT/SEC
    2.564361         1.742287  AVERAGE VELOCITY,  FT/SEC
       5.815            8.559  FLOW TRANSIT TIME, SEC
     31.0181          39.3019  REYNOLDS NO.
      5.5348           6.5322 NUSSELT,  NU = .5*RE**.7
      5.9404           5.2132  H:  HT TRANS COEFF, BTU/HR FT2 F
    246.4000         246.4000  K/DX EFF OF ROCK, BTU/HR FT2 F
      5.8005           5.1052  U:  OVERALL HT TRNS COEFF, BTU/HR FT2 F
  1.075801E+09  9.441133E+08  HA:BED    BTU/HR F
  1.050475E+09  9.245520E+08  UA:BED    BTU/HR F
    9.875140E+08  UA:AVG,   BTU/HR F
       505.8374  NTU
    23.83723        12.78198  DEL P:   LAMIN   PSF
    11.29684         7.67534  DEL P:   TURBT   PSF
    35.13407        20.45732  TOTAL DELTA PRESS   PSF
    5268.231        2084.134  FAN POWER,   KW
 FAN EFF = 75.0 %
```

APPENDIX H
MATERIAL PROPERTIES

AIR: (Ref. 8, 9)

$$C_p \left(\frac{BTU}{lb_m\,°F}\right) = 0.239 + 0.90\times10^{-5}\,T + 0.14\times10^{-7}\,T^2$$

$$\bar{C}_p = \frac{\int c_p\,dT}{\int dT} = 0.239 + \frac{0.90\times10^{-5}}{2}\left(T_{HOT} - T_{COLD}\right) + \frac{0.14\times10^{-7}}{3}\left(T_{HOT}^2 + T_{HOT}T_{COLD} + T_{COLD}^2\right)$$

$$\mu\left(\frac{lb_m}{hr\,ft}\right) = 0.03996 + 0.6336\times10^{-4}\,T - 0.144\times10^{-7}\,T^2$$

$$k\left(\frac{BTU}{hr\,ft\,°F}\right) = 0.0133 + 0.206\times10^{-4}\,T - 0.2\times10^{-8}\,T^2$$

$$\rho\left(\frac{lb_m}{ft3}\right) = 39.65874/(T + 459.69) \qquad \text{(at 14.696 psia).}$$

$$Pr = \frac{C_p\,\mu}{k}$$

$$T = °F$$

ROCK: (Ref. 5) Pg 200

$$C_p\left(\frac{BTU}{lb_m\,°F}\right) = 0.25$$

$$\rho\left(\frac{lb_m}{ft^3}\right) = 165 \qquad \text{(No Voids)}$$

$$k\left(\frac{BTU}{hr\,ft\,°F}\right) = 1.0$$

APPENDIX H

A COMPARISON OF ALTERNATIVE WAYS OF RECOVERING THE HYDRAULIC HEAD FROM THE ADVANCED SOLAR RECEIVER TOWER

CONTENTS

FIGURES

I. INTRODUCTION

The reference design is shown in Figure 1. In this design, the hot and cold storage tank ullages are at atmospheric pressure. The expansion tank liquid level elevation is 221 m (724 ft) above the average level in the storage tanks. The energy represented by this elevation difference is dissipated in the drag valve during operation. The idealized hydraulic energy converted into heat in the drag valve is approximately 2.2 Mw. This energy is supplied by the Receiver Pump P-1 and represents about 18% of the hotel load or 2.2% of net plant output.

All of this energy is not wasted since about 43% of it is reconverted back into electricity in the plant cycle. What remains to be recovered is 57% of 2.2 Mw or 1.25 Mw.

The purpose of this study is to compare the cost effectiveness of alternate ways of accomplishing this recovery and to make a recommendation for the selection of one of them for the short term and indicate if additional improvement might be possible in the longer term with additional development work.

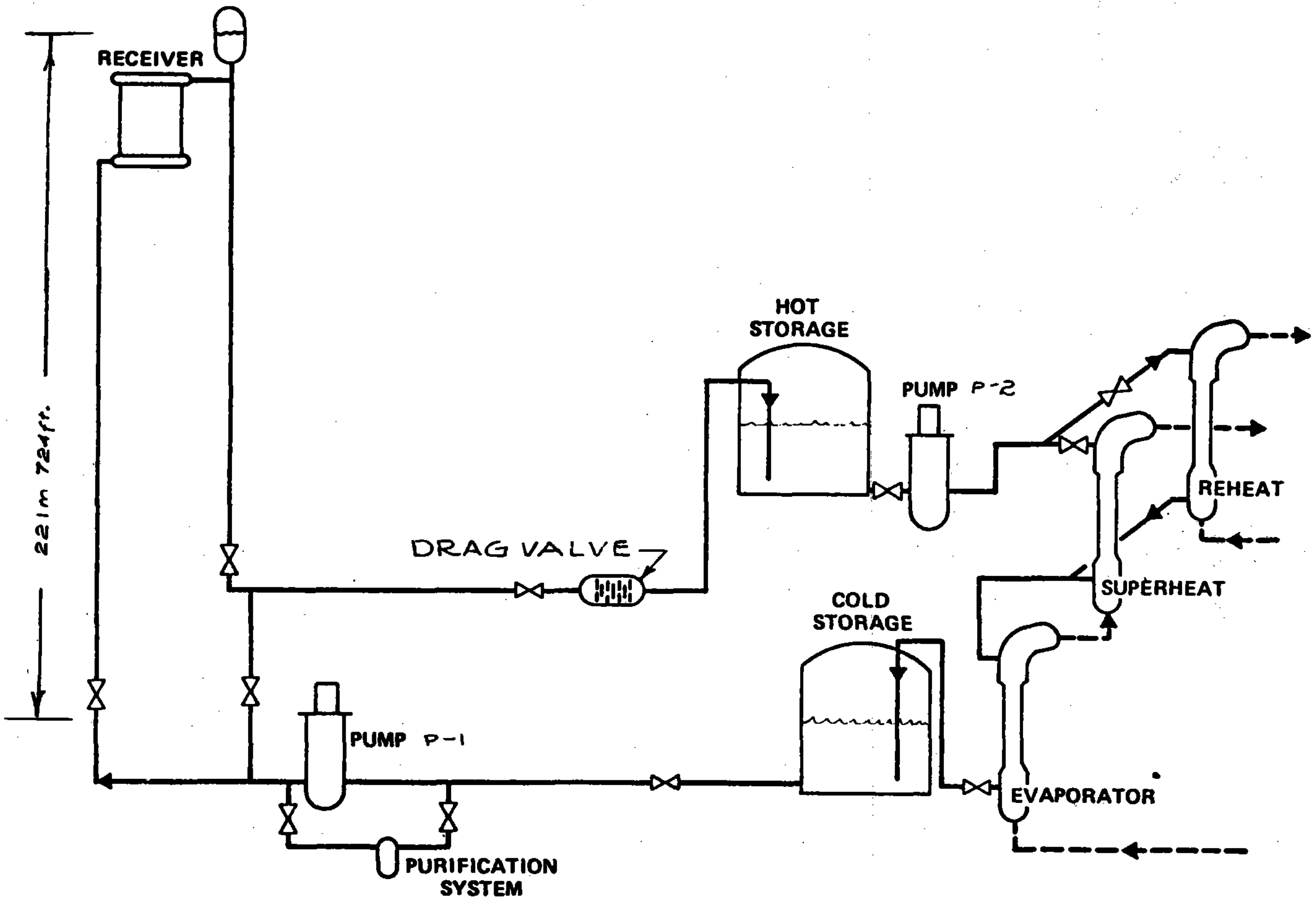

FIGURE 1
REFERENCE DESIGN

II. SUMMARY CONCLUSIONS AND RECOMMENDATIONS

An earlier trade study (Reference 1) examined the possibility of recovering the head by utilizing a high-pressure loop and a low-pressure loop thermally coupled by a heat exchanger (Figure 2). It was determined that the value of the power savings was less than the cost of the heat exchanger. This system was judged not cost effective. An additional eight other methods were examined. These schemes, their summary evaluation, and recommendations are as follows.

A. SUMMARY OF ALTERNATE SCHEMES

	Scheme	Result
1.	Elevated Hot Tank	Not cost effective
2.	Elevated Cold Tank	Not cost effective
3.	Parallel Storage Tanks	Not cost effective
4.	Reduced Downcomer Diameter	Net savings $\$0.6 \times 10^6$
5.	Sodium Turbo Pump Addition	Net savings $\$0.8 \times 10^6$
6.	Jet Pump Addition	Net savings $\$0.85 \times 10^6$
7.	Magnetohydrodynamic (MHD) Addition	Net savings $\$1.2 \times 10^6$
8.	Helical Rotor Generator Addition	Net savings $\$1.2 \times 10^6$

B. RECOMMENDATIONS

For the near term, Scheme 4 is recommended with Scheme 6 as the "fallback" scheme.

For the long term, Scheme 7 is the recommended approach and Scheme 8 the "fallback" scheme.

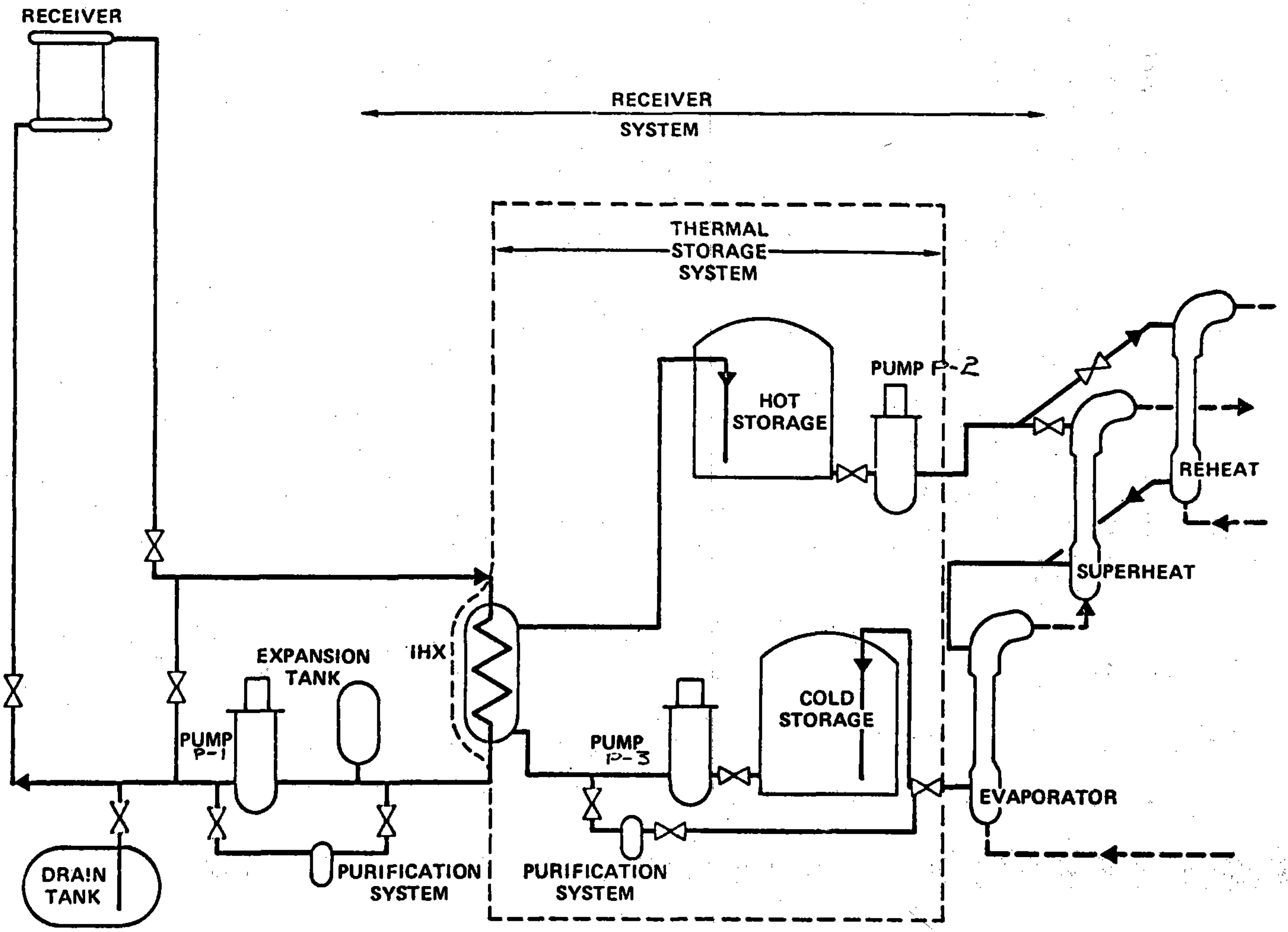

FIGURE 2

TWO LOOPS WITH IHX

III. DISCUSSION

A. GENERAL

The rough cost estimates given include factors for capital costs, operating and maintenance costs, and changes in the plant capacity factor.

B. ALTERNATE SYSTEMS

1. Elevated Hot Tank (Figure 3)

By elevating the hot storage tank by 61 m (200 ft), it is possible to eliminate the P-2 pump and the power required to operate it. The cost savings derive from decreasing the auxiliary power requirements and eliminating the cost of the P-2 pump. The estimated savings are \$0.53 x 10^6 due to plant size reduction, \$0.64 x 10^6 due to an improvement in plant capacity factor, and \$0.5 x 10^6 due to eliminating the pump. The total is approximately \$1.67 x 10^6. The additional cost of the tower to support the tank at the 61-m (200-ft) level is estimated (Reference 2) at \$1.75 x 10^6. The added tank support cost is estimated at \$0.5 x 10^6 for a total additional cost of \$2.25 x 10^6. The operational aspects of this arrangement are excellent; however, because of the higher cost, it is considered to be not cost effective.

2. Elevated Cold Tank (Figure 4)

By elevating the cold tank 85 m (280 ft), it is possible to divide the tower head between the two Pumps P-1 and P-2. This arrangement allows the P-1 pump to be changed from a two-stage design to a single-stage design and divides the engineering, QA, and spare parts costs between the two. The savings accruing from the commonality are estimated at approximately \$0.5 x 10^6. From the Case 1 cost estimate for elevating the tank, it is clear that this scheme is not cost effective.

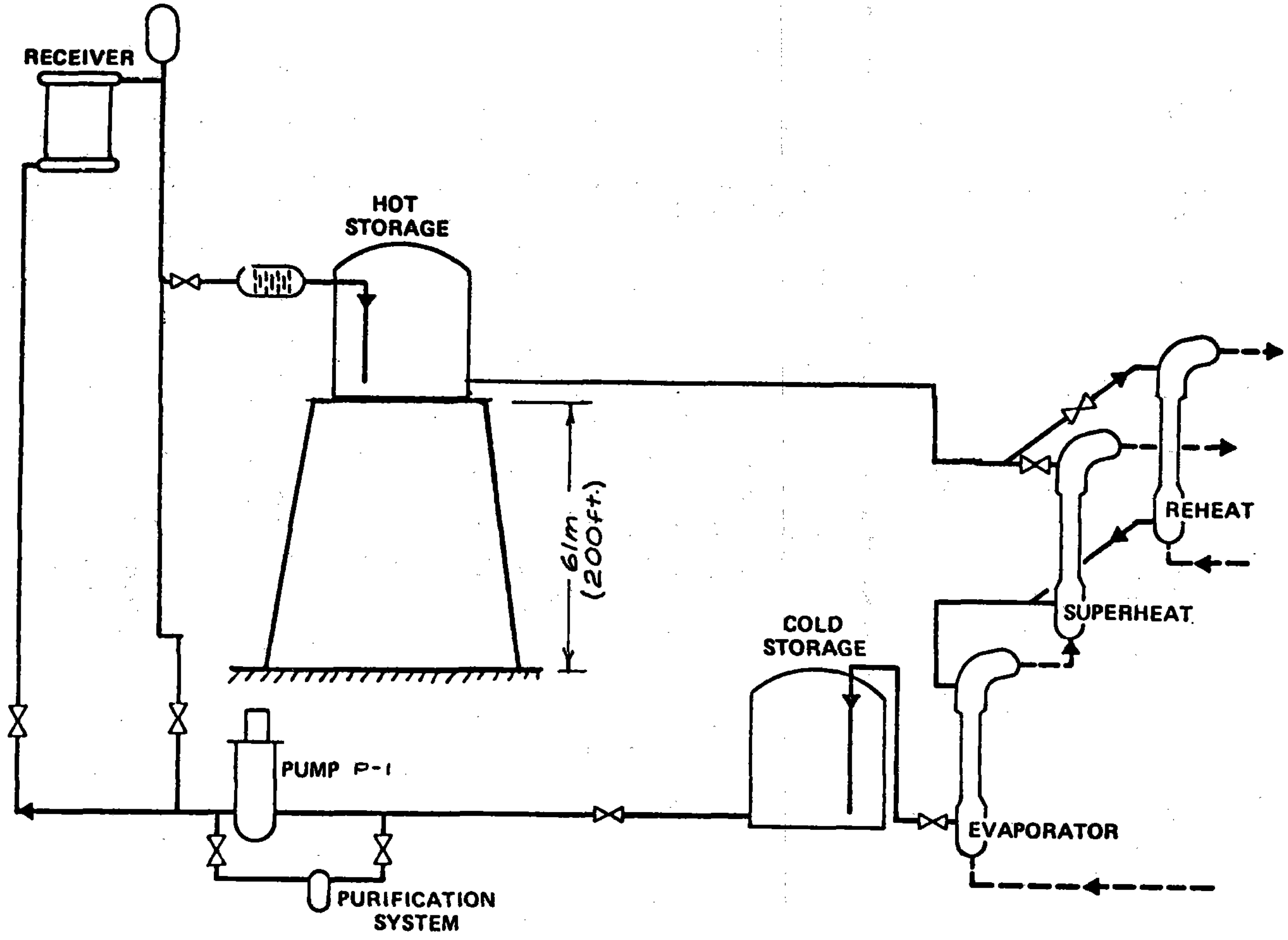

FIGURE 3

ELEVATED HOT STORAGE TANK

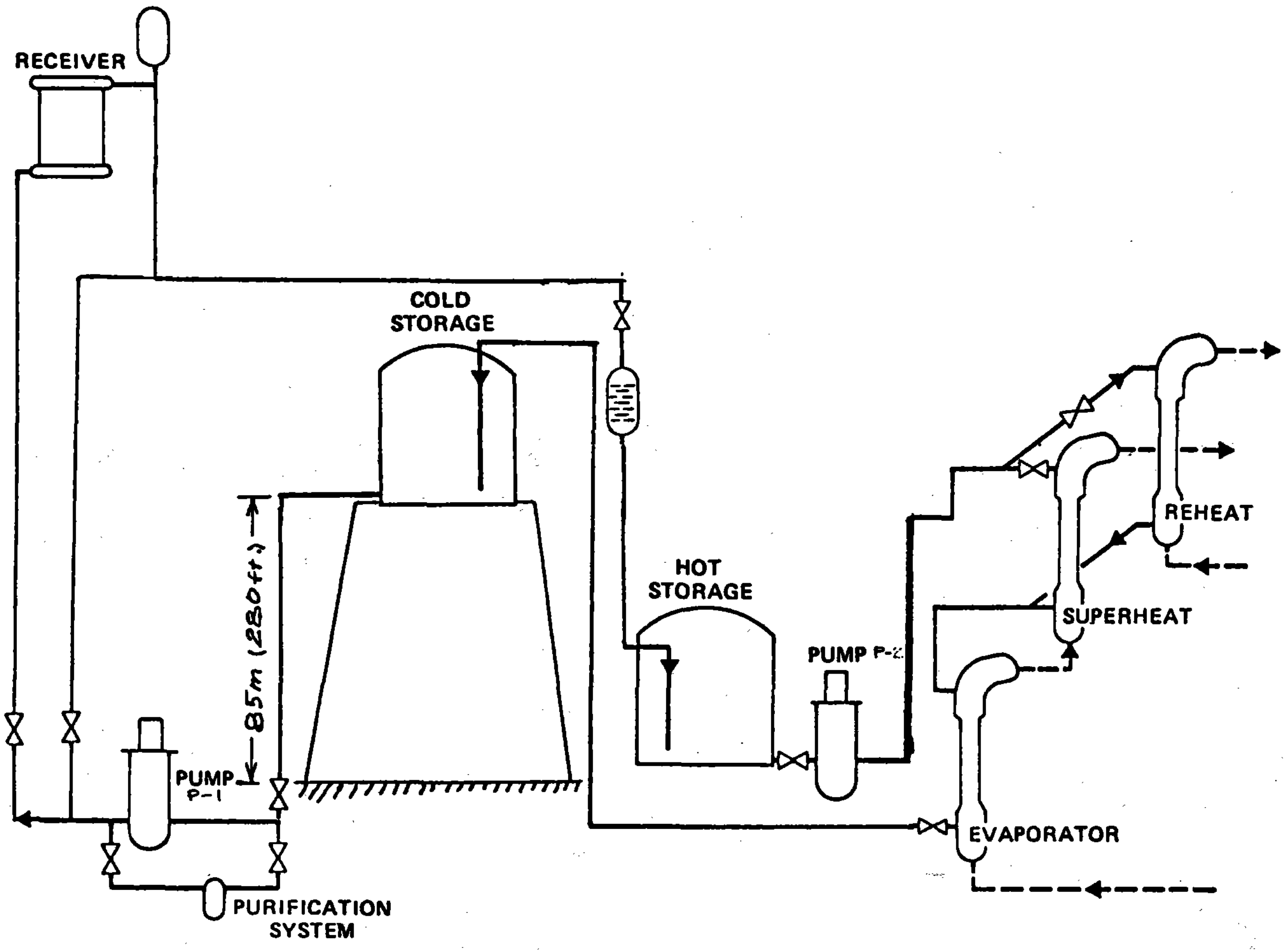

FIGURE 4
ELEVATED COLD STORAGE TANK

3. Parallel Storage Tanks (Figure 5)

In this scheme, the storage system is bypassed on direct operation, thus, all of the available tower head is conserved. The energy savings is 1.2 MWe which translates into approximately $\$1.2 \times 10^6$ of capital cost on plant size reduction and approximately $\$0.5 \times 10^6$ (the pump will be running on standby) due to improved capacity factor for a total savings of $\$1.7 \times 10^6$. To retain the feature of being able to operate from storage while charging to storage simultaneously requires that the P-2 pump develop the same head as the P-1 pump. The additional cost for this change is estimated at $\$0.5 \times 10^6$ (P-1 pump cost less P-2 pump loss, less the pump commonality, savings of $\$0.5 \times 10^6$, see Scheme 2). An additional cost for control values to regulate this together with the control system is estimated at $\$1.0 \times 10^6$. The net savings is about $\$0.2 \times 10^6$. However, the thermal buffering benefit of the large sodium storage tanks is lost. It is judged that this benefit is worth more than the cost saving, thus, this system is judged not cost effective.

4. Reduced Downcomer Diameter (Figure 6)

In this scheme, the pipe velocity limit is increased to 17 m/sec (56 ft/sec) (this velocity limit is greater than "conventional practice" for sodium flowing in pipes but less than sodium pump velocity practice of 60 m/sec [200 ft/sec] or sodium jet pump successful experience 20 m/sec [65 ft/sec], Reference 3.) The savings are obtained by reducing downcomer pipe diameter. The savings on the installed downcomer pipe is approximately $\$0.5 \times 10^6$. The drag valve savings is approximately $\$0.1 \times 10^6$ for a total savings of $\$0.6 \times 10^6$. This approach appears cost effective.

5. Sodium Turbo Pump Addition (Figure 7)

In this scheme, a sodium driver turbine is installed in the downcomer which drives a directly connected pump located in the riser. This pump acts as a booster pump in series with the P-1 pump. The arrangement decreased the peak power requirement by approximately 1.81 MWe, however,

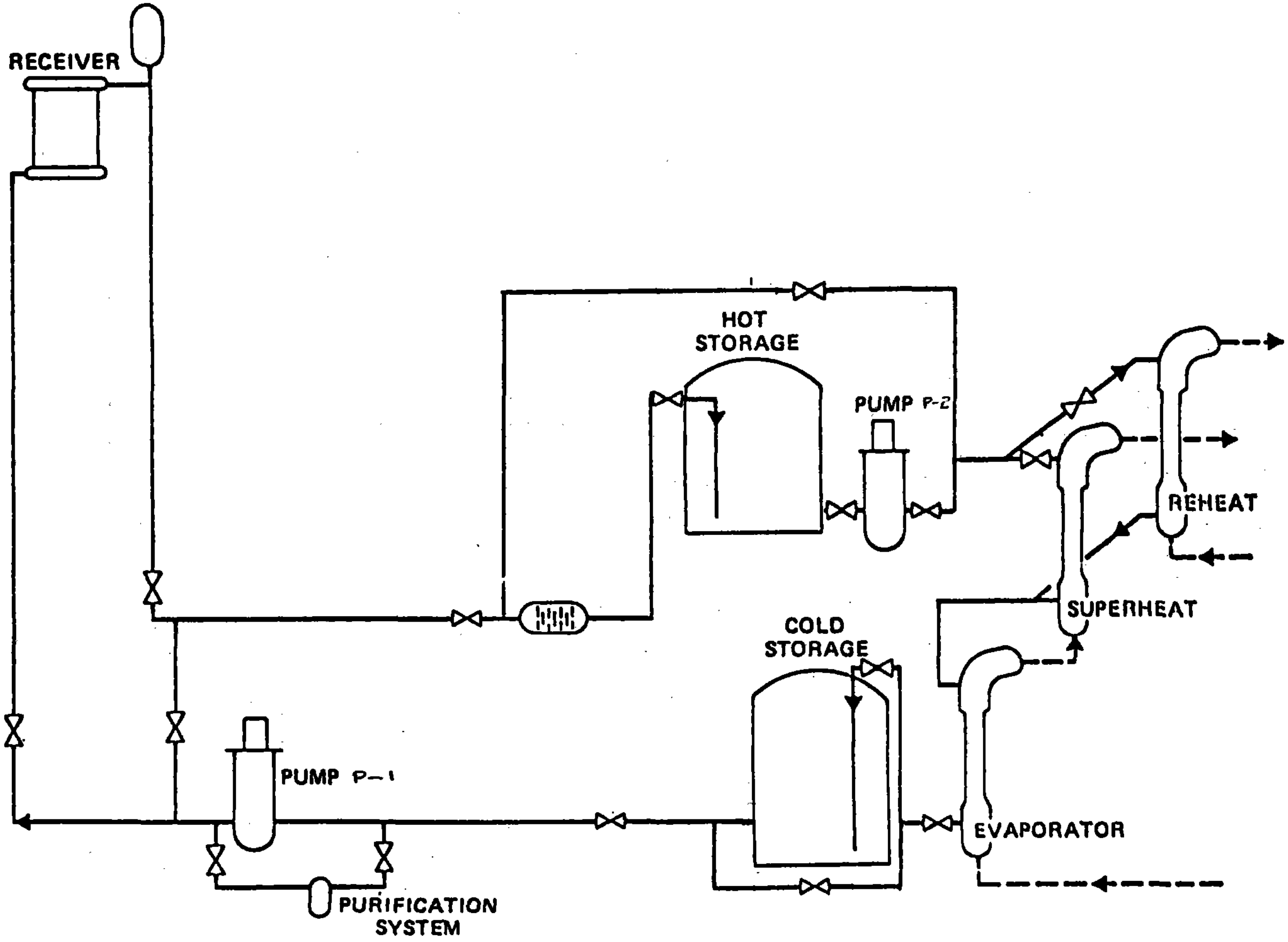

FIGURE 5
PARALLEL STORAGE TANKS

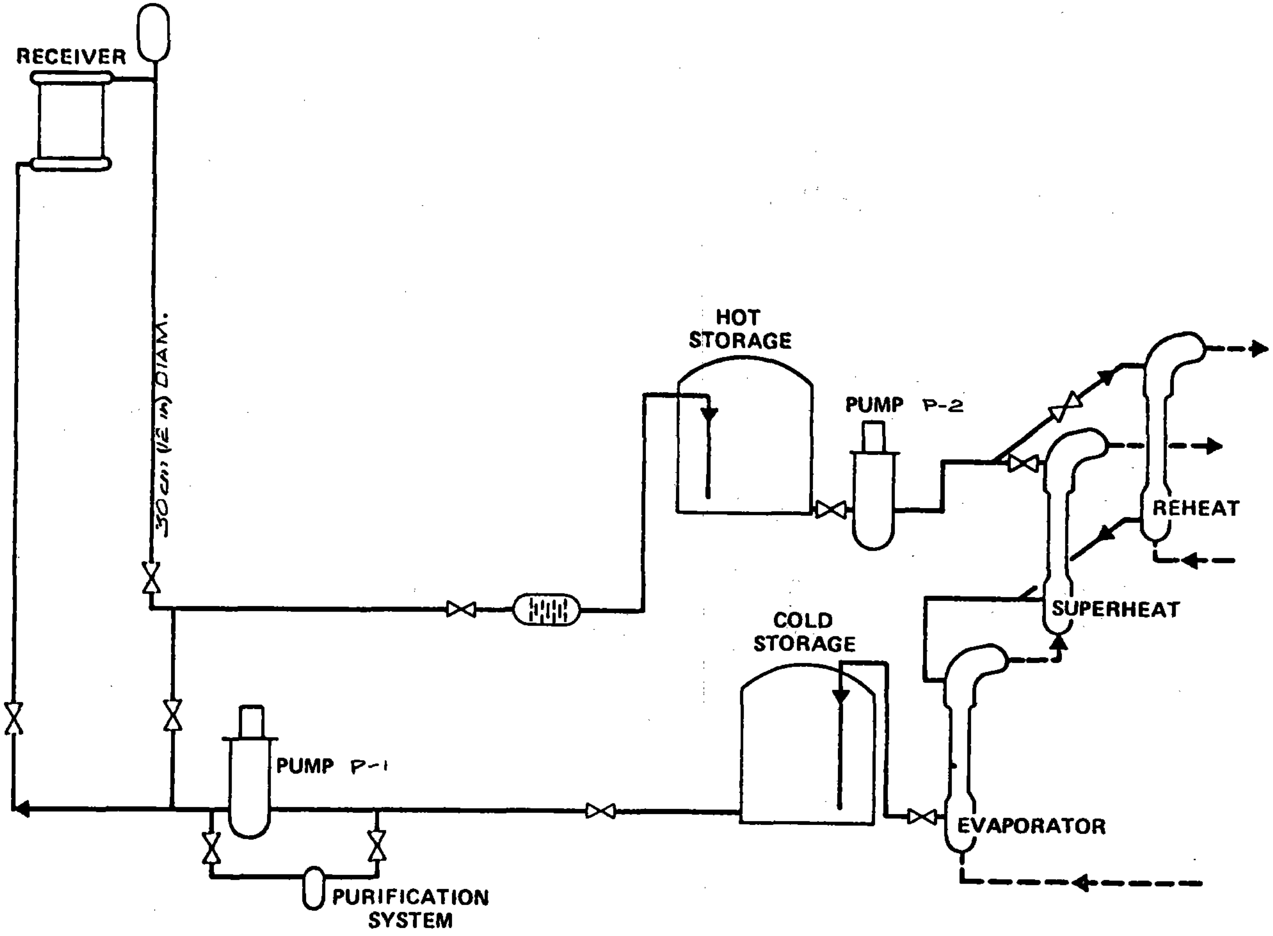

FIGURE 6

REDUCED DOWNCOMER DIAMETER

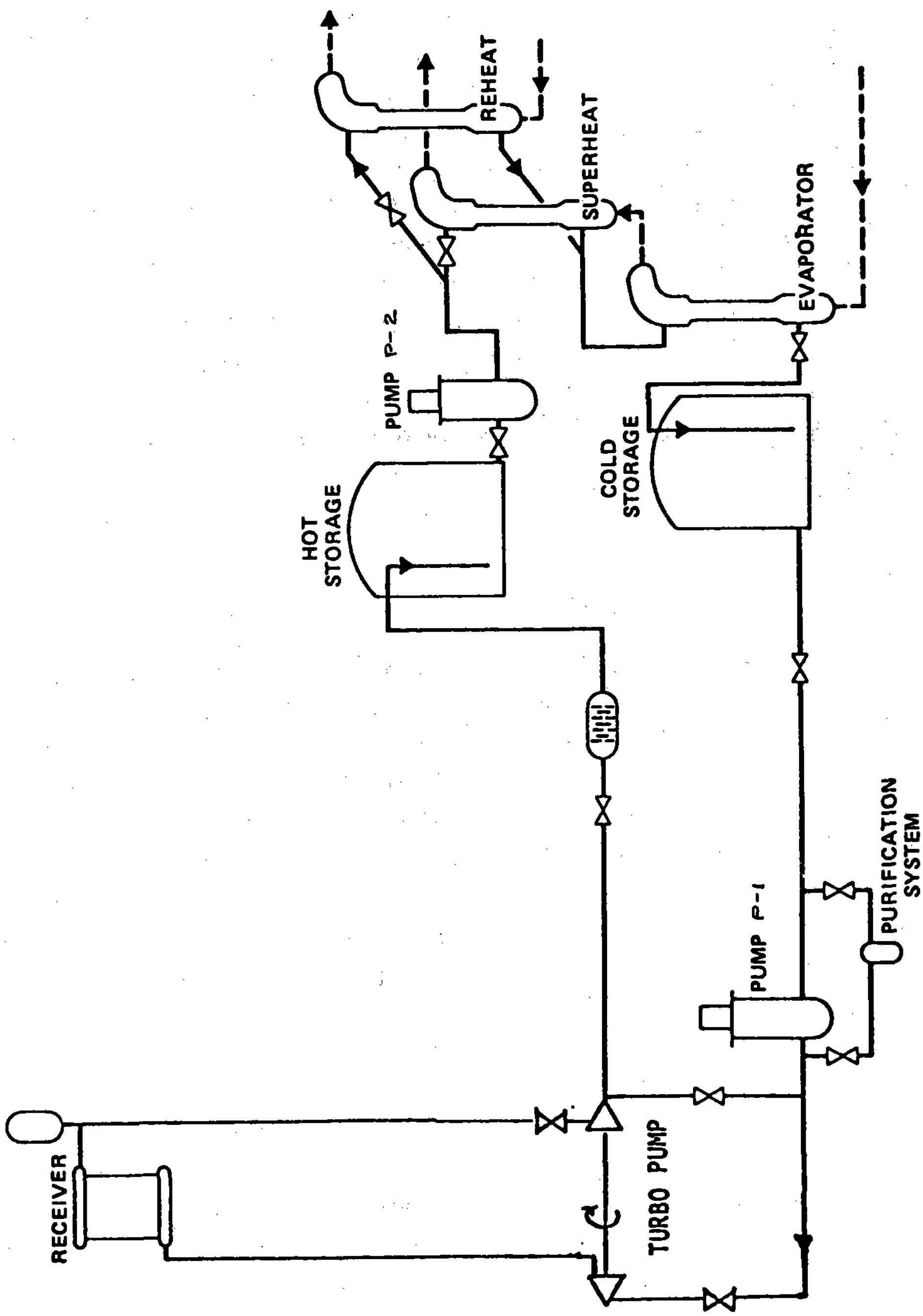

FIGURE 7
ADDITION OF TURBO PUMP

it is only effective down to about 70% of flow because of the fact that the power of the turbine under throttled operation decreases as the cube of the flow. In addition, full credit cannot be taken for the 1.81 MWe. Approximately 43% of this is recoverable as heat energy which can be reconverted to electricity in the conventional part of the plant. The effective power savings amounts to 0.66 MWe which improves the plant capacity factor, resulting in a reduction in the levelized bus bar cost of 0.446 mils/kWh. This is the equivalent of \$0.8 x 10^6 of capital outlay. The reduction in plant size at peak load is 1.0 MWe. This reduction in auxiliary power capacity is worth approximately \$1 x 10^6 The total installed cost for this equipment is estimated at \$1.0 x 10^6. Thus, the net savings is approximately \$0.8 x 10^6. This system is cost effective if the sodium turbopump component can be installed as a developed item. Maintenance of this unit requires entrance into the sodium system.

6. Jet Pump Addition (Figure 8)

This scheme is similar to Scheme 3 except that the storage capacity is coupled to the loop through the jet pumps which function automatically except at startup when the P-2 pump bypass line is used to "bootstrap" the system into operation. As shown in the figure, Jet Pump 2 is driven by the downcomer head and provides a high inlet pressure for the centrifugal pump. This arrangement functions as a two-stage pump which raises the outlet pressure of the P-2 pump. The higher outlet pressure increment is transferred through the steam generators and supplies the driving head for Jet Pump 1. The output head of Jet Pump 1 adds to the head of the P-1 centrifugal pump. Because of the realtively low efficiency of the jet pump, the expected savings in power will be no more than 0.746 MWe (1000 hp) (Reference 4) but additional benefits accrue since the tower lift can be shared between the two centrifugal pumps as in Scheme 2. This is similar in function to the turbo pumped system but with less hydraulic efficiency. The jet pumps are simpler mechanically. They have no moving parts and, thus, should have a higher reliability. The expected savings are estimated to be \$0.42 x 10^6 due to plant size reduction and \$0.34 x 10^6 due to capacity factor improvement. Pump simplification and commonality savings amount to \$0.5 x 10^6. The cost of the jet pumps is estimated at

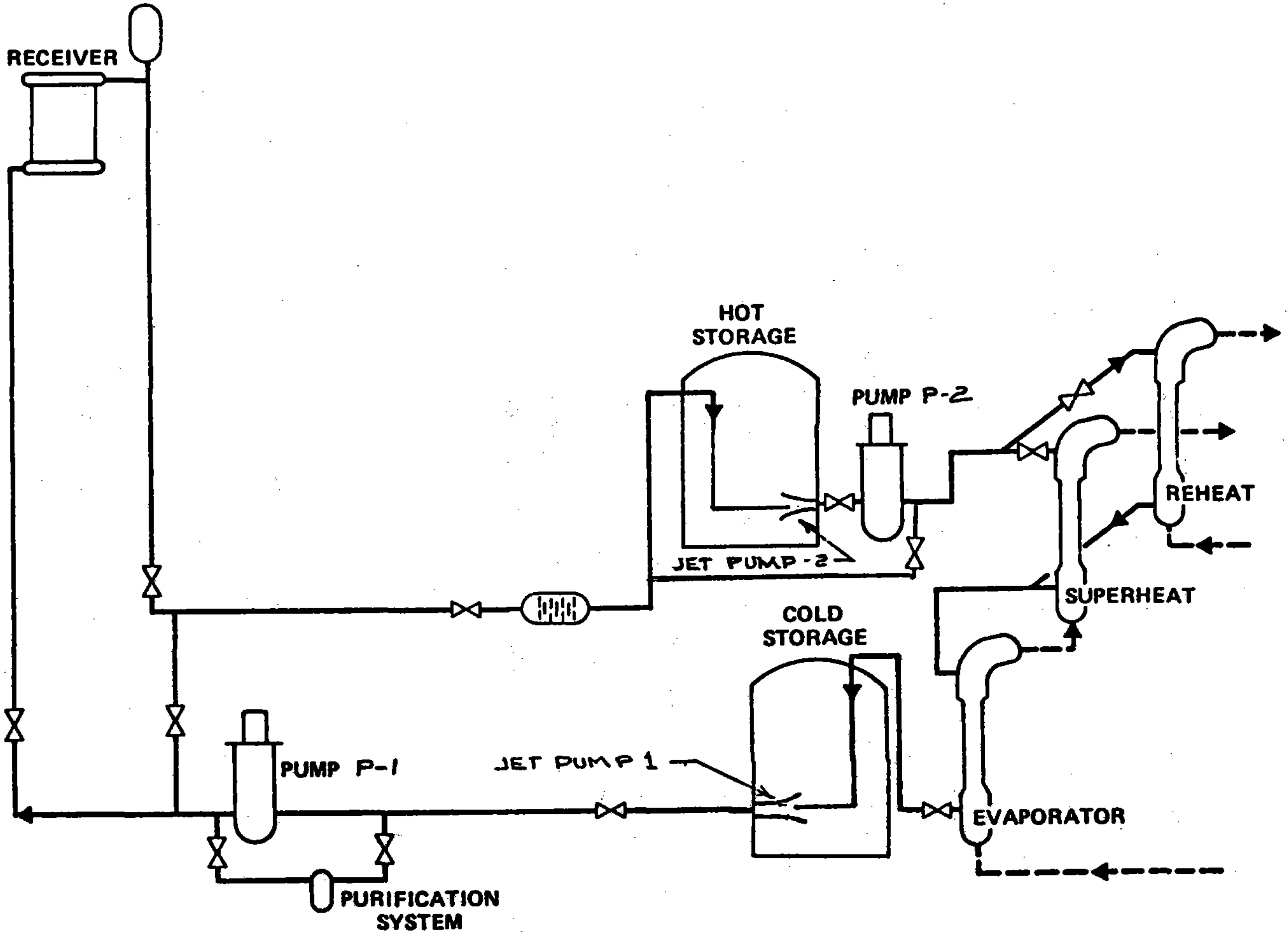

FIGURE 8
ADDITION OF JET PUMPS

$0.1 x 10^6. The net savings is $0.85 x 10^6. Sodium jet pumps are considered to be existing technology. This system appears to be cost effective.

7. Addition of Magnetohydrodynamic Generator (Figures 9 and 10)

In this scheme, an alternating current liquid metal magnetohydrodynamic (MHD) induction generator replaces the drag valve. This device acts like an electromagnetic brake on the system and converts the tower head to ac power. It would be operated in the constant voltage mode with flow control affected by varying the load on the unit. The electrical conversion efficiency is similar to the Scheme 5 turbo pump except that the unit operates over the entire flow range. The effective electrical savings is 1.0 MWe or 0.67 mills/kWh due to the improvement in capacity factor. This is equivalent to $1.2 x 10^6 of capital outlay. There is also a reduction in plant size due to reducing the auxiliary power requirements. This unit also replaces the drag valve which is estimated at $0.5 x 10^6. The total savings is $2.7 x 10^6. The estimated cost of the unit is $1.5 x 10^6. The net savings is then $1.2 x 10^6. This system is cost effective provided that the unit is installed as a developed item. The system has no moving parts and the stator can be designed to be removable for repairs without entering the sodium system (Figure 8).

8. Helical Rotor Generator Addition (Figures 11 and 12)

In this scheme, a helical rotor generator replaces the drag valve. The unit can generate direct current power which is converted to ac power or ac power directly if a variable speed coupling is used. The technology is similar to that of the helical rotor pumps, Reference 6. The economics are similar to those of the MHD unit and appears cost effective provided it is installed as a developed item. The electrical part of this component operates in air and may be removed for maintenance without cutting into the sodium system. It operates at low speed (~5 rps), thus, generating low frequencies which lead to low electrical losses in the flow passage walls. This in turn permits increasing this wall thickness to standard tube dimensions and should enhance reliability.

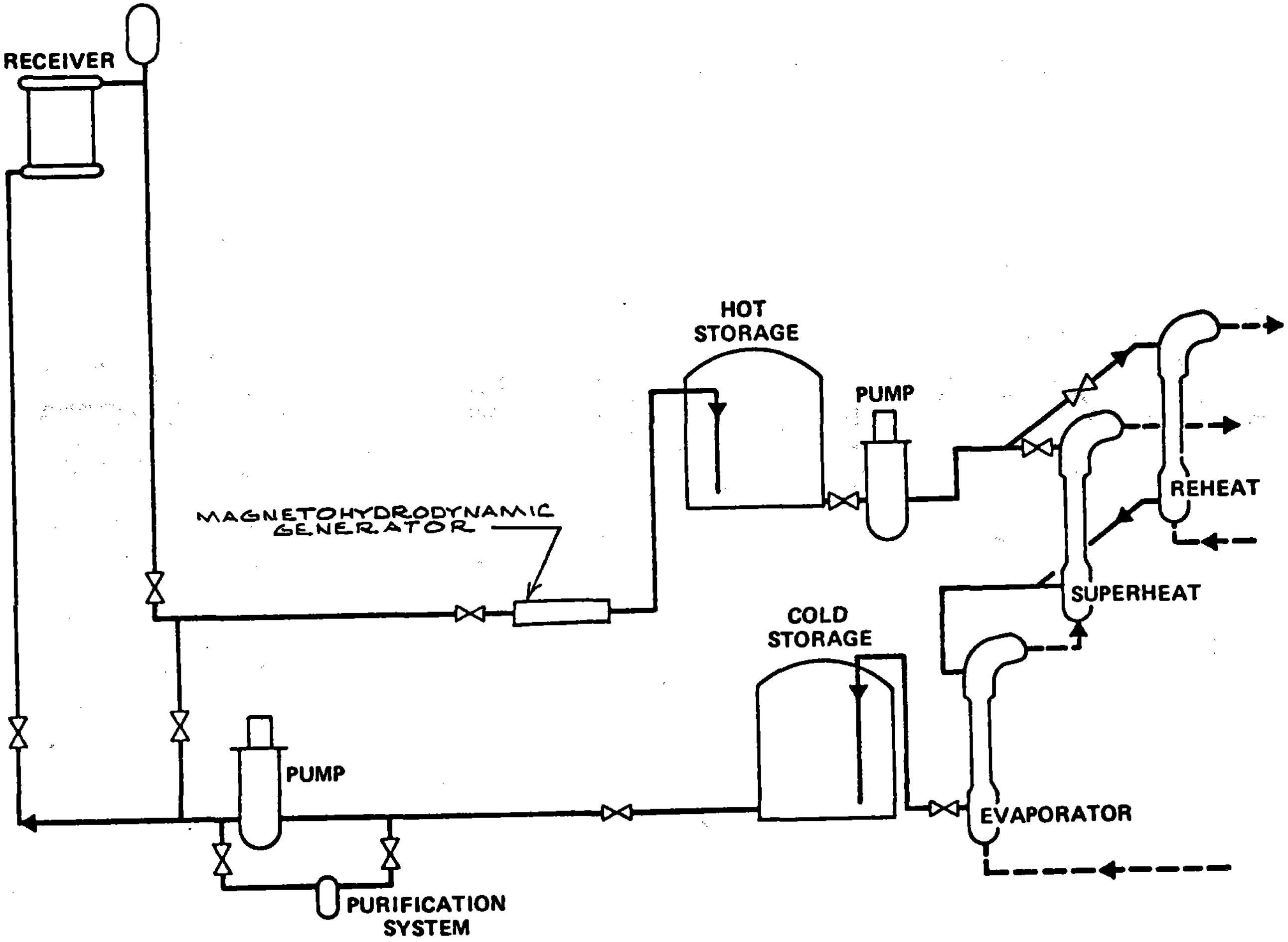

FIGURE 9

ADDITION OF MAGNETOHYDRODYNAMIC GENERATOR

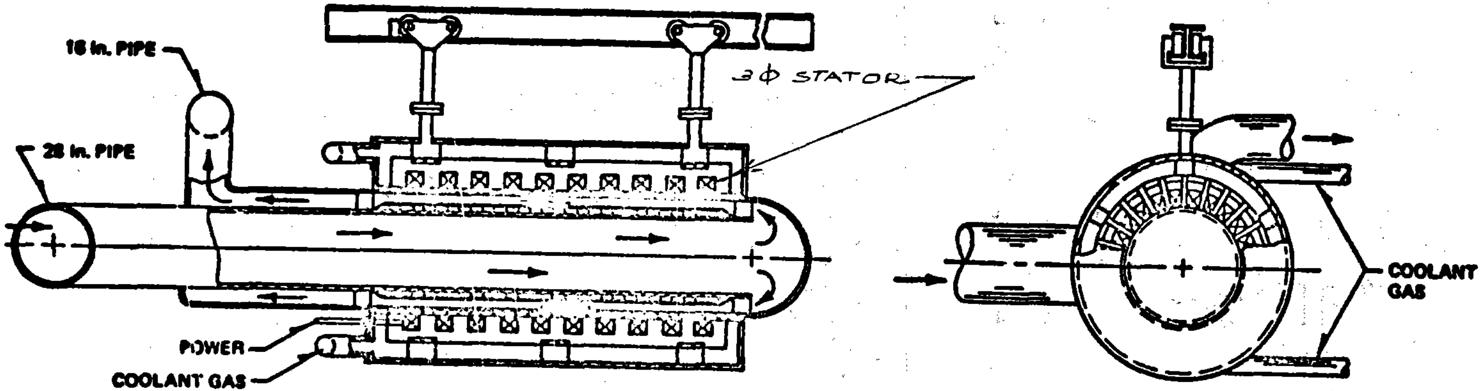

FIGURE 10
Na AC MAGNETOHYDRODYNAMIC GENERATOR

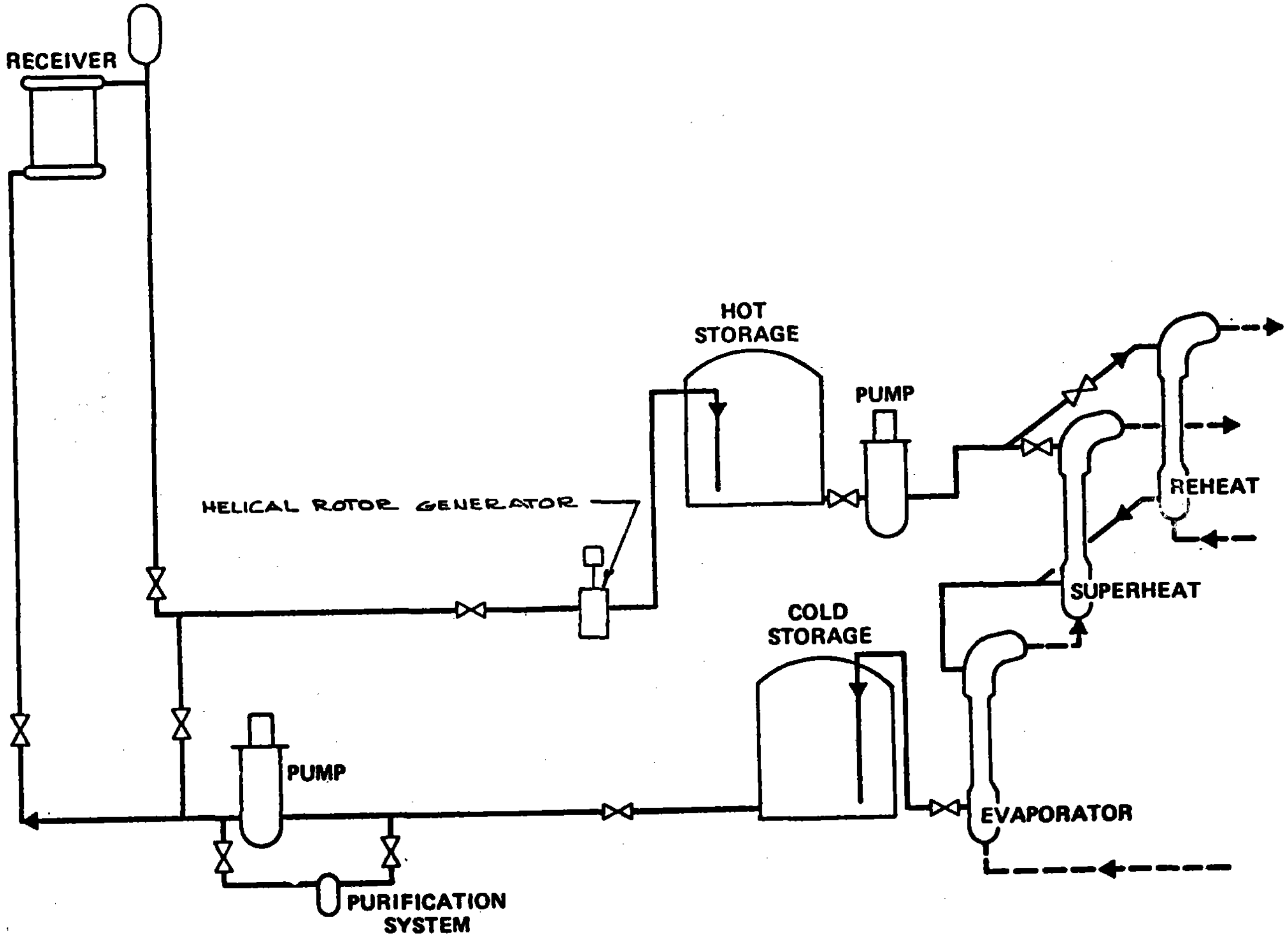

FIGURE 11

HELICAL ROTOR GENERATOR ADDITION

CUTAWAY VIEW OF HELICAL-ROTOR ELECTROMAGNETIC GENERATOR WITH ANNULAR FLOW PASSAGE

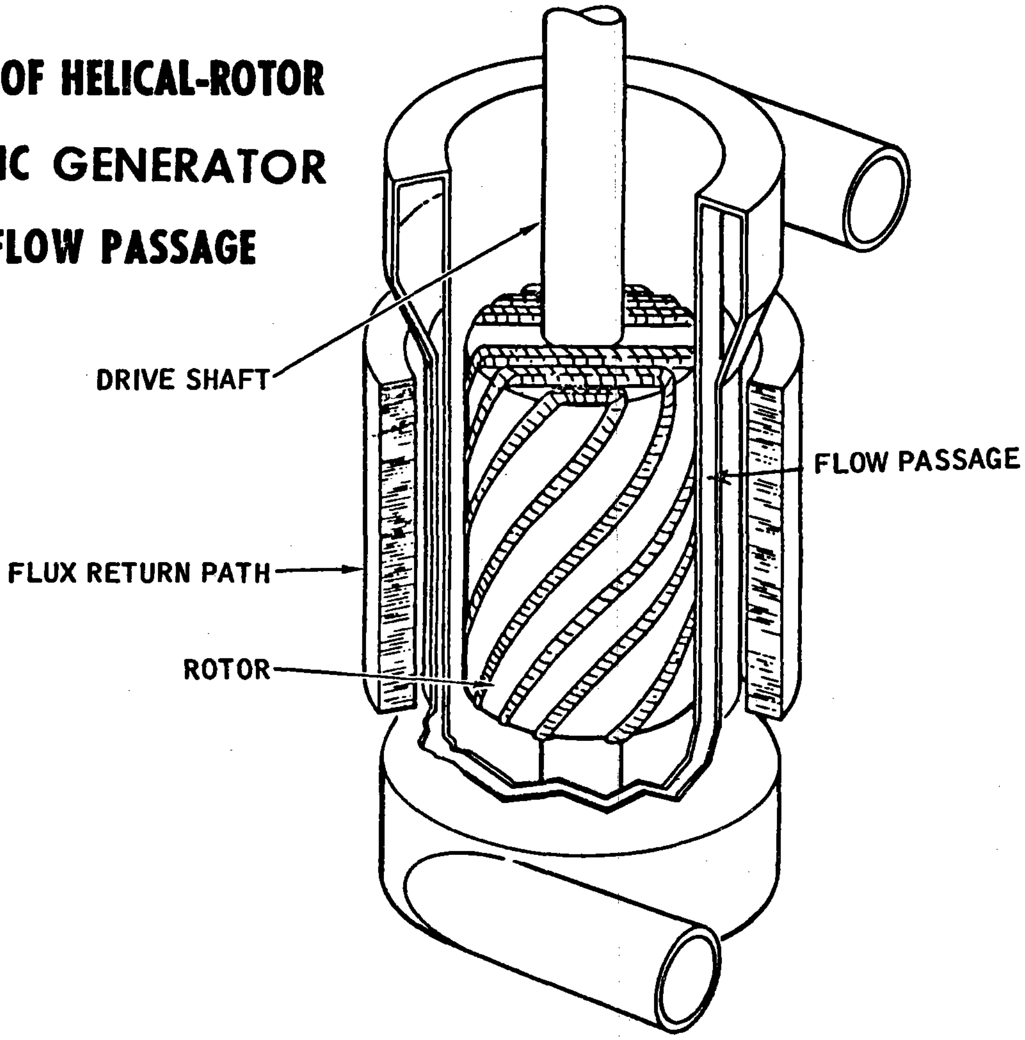

FIGURE 12
HELICAL ROTOR GENERATOR

IV. CONCLUSIONS

The scheme that represents the least departure from the reference system that is cost effective is Scheme 4. This scheme should require no R&D and should save at least \$0.6 x 10^6. It would appear to be the best short-term choice. An alternate candidate is the jet pump scheme which also requires no R&D and is cost effective.

For a longer range approach requiring some R&D, the MHD generator appears to be the most cost effective. The helical rotor generator appears as attractive but does involve rotating parts and would be expected to show a lower reliability than the MHD unit.

V. REFERENCES

1. Lorin L. Vant-Hull, Gerry Coleman, Tom Springer, Jerry Friefeld, "Liquid Metal Cooled Solar Central Receiver Feasibility Study and Heliostat Field Analysis," ORO 5178-78-1, UG62, p. 5-11, 1977

2. Stearns-Roger Letter C-20325-13 dated February 17, 1978, A. W. McKensie to Tom Springer, "Central Receiver Tower Study Advanced Central Receiver Power System"

3. D. A. Manner, "Effects of Long Term Exposure on Materials in the Sodium Reactor Experiment," AI-66-53, 1966, p. 33-37

4. IL dated May 11, 1978, J. O. Pfouts to L. E. Glasgow, "Use of Jet Pumps in a Solar Collector System"

5. T. C. Wang and S. J. Dudzinsky, "Theoretical and Experimental Study of a Liquid Metal MHD Induction Generator," AIAA Journal 5, p. 107-112, 1967

6. R. S. Baker, "Theory, Design and Performance of the Helical-Rotor Electromagnetic Pump," NAA-SR-7455-1963

APPENDIX I

CENTRAL RECEIVER TOWER STUDY

D/700 Correspondence
ACTION

REPLY
(

REPLY DUE

REMARKS
Encls. To Springer

NDERSON, S. H.
A JUTH
ALENT
ACHMASH
TTS
RINDLEY
ARDENAS
OCHRAN, J.C.
ROGRAM DATA
GMT
RAWFORD
E LOS PRADOS
TTERMAN
URAND
ILER
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ARTZLER
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DONALD, J S
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EYERS, G W
OREWITZ
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HRM
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Stearns-Roger
ENGINEERING CO.

APPENDIX I

RECEIVED
FEB 21 1978
Correspondence Dept.

February 17, 1978

Atomics International Division
Rockwell International
8900 DeSota Avenue
Canoga Park, California 91304

Re: C-20325-13

Attention: Tom Springer
Project Manager

Subject: Central Receiver Tower Study
Advanced Central Receiver Power System

Reference: AI Contract N311-0002 FX
DOE Contract EG-77-C-03-1483

Dear Tom:

Enclosed herewith please find the results of our central receiver tower sensitivity analysis recently completed. The following data is enclosed:

1. Receiver tower model with design criteria used in the analysis, dated February 6, 1978, including the following tables of results:

   Table 1 - Tower and Mat Dimensions
   Table 2 - Dynamic Response (Seismic)
   Table 3 - Tower and Mat Material Quantity

2. Plot of tower cost vs. tower height and receiver weight, dated February 14, 1978.

3. Cost Estimates for the sixteen tower height and receiver weight combinations considered.

Please be advised that the results of this study shows the relative cost of towers vs. tower height for various receiver weights; however we have not attempted to optimize tower cost for any specific tower height/receiver weight combination.

2/14/78

700 SOUTH ASH • P.O. BOX 5888 • DENVER, COLORADO 80217 • PHONE (303) 758-1122 • TWX 910 931 0451 TELEX 045-510

Atomics International Division
Canoga Park, California 91403
ATTN: Tom Springer

February 17, 1978

Please let us know if you have any questions, or require additional information.

Very truly yours,

STEARNS-ROGER ENGINEERING CO.

AWMcKenzie
A. W. McKenzie
Project Engineer

AWMc/vr

Enclosure

cc: (w/encl.)
G. C. Coleman - MDAC
W. R. Lang
R. E. Williamson
J. R. Linger/R. J. Colasanti
A. W. McKenzie
R. K. Jones/Job File

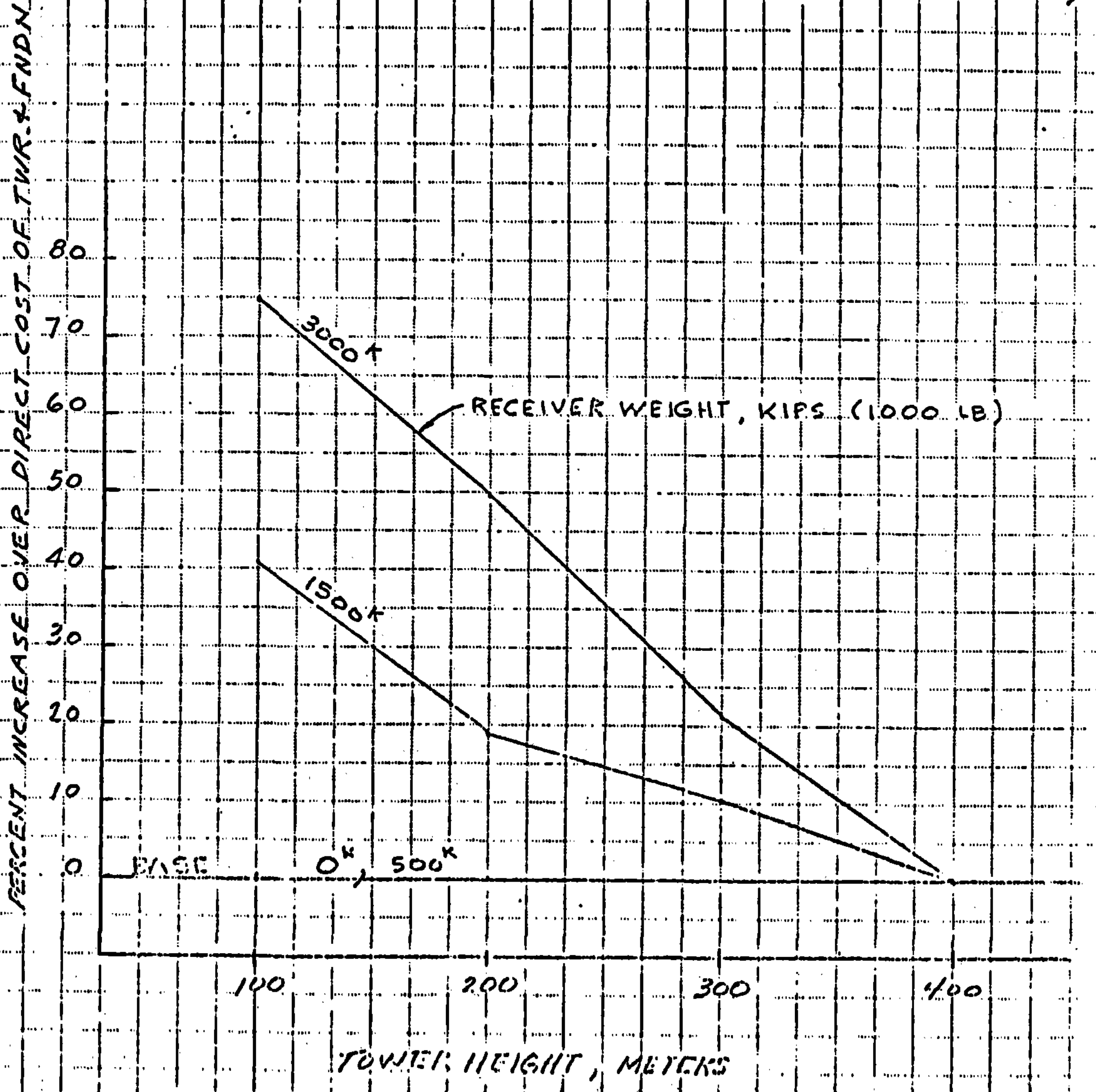
FORM 62-114
REV. 4-75

Stearns-Roger

Atomics Int'l

PAGE 1 OF 1
JOB NO. C 20325 DATE 2-17-78 BY AWM CH'K
CUSTOMER Atomics Int'l PROJECT ADVANCED CENTRAL RECEIVER
SUBJECT AFFECT OF RECEIVER WEIGHT ON TOWER DIRECT COST

(FROM PLOT OF TOWER COST VS HEIGHT DATED 2/14/78 BY GUP)



FORM 62.114
REV. 4.75

PAGE 1 OF 4

JOB NO. 20325 DATE 2/6/78 BY RJC CH'K.

CUSTOMER ATOMICS INTERNAT'L PROJECT ADVANCED CENTRAL RECEIVER

SUBJECT RECEIVER TOWER

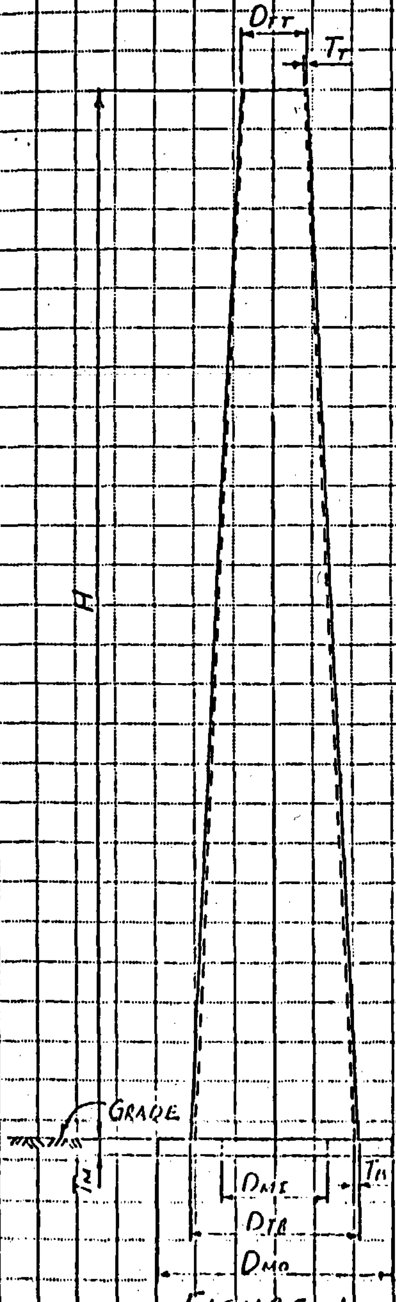


FIGURE 1

D_{TT} = OUTSIDE DIAMETER AT TOP OF TOWER.
D_{TB} = OUTSIDE DIAMETER AT BOT. OF TOWER.
T_T = TOWER WALL THICKNESS AT TOP.
T_B = TOWER WALL THICKNESS AT BOTTOM.
D_{MO} = OUTSIDE DIAMETER OF MAT.
D_{MI} = INSIDE DIAMETER OF MAT.
T_M = MAT THICKNESS.
H = TOWER HEIGHT.

NOTE: TOWER WALL THICKNESS VARIES LINEARLY FROM TOP TO BOTTOM.

REFERENCES:

1) "BUILDING CODE REQUIREMENTS FOR REINFORCED CONCRETE" (ACI 318-71).
2) "SPECIFICATION FOR THE DESIGN AND CONSTRUCTION OF REINFORCED CONCRETE CHIMNEYS" (ACI 307-69).
3) "DESIGN RESPONSE SPECTRA FOR SEISMIC DESIGN OF NUCLEAR POWER PLANTS" (NRC REG. GUIDE 1.60).
4) "DAMPING VALUES FOR SEISMIC DESIGN OF NUCLEAR POWER PLANTS" (NRC REG. GUIDE 1.61).

TOWER DESIGN BASED ON .25 G MAX. GROUND ACCELERATION IN BOTH THE VERTICAL AND HORIZONTAL DIRECTIONS WITH 7% DAMPING.
CONCRETE f'_c = 4. KSI.
REBAR f_y = 60 KSI.
SOIL BRG PRESS = 10 KSF (ALLOW 1/3 INCREASE FOR SEISMIC).

TOWER HEIGHT, METERS	DIMENSIONS, FT.*	RECEIVER WEIGHT, KIPS			
		0	500	1500	3000
100	D_{TT}	20.0	20.0	20.0	20.0
	D_{TB}	53.0	53.0	53.0	53.0
	T_{TT}	0.5833	0.5833	0.8333	1.0
	T_{TB}	0.9167	0.9167	1.25	1.5
	D_{MO}	90.0	90.0	100.0	106.0
	D_{MI}	0.0	0.0	0.0	0.0
	T_M	8.0	8.0	9.0	10.0
200	D_{TT}	40.0	40.0	40.0	40.0
	D_{TB}	106.0	106.0	106.0	106.0
	T_{TT}	0.8333	0.8333	1.0	1.25
	T_{TB}	1.5	1.5	1.875	2.25
	D_{MO}	160.0	160.0	168.0	170.0
	D_{MI}	52.0	52.0	44.0	42.0
	T_M	11.0	11.0	11.0	14.0
300	D_{TT}	60.0	60.0	60.0	60.0
	D_{TB}	159.0	159.0	159.0	159.0
	T_{TT}	1.0	1.0	1.125	1.25
	T_{TB}	2.0	2.0	2.25	2.5
	D_{MO}	220.0	220.0	224.0	230.0
	D_{MI}	98.0	98.0	94.0	88.0
	T_T	15.0	15.0	15.0	15.0
400	D_{TT}	80.0	80.0	80.0	80.0
	D_{TB}	212.0	212.0	212.0	212.0
	T_{TT}	1.25	1.25	1.25	1.25
	T_{TB}	2.5833	2.5833	2.5833	2.5833
	D_{MO}	284.0	284.0	284.0	284.0
	D_{MI}	140.0	140.0	140.0	140.0
	T_M	15.0	15.0	15.0	15.0

*Refer to Figure 1

TABLE 1

ADVANCED CENTRAL RECEIVER - JOB NO. 20325
TOWER AND MAT DIMENSIONS

STEARNS-ROGER
FEBRUARY 6, 1978

TOWER HEIGHT METERS	PARAMETER	RECEIVER WEIGHT, KIPS*			
		0	500	1500	3000
100	Fund. Hor. Freq., Hz	1.25	0.83	0.62	0.50
	Rcv. Hor. Accel., G's	1.35	0.73	0.49	0.39
	Rcv. Hor. Defl., In.	4.61	6.18	7.36	8.75
	Fund. Vert. Freq., Hz	10.49	8.77	7.34	6.23
	Rcv. Vert. Accel., G's	0.86	0.90	0.85	0.81
	Rcv. Vert. Defl., In.	0.07	0.11	0.14	0.19
200	Fund. Hor. Freq., Hz	0.65	0.59	0.53	0.47
	Rcv. Hor. Accel., G's	1.39	1.48	0.96	0.71
	Rcv. Hor. Defl., In.	10.43	12.29	12.71	13.30
	Fund. Vert. Freq., Hz	5.36	5.20	5.00	4.74
	Rcv. Vert. Accel., G's	1.08	1.09	1.10	1.09
	Rcv. Vert. Defl., In.	0.32	0.35	0.38	0.42
300	Fund. Hor. Freq., Hz	0.44	0.43	0.41	0.38
	Rcv. Hor. Accel., G's	1.26	1.89	1.38	1.03
	Rcv. Hor. Defl., In.	16.66	19.26	19.68	20.09
	Fund. Vert. Freq., Hz	3.63	3.59	3.53	3.45
	Rcv. Vert. Accel., G's	1.22	1.21	1.22	1.21
	Rcv. Vert. Defl., In.	0.77	0.79	0.83	0.86
400	Fund. Hor. Freq., Hz	0.34	0.33	0.32	0.31
	Rcv. Hor. Accel., G's	1.21	2.09	1.70	1.26
	Rcv. Hor. Defl., In.	23.41	26.87	27.21	27.61
	Fund. Vert. Freq., Hz	2.74	2.72	2.70	2.66
	Rcv. Vert. Accel., G's	1.10	1.08	1.08	1.08
	Rcv. Vert. Defl., In.	1.12	1.12	1.14	1.16

*Accelerations and deflections for "zero-weight" receiver are referred to top of tower. Accelerations and deflections for 500, 1500 and 3000 kip receivers are referred to receiver centroid, assumed 0.08H above top of tower.

TABLE 2

ADVANCED CENTRAL RECEIVER - JOB NO. 20325
DYNAMIC RESPONSE (SEISMIC)

STEARNS-ROGER
FEBRUARY 6, 1978

TOWER HEIGHT, METERS	QUANTITY	RECEIVER WEIGHT, KIPS			
		0	500	1500	3000
100	Tower Concrete, cu yd	1057.9	1057.9	1452.9	1733.3
	Tower Steel, tons	66.0	75.8	118.4	161.5
	Mat Concrete, cu yd	1885.0	1885.0	2618.0	3268.4
	Mat Steel, tons	103.7	103.7	144.0	179.8
	Soil Excavation, cu yd	2719.0	2719.0	3714.0	4628.0
200	Tower Concrete, cu yd	6772.6	6772.6	8214.8	9930.6
	Tower Steel, tons	529.0	539.2	674.1	839.3
	Mat Concrete, cu yd	7326.2	7326.2	8411.6	11051.0
	Mat Steel, tons	402.9	402.9	462.6	607.8
	Soil Excavation, cu yd	10496.0	10496.0	11443.0	15354.0
300	Tower Concrete, cu yd	19483.0	19483.0	21881.5	24269.1
	Tower Steel, tons	1754.8	1772.7	2017.4	2247.5
	Mat Concrete, cu yd	16927.9	16927.9	18038.0	19703.0
	Mat Steel, tons	931.0	931.0	992.1	1083.7
	Soil Excavation, cu yd	23866.0	23866.0	24976.0	26641.0
400	Tower Concrete, cu yd	44372.8	44372.8	44372.8	44372.8
	Tower Steel, tons	3880.1	3884.4	3887.9	3874.7
	Mat Concrete, cu yd	26640.7	26640.7	26640.7	26640.7
	Mat Steel, tons	1465.2	1465.2	1465.2	1465.2
	Soil Excavation, cu yd	35891.0	35891.0	35891.0	35891.0

NOTES:
1) Min. Concrete Strength shall be 4000 PSI Compressive Strength at 28 days.
2) Reinforcing bars shall be new intermediate grade deformed bars which shall conform to ASTM 615 Grade 60.

TABLE 3

ADVANCED CENTRAL RECEIVER - JOB NO. 20325
TOWER AND MAT MATERIAL QUANTITY

STEARNS-ROGER
FEBRUARY 6, 1978

FORM 62.114
REV. 4.75

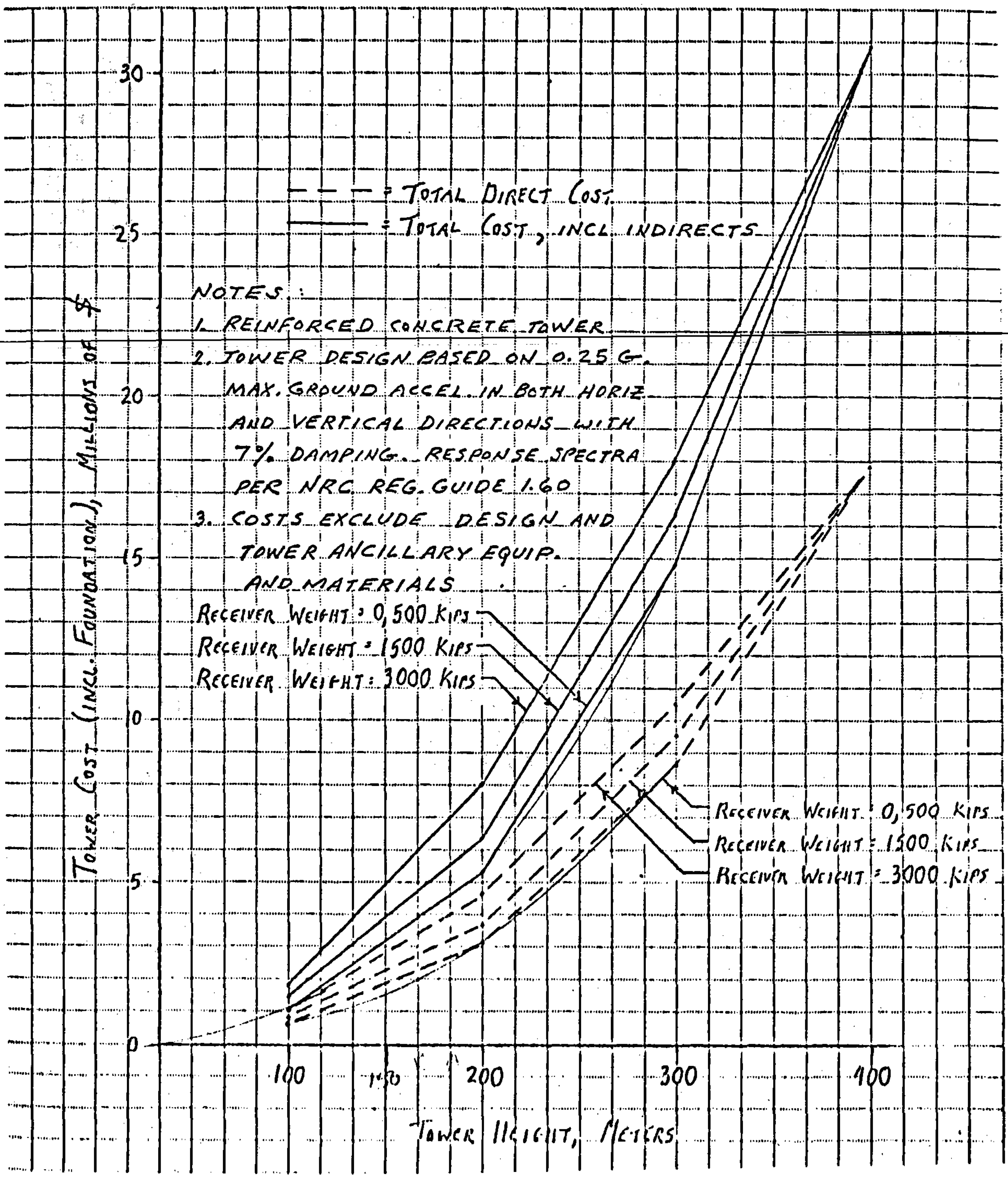
Stearns-Roger

PAGE 1 OF 1

JOB NO. 20325 DATE 2/14/78 BY EJP CH'K.

CUSTOMER Atomics Int'l PROJECT Advanced Central Receiver

SUBJECT Tower Cost vs Tower Height and Receiver Weight



NOTES:

1. REINFORCED CONCRETE TOWER
2. TOWER DESIGN BASED ON 0.25 G. MAX. GROUND ACCEL. IN BOTH HORIZ AND VERTICAL DIRECTIONS WITH 7% DAMPING. RESPONSE SPECTRA PER NRC REG. GUIDE 1.60
3. COSTS EXCLUDE DESIGN AND TOWER ANCILLARY EQUIP. AND MATERIALS

CUSTOMER ATOMICS INTERNATIONAL
PROP NO.
LOCATION
JOB NO. 20325
PROJECT ADVANCED CENTRAL RECEIVER
(100 METERS HEIGH / NONE KIPS)
DATE 2-6-78
BY J.W.S.F.
REV. NO.
REV. DATE
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	SUBCONTRACT	TOTAL
A	EARTHWORK	462	5 540	2 800	1 770	10 110
B	CONCRETE	29 037	438 540	163 090		601 630
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	29 499	444 080	165 890	1 770	611 740
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70 % OF	DIRECT	LABOR	310 855
	TOTAL FIELD COST					922 595
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG COST					
Q	SALES TAX 4% OF MAT'L COST					6 635
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½ % OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					69 560
	SUB TOTAL					998 790
Y	FEE 5% OF SUBTOTAL					49 940
	TOTAL					1 048 730

Stearns-Roger
INCORPORATED

LIENT ATOMICS INTERNATIONAL
RDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-10-78

COUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS UNIT	MANHOURS TOTAL	MANHOURS $/MH	LABOR	MATERIAL	OTHER	TOTAL
	TOWER:										
	HEIGHT 100 METERS										
	RECV. WT NONE KIPS										
A	SOIL EXCAVATION	2,719	CY	–	.08	217	12^{00}	2,600	—	1,070	3,670
A	BACK-FILL (COMPACTED STRUCT.)	700	CY	[illegible]	.35	245	12^{00}	2,940	2,800	700	6,[illegible]
3	TOWER CONCRETE – $f_c' = 4000$ psi	1,058	CY	30	10	10,580	15^{00}	158,700	31,740		170,4[illegible]
3	TOWER STEEL – f_y = GR.60	66	TONS	440^{00}	10	660	17^{00}	11,220	29,040		[illegible]
3	MAT CONCRETE – $f_c' = 4000$ psi	1,885	CY	[illegible]	9	16,965	15^{00}	254,475	56,550		311,025
3	MAT STEEL – f_y = GR.60	104	TONS	4[illegible]	8	832	17^{00}	14,145	45,760		59,90[illegible]
	TOTAL					29,499		444,080	165,890	1,770	611,740

FORM 22-233 REV 10

Stearns-Roger

ORDER OF MAGNITUDE
ESTIMATE SUMMARY

CUSTOMER ATOMICS INTERNATIONAL | PROP NO.

LOCATION | JOB NO. 20325

PROJECT ADVANCED CENTRAL RECEIVER | DATE 2-6-78

(100 METERS HEIGHT / 500 KIPS) | BY J. W. F.

REV. NO. | REV/DATE | BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	SUBCONTRACT	TOTAL
A	EARTHWORK	1462	5540	2 800	1 770	10 110
B	CONCRETE	29 137	440 240	167 490		607 730
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	27 599	445 780	170 290	1 770	617 840
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70% OF DIRECT LABOR			312 045
	TOTAL FIELD COST					927 885
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG. COST					
O	SALES TAX 4% OF MAT'L COST					6 810
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½% OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					70 120
	SUB TOTAL					1 006 815
Y	FEE 5% OF SUBTOTAL					50 34
	TOTAL					1 057 155

Stearns-Roger
INCORPORATED

IENT ATOMICS INTERNATIONAL
DER NO. 20325 LOCATION

SHEET NO. 1
BY J.W.F.
DATE 2-10-78

COUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS UNIT	MANHOURS TOTAL	MANHOURS $/MH	LABOR	MATERIAL	OTHER	TOTAL
	TOWER										
	HEIGHT 100 METERS										
	RECV. WT 500 KIPS										
A	SOIL EXCAVATION	2,719	CY	—	.08	217	12^{00}	2600	—	1,070	3,670
A	BACK-FILL (COMPACTED STRUCT.)	700	CY	4^{00}	.35	245	12^{00}	2,940	2,800	700	6,440
3	TOWER CONCRETE — f'_c = 4000ps	1,058	CY	30^{00}	10	10,580	15^{00}	158,700	31,740		190,440
3	TOWER STEEL — f_y = GR.60	76	TONS	440^{00}	10	760	17^{00}	12,920	33,440		46,360
3	MAT CONCRETE — f'_c = 4000psi	1,885	CY	30^{00}	9	16,965	15^{00}	254,475	56,550		311,025
3	MAT STEEL — f_y = GR.60	104	TONS	440^{00}	8	832	17^{00}	14,145	45,760		59,905
	TOTAL					29,599		445,780	170,290	1,770	617,840

FORM 22-288 REV 10

CUSTOMER ATOMICS INTERNATIONAL
PROP NO.
LOCATION
JOB NO. 20325
PROJECT ADVANCED CENTRAL RECEIVER
(100 METERS HEIGHT / 1,500 KIPS)
DATE 2-6-78
BY J. W. R.
REV. NO.
REV. DATE
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	SUBCONTRACT	TOTAL
A	EARTHWORK	612	7 345	3 600	2 350	13 295
B	CONCRETE	40 429	611 110	237 630		848 740
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	41 041	618 455	241 230	2 350	862 035
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70 % OF	DIRECT	LABOR	432 920
	TOTAL FIELD COST					1 294 955
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG. COST					
Q	SALES TAX 4% OF MAT'L COST					9 650
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½ % OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					97 670
	SUB TOTAL					1 402 275
Y	FEE 5% OF SUBTOTAL					70 115
	TOTAL					1 472 390

Stearns-Roger
INCORPORATED

LIENT ATOMICS INTERNATIONAL
RDER NO. 20325 LOCATION

SHEET NO. 1 OF 1
BY 2-6-78
DATE J.W.F.

COUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS UNIT	MANHOURS TOTAL	$/MH	LABOR	MATERIAL	OTHER	TOTAL
	TOWER:										
	HEIGHT 100 METERS										
	RECV. WT 1,500 KIPS										
A	SOIL EXCAVATION	3,714	CY	—	.08	297	12^{00}	3,565	—	1,450	5,015
A	BACK-FILL (COMPACTED STRUCT.)	900	CY	4^{00}	.35	315	12^{00}	3,780	3,600	900	8,28
3	TOWER CONCRETE — f'_c = 4000 psi	1,453	CY	30^{00}	10	14,530	15^{00}	217,950	43,590		261,540
3	TOWER STEEL — f_y = GR.60	118.5	TONS	440^{00}	10	1,185	17^{00}	20,145	52,140		72,28
3	MAT CONCRETE — f'_c = 4000 psi	2,618	CY	30^{00}	9	23,562	15^{00}	353,430	78,540		431,97
3	MAT STEEL — f_y = GR.60	144	TONS	440^{00}	8	1,152	17^{00}	19,585	63,360		82,94
	TOTAL					41,041		618,455	241,230	2,350	862,03

FORM 22-288 REV 10

Stearns-Roger

ESTIMATE SUMMARY

CUSTOMER *ATOMICS INTERNATIONAL* PROP NO.
LOCATION JOB NO. 20325
PROJECT *ADVANCED CENTRAL RECEIVER* DATE 2-13-78
(200 METERS HEIGHT / NONE KIPS) BY J. W. F.
REV. NO. REV. DATE BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	1 750	21 000	10 400	6 690	38 090
B	CONCRETE	149 776	2 260 290	833 050		3 093 340
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	151 526	2 281 290	843 450	6 690	3 131 430
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70% OF	DIRECT	LABOR	1 596 905
	TOTAL FIELD COST					4 728 335
J	ENGINEERING *BY OTHERS*					
	TOTAL FIELD & ENG. COST					
Q	SALES TAX *4% OF MAT'L COST*					33 740
R	PREMIUM PAY *NONE*					
	ESCALATION *CURRENT PRICES AND LABOR RATES*					
	CONTINGENCY *7½% OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT*					356 655
	SUB TOTAL					5 118 730
Y	FEE *5% OF SUBTOTAL*					255 935
	TOTAL					5 374 665

Stearns-Roger
INCORPORATED

IENT ATOMICS INTERNATIONAL
DER NO. 20325 LOCATION

SHEET NO. 1 of 1
BY J. W. F.
DATE 2-6-78

COUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS			LABOR	MATERIAL	OTHER	TOTAL
					UNIT	TOTAL	$/MH				
	TOWER:										
	HEIGHT 100 METERS										
	RECV. WT 3,000 KIPS										
4	SOIL EXCAVATION	4,628	CY	–	.08	370	12.00	4,440	–	1,850	6,290
A	BACK-FILL (COMPACTED STRUCT.)	1,100	CY	4.00	.35	385	12.00	4,620	4,400	1,100	10,120
3	TOWER CONCRETE – f'_c = 4000 psi	1,733	CY	30.00	10	17,330	15.00	259,950	51,990		311,940
5	TOWER STEEL – f_y = GR. 60	162	TONS	440.00	10	1,620	17.00	27,540	71,250		[illegible]
3	MAT CONCRETE – f'_c = 4000 psi	3,269	CY	30.00	9	29,421	15.00	444,315	95,070		539,385
2	MAT STEEL – f_y = GR. 60	180	TONS	440.00	8	1,440	17.00	24,480	79,200		103,680
	TOTAL					50,566		762,345	304,940	2,950	1,073,[illegible]

FORM 22-288 REV 10/7

Stearns-Roger
INCORPORATED

LIENT ATOMICS INTERNATIONAL
RDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-13-78

COUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS			LABOR	MATERIAL	OTHER	TOTAL
					UNIT	TOTAL	$/MH				
	TOWER :										
	HEIGHT : 200 METERS										
	RECV. WT NONE KIPS										
A	SOIL EXCAVATION	10,496	CY	—	.08	840	12^{00}	10,080	—	4,090	14,1
A	BACK-FILL (COMPACTED STRUCT)	2,600	CY	4^{00}	.35	910	12^{00}	10,920	10,400	2,600	23,92
						1750		[illegible]	10,[illegible]	[illegible]	[illegible]
3	TOWER CONCRETE - f'_c = 4000 psi	6,773	CY	30^{00}	11	74,503	15^{00}	1,117,545	203,190		1,320,73
3	TOWER STEEL - f_y = GR. 60	529	TONS	440^{00}	11	5,819	17^{00}	98,925	232,760		331,6
3	MAT CONCRETE - f'_c = 4000 psi	7,326	CY	30^{00}	9	65,934	15^{00}	989,010	219,780		1,208,7
3	MAT STEEL - f_y = GR. 60	403	TONS	440^{00}	8	3,520	17^{00}	54,810	177,320		232,13
						149,771		[illegible]	832,050		[illegible]
	TOTAL					151,526		2,281,290	843,450	6,690	3,131,43

FORM 22-208 REV

ESTIMATE SUMMARY

CUSTOMER ATOMICS INTERNATIONAL
PROP NO.
LOCATION
JOB NO. 20325
PROJECT ADVANCED CENTRAL RECEIVER (200 METERS HEIGHT / .500 KIPS)
DATE 2-13-78
BY J. W. F.
REV. NO.
REV. DATE
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	1750	21000	10400	6690	38090
B	CONCRETE	149592	2262195	837540		3099735
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	151342	2283195	847940	6690	3137825
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70% OF	DIRECT	LABOR	1598235
	TOTAL FIELD COST					4736060

ACT		TOTAL
J	ENGINEERING BY OTHERS	
	TOTAL FIELD & ENG. COST	
Q	SALES TAX 4% OF MAT'L COST	33920
R	PREMIUM PAY NONE	
	ESCALATION CURRENT PRICES AND LABOR RATES	
	CONTINGENCY 7½% OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT	357245
	SUB TOTAL	5127225
Y	FEE 5% OF SUBTOTAL	256360
	TOTAL	5383585

Stea[illegible]is-Roger
INCORPORATED

CLIENT Atomics International
ORDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-13-78

ACCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS			LABOR	MATERIAL	OTHER	TOT
					UNIT	TOTAL	$/MH				
	TOWER :										
	HEIGHT : 200 METERS										
	RECV. WT 500 KIPS										
A	SOIL EXCAVATION	10,496	CY	-	.08	840	12^{00}	10,080	-	4,090	14,17
A	BACK-FILL (COMPACTED STRUCT)	2,600	CY	4^{00}	.35	910	12^{00}	10,920	10,400	2,600	23,7
						1750		[illegible]	[illegible]		[illegible]
B	TOWER CONCRETE - f'_c = 4000 psi	6,773	CY	30^{00}	11	74,503	15^{00}	1,117,545	203,190		1,320,
B	TOWER STEEL - f_y = GR. 60	539.2	TONS	440^{00}	11	5,931	17^{00}	100,830	237,250		338,
B	MAT CONCRETE - f'_c = 4000 psi	7,326	CY	30^{00}	9	65,934	15^{00}	989,010	219,780		1,20
B	MAT STEEL - f_y = GR. 60	403	TONS	440^{00}	8	3,224	17^{00}	54,810	177,320		232,
						149,592		[illegible]	837,5[illegible]		3,
	TOTAL					151,342		2,283,195	847,940	6,690	3,137,

FORM 22-253 REV

ESTIMATE SUMMARY

CUSTOMER ATOMICS INTERNATIONAL
PROP NO.
LOCATION
JOB NO. 20325
PROJECT ADVANCED CENTRAL RECEIVER (200 METERS HEIGHT/ 1,500 KIPS)
DATE 2-13-78
BY J. W. F.
REV. NO.
REV. DATE
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	1 930	23 160	11 600	7 370	42 130
B	CONCRETE	177 219	2 680 525	999 125		3 679 650
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	179 149	2 703 685	1 010 725	7 370	3 721 780
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70% OF DIRECT LABOR			1 892 580
	TOTAL FIELD COST					5 614 360
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG. COST					
O	SALES TAX 4% OF MAT'L COST					40 430
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½% OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					418 600
	SUB TOTAL					6 073 390
Y	FEE 5% OF SUBTOTAL					303 670
	TOTAL					6 377 060

Stearns-Roger
INCORPORATED

CLIENT ATOMICS INTERNATIONAL
ORDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-13-78

ACCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS			LABOR	MATERIAL	OTHER	TOTAL
					UNIT	TOTAL	$/MH				
	TOWER :										
	HEIGHT : 200 METERS										
	RECV. WT 1,500 KIPS										
A	SOIL EXCAVATION	11,443	CY	–	.08	915	12^{00}	10,980	–	4,470	15,4
A	BACK-FILL (COMPACTED STRUCT)	2,900	CY	4^{00}	.35	1,015	12^{00}	12,180	11,600	2,900	26,6
						1,930		[illegible]	[illegible]	[illegible]	[illegible]
3	TOWER CONCRETE – f'_c = 4000 psi	8,215	CY	30^{00}	11	90,365	15^{00}	1,355,475	246,450		1,601,9
3	TOWER STEEL – f_y = GR. 60	674.1	TONS	440^{00}	11	7,415	17^{00}	126,055	296,605		422,6
3	MAT CONCRETE – f'_c = 4000 psi	8,412	CY	30^{00}	9	75,735	15^{00}	1,136,025	252,350		1,3
3	MAT STEEL – f_y = GR. 60	463	TONS	440^{00}	8	3,704	17^{00}	62,970	203,720		266,
						177,214		[illegible]	[illegible]		[illegible]
	TOTAL					179,149		2,703,685	1,010,725	7,370	3,721,7

FORM 22-283 REV

ESTIMATE SUMMARY

CUSTOMER ATOMICS INTERNATIONAL
PROP NO.
LOCATION
JOB NO. 20325
PROJECT ADVANCED CENTRAL RECEIVER (200 METERS HEIGHT/3,000 KIPS)
DATE 2-13-78
BY J. W. P.
REV. NO.
REV. DATE
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	2 558	30 700	15 200	9 790	55 690
B	CONCRETE	222 796	3 370 140	1 766 270		4 636 410
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	225 354	3 400 840	1 281 470	9 790	4 692 100
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70 % OF	DIRECT	LABOR	2 380 590
	TOTAL FIELD COST					7 072 690
J	ENGINEERING	BY OTHERS				
	TOTAL FIELD & ENG. COST					
O	SALES TAX	4% OF MAT'L COST				51 260
R	PREMIUM PAY	NONE				
	ESCALATION	CURRENT PRICES AND LABOR RATES				
	CONTINGENCY	7½ % OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT				527 340
	SUB TOTAL					7 651 270
	FEE	5% OF SUBTOTAL				382 565
	TOTAL					8 033 835

Stearns-Roger
INCORPORATED

SHEET NO. 1
BY J.W.F.
DATE 2-13-78

CLIENT ATOMICS INTERNATIONAL
ORDER NO. 20325 LOCATION

ACCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS			LABOR	MATERIAL	OTHER	TOT
					UNIT	TOTAL	$/MH				
	TOWER :										
	HEIGHT : 200 METERS										
	RECV. WT 3,000 KIPS										
A	SOIL EXCAVATION	15,354	CY	–	.08	1,228	12^{00}	14,740	–	5,990	20,7
A	BACK-FILL (COMPACTED STRUCT)	3,800	CY	4^{00}	.35	1,330	12^{00}	15,960	15,200	3,800	34,9
						2,558		[illegible]	[illegible]	[illegible]	[illegible]
3	TOWER CONCRETE – f'_c = 4000 psi	9,931	CY	30^{00}	11	109,241	15^{00}	1,638,615	297,930		1,936,
B	TOWER STEEL – f_y = GR. 60	839.3	TONS	440^{00}	11	9,232	17^{00}	156,950	369,290		526,
B	MAT CONCRETE – f'_c = 4000 psi	11,051	CY	30^{00}	9	99,459	15^{00}	1,491,885	331,530		1,823,
B	MAT STEEL – f_y = GR. 60	608	TONS	440^{00}	8	4,864	17^{00}	82,690	267,520		350,
						222,796		[illegible]	1,266,27		[illegible]
	TOTAL					225,354		3,400,840	1,281,470	9,790	4,692,

FORM 22-208 REV 1

Stearns-Roger

ESTIMATE SUMMARY

CUSTOMER ATOMICS INTERNATIONAL
PROP NO.
LOCATION
JOB NO. 20325
PROJECT ADVANCED CENTRAL RECEIVER
(300 METERS HEIGHT / NONE KIPS)
DATE 2-13-78
BY J. W. F.
REV. NO.
REV. DATE
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	3 974	47 690	23 600	15 210	86 500
B	CONCRETE	414 656	6 276 855	2 274 170		8 551 025
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	418 630	6 324 545	2 297 770	15 210	8 637 525
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70% OF	DIRECT	LABOR	4 427 180
	TOTAL FIELD COST					13 064 705
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG. COST					
Q	SALES TAX 4% OF MAT'L COST					91 910
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½% OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					985 605
	SUB TOTAL					14 142 220
Y	FEE 5% OF SUBTOTAL					707 110
	TOTAL					14 849 330

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CLIENT ATOMICS INTERNATIONAL
ORDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-13-78

ACCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS UNIT	MANHOURS TOTAL	MANHOURS $/MH	LABOR	MATERIAL	OTHER	TOT
	TOWER :										
	HEIGHT : 300 METERS										
	RECV. WT NONE KIPS										
A	SOIL EXCAVATION	23,866	CY	-	.08	1,909	12.00	22,910	-	9,310	32,2
A	BACK-FILL (COMPACTED STRUCT)	5,900	CY	4.00	.35	2,065	12.00	24,780	23,600	5,900	54,
						174		[illegible]	[illegible]	[illegible]	[illegible]
B	TOWER CONCRETE - f'_c = 4000 psi	19,483	CY	30.00	12	233,796	15.00	3,506,940	584,490		4,09
B	TOWER STEEL - f_y = GR. 60	1,755	TONS	440.00	12	21,060	17.00	358,020	772,200		1,130
B	MAT CONCRETE - f'_c = 4000 psi	16,928	CY	30.00	9	152,352	15.00	2,285,280	507,840		2,79
B	MAT STEEL - f_y = GR. 60	931	TONS	440.00	8	7,448	17.00	126,615	409,640		53
						44,651		[illegible]	2,274,170		[illegible]
	TOTAL					418,630		6,324,545	2,297,770	5,210	8,63

FORM 22-288 REV

CUSTOMER *ATOMICS INTERNATIONAL*
LOCATION
PROJECT *ADVANCED CENTRAL RECEIVER (300 METERS HEIGHT / 500 KIPS)*
REV. NO. REV. DATE

PROP NO.
JOB NO. *20325*
DATE *2-13-78*
BY *J. W. F.*
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	3 774	47 690	23 600	15 210	86 500
B	CONCRETE	414 872	6 281 525	2 282 090		8 562 615
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	418 846	6 328 215	2 305 640	15 210	8 649 115
~~H~~	~~FIELD EXPENSE~~					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
T	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70% OF	DIRECT	LABOR	4 429 750
	TOTAL FIELD COST					13 078 865
J	ENGINEERING *BY OTHERS*					
	TOTAL FIELD & ENG. COST					
Q	SALES TAX *4% OF MAT'L COST*					92 230
R	PREMIUM PAY *NONE*					
	ESCALATION *CURRENT PRICES AND LABOR RATES*					
	CONTINGENCY *7½% OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT*					986 690
	SUB TOTAL					14 157 185
	FEE *5% OF SUBTOTAL*					707 859
	TOTAL					14 865 615

Stea[illegible]s-Roger
INCORPORATED

CLIENT ATOMICS INTERNATIONAL
ORDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-13-78

ACCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS			LABOR	MATERIAL	OTHER	TOT
					UNIT	TOTAL	$/MH				
	TOWER :										
	HEIGHT : 300 METERS										
	RECV. WT 500 KIPS										
A	SOIL EXCAVATION	23,866	CY	–	.08	1,909	12^{00}	22,910	–	9,310	32,2
A	BACK-FILL (COMPACTED STRUCT)	5,900	CY	4^{00}	.35	2,065	12^{00}	24,780	23,600	5,900	54
						[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
B	TOWER CONCRETE - $f'_c = 4000$ psi	19,483	CY	30^{00}	12	233,796	15^{00}	3,506,940	584,490		4,091
B	TOWER STEEL - f_y = GR. 60	1,773	TONS	440^{00}	12	21,276	17^{00}	361,690	780,120		1,141
B	MAT CONCRETE - $f'_c = 4000$ psi	16,928	CY	30^{00}	9	152,352	15^{00}	2,285,280	507,840		2,79
B	MAT STEEL - f_y = GR. 60	931	TONS	440^{00}	8	7,448	17^{00}	126,615	409,640		53
						414,872		[illegible]	[illegible]		[illegible]
	TOTAL					418,846		6,328,215	2,305,690	15,210	8,64

FORM 22-208 REV

Stearns-Roger

ESTIMATE SUMMARY

CUSTOMER ATOMICS INTERNATIONAL
PROP NO.
LOCATION
JOB NO. 20325
PROJECT ADVANCED CENTRAL RECEIVER (300 METERS HEIGHT / 1,500 KIPS)
DATE 2-13-78
BY J. W. F.
REV. NO.
REV. DATE
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	4,168	50,015	24,800	15,945	90,760
B	CONCRETE	457,073	6,920,385	2,521,825		9,442,210
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	461,241	6,970,400	2,546,625	15,945	9,532,970
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70% OF	DIRECT	LABOR	4,879,280
	TOTAL FIELD COST					14,412,250
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG. COST					
Q	SALES TAX 4% OF MAT'L COST					101,865
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½% OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					1,087,365
	SUB TOTAL					15,601,480
Y	FEE 5% OF SUBTOTAL					780,075
	TOTAL					16,381,555

Stearns-Roger
INCORPORATED

CLIENT ATOMICS INTERNATIONAL
ORDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-13-78

CCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS UNIT	MANHOURS TOTAL	MANHOURS $/MH	LABOR	MATERIAL	OTHER	TOT
	TOWER :										
	HEIGHT : 300 METERS										
	RECV. WT 1,500 KIPS										
A	SOIL EXCAVATION	24,976	CY	—	.08	1,998	12^{00}	23,975	—	9,745	33,
A	BACK-FILL (COMPACTED STRUCT)	6,200	CY	4^{00}	.35	2,170	12^{00}	26,040	24,800	6,200	57,
						4,168		[illegible]	24,[illegible]	[illegible]	[illegible]
3	TOWER CONCRETE – $f'_c = 4000$ psi	21,882	CY	30^{00}	12	262,584	15^{00}	3,938,760	656,460		4,595,
3	TOWER STEEL – f_y = GR. 60	2,017.5	TONS	440^{00}	12	24,210	17^{00}	411,570	887,700		1,299,
3	MAT CONCRETE – $f'_c = 4000$ psi	18,038	CY	30^{00}	9	162,342	15^{00}	2,435,130	541,140		2,976,
3	MAT STEEL – f_y = GR. 60	992.1	TONS	440^{00}	8	7,937	17^{00}	134,925	436,525		571,
						457,072		[illegible]	2,521,8[illegible]		[illegible]
	TOTAL					461,241		6,970,400	2,546,625	15,945	9,532,

FORM 22-208 REV

Stearns-Roger

ESTIMATE SUMMARY

CUSTOMER ATOMICS INTERNATIONAL
PROP NO.
LOCATION
JOB NO. 20325
PROJECT ADVANCED CENTRAL RECEIVER (300 METERS HEIGHT / 3,000 KIPS)
DATE 2-13-78
BY J. W. F.
REV. NO.
REV. DATE
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	4 441	53 290	26 400	16 995	96 685
B	CONCRETE	504 203	7 634 340	2 785 240		10 419 580
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	508 644	7 687 630	2 811 640	16 995	10 516 265
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70 % OF	DIRECT	LABOR	5 381 340
	TOTAL FIELD COST					15 897 605
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG. COST					
Q	SALES TAX 4% OF MAT'L COST					112 465
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½ % OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					1 199 480
	SUB TOTAL					17 209 550
Y	FEE 5% OF SUBTOTAL					860 480
	TOTAL					18 070 030

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INCORPORATED

CLIENT ATOMICS INTERNATIONAL
ORDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-13-78

ACCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS			LABOR	MATERIAL	OTHER	TOTAL
					UNIT	TOTAL	$/MH				
	TOWER:										
	HEIGHT: 300 METERS										
	RECV. WT 3,000 KIPS										
A	SOIL EXCAVATION	26,641	CY	—	.08	2,131	12^{00}	25,570	—	10,395	35,96
						&					
A	BACK-FILL (COMPACTED STRUCT)	6,600	CY	4^{00}	.35	2,310	12^{00}	27,720	26,400	6,600	60,7
						[illegible],441		[illegible]	26,[illegible]	1[illegible]	[illegible]
B	TOWER CONCRETE - f'_c = 4000 psi	24,269	CY	30^{00}	12	291,228	15^{00}	4,368,420	728,070		5,096,4
B	TOWER STEEL - f_y = GR. 60	2,248	TONS	440^{00}	12	26,976	17^{00}	458,590	989,120		1,447,7
B	MAT CONCRETE - f'_c = 4000 psi	19,703	CY	30^{00}	9	177,327	15^{00}	2,659,905	591,090		3,250
B	MAT STEEL - f_y = GR. 60	1,084	TONS	440^{00}	8	8,672	17^{00}	147,425	476,960		624,3
						[illegible]4,203		7[illegible]	2,[illegible],24[illegible]		[illegible]
	TOTAL					508,644		7,687,630	2,811,640	16,995	10,516

FORM 22-288 REV 10

Stearns-Roger

ESTIMATE SUMMARY

CUSTOMER ATOMICS INTERNATIONAL
LOCATION
PROJECT ADVANCED CENTRAL RECEIVER
(400 METERS HEIGHT / NONE KIPS)
REV. NO.
REV. DATE

PROP NO.
JOB NO. 20325
DATE 2-13-78
BY J.W.F.
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	6021	72250	36000	23000	131250
B	CONCRETE	874898	13240030	4482220		17722250
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	880919	13312280	4518220	23000	17853500
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP					
	INDIRECT FIELD COST		70% OF	DIRECT	LABOR	9318595
	TOTAL FIELD COST					27172095
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG. COST					
O	SALES TAX 4% OF MAT'L COST					180730
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½% OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					2049738
	SUB TOTAL					29402560
Y	FEE 5% OF SUBTOTAL					1470130
	TOTAL					30872690

Stearns-Roger
INCORPORATED

CLIENT ATOMICS INTERNATIONAL
ORDER NO. 20325 LOCATION

SHEET NO. 1
BY J.W.F.
DATE 2-13-78

ACCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS UNIT	MANHOURS TOTAL	$/MH	LABOR	MATERIAL	OTHER	TO
	TOWER :										
	HEIGHT : 400 METERS										
	RECV. WT NONE KIPS										
A	SOIL EXCAVATION	35,891	CY	—	.08	2,871	12.00	34,450	—	14,000	48,
A	BACK-FILL (COMPACTED STRUCT)	9,000	CY	4.00	.35	3,150	12.00	37,800	36,000	9,000	82
						6,021		[illegible]	36,000	[illegible]	[illegible]
3	TOWER CONCRETE – $f'_c = 4000$ psi	44,373	CY	30.00	13	576,849	15.00	8,652,735	1,331,190		9,9
3	TOWER STEEL – f_y = GR. 60	3,880	TONS	440.00	12	46,560	17.00	791,520	1,707,200		2,49
3	MAT CONCRETE – $f'_c = 4000$ psi	26,641	CY	30.00	9	239,769	15.00	3,596,535	799,230		4,3
3	MAT STEEL – f_y = GR. 60	1,465	TONS	440.00	8	11,720	17.00	199,240	644,600		84
						[illegible]		[illegible]	4,422,220		7,72
	TOTAL					880,919		13,312,280	4,518,220	23,000	17,8

FORM 22-203 REV

CUSTOMER ATOMICS INTERNATIONAL
LOCATION
PROJECT ADVANCED CENTRAL RECEIVER
(400 METERS HEIGHT / 500 KIPS)
REV. NO. REV. DATE

PROP NO.
JOB NO. 20325
DATE 2 - 13 - 78
BY J. W. T.
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	61 021	72 250	36 000	23 000	131 250
B	CONCRETE	874 958	13 241 050	4 484 420		17 725 470
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	880 979	13 313 300	4 520 420	23 000	17 856 720
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70 % OF	DIRECT	LABOR	9 319 310
	TOTAL FIELD COST					27 185 030
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG. COST					
Q	SALES TAX 4 % OF MAT'L COST					180 815
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½ % OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					2 050 715
	SUB TOTAL					29 416 560
Y	FEE 5 % OF SUBTOTAL					1 470 830
	TOTAL					30 887 390

Stearns-Roger
INCORPORATED

CLIENT ATOMICS INTERNATIONAL
ORDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-13-78

CCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS UNIT	MANHOURS TOTAL	MANHOURS $/MH	LABOR	MATERIAL	OTHER	TOTAL
	TOWER :										
	HEIGHT : 400 METERS										
	RECV. WT 500 KIPS										
A	SOIL EXCAVATION	35,891	CY	–	.08	2,871	12^{00}	34,450	–	14,000	48,45
A	BACK-FILL (COMPACTED STRUCT)	9,000	CY	4^{00}	.35	3,150	12^{00}	37,800	36,000	9000	82,8
						6,021		[illegible]	36,000	[illegible]	[illegible]
3	TOWER CONCRETE – $f_c' = 4000$ psi	44,373	CY	30^{00}	13	576,849	15^{00}	8,652,735	1,331,190		9,983,
3	TOWER STEEL – f_y = GR.60	3,885	TONS	440^{00}	12	46,620	17^{00}	792,540	1,709,400		2,501,
3	MAT CONCRETE – $f_c' = 4000$ psi	26,641	CY	30^{00}	9	239,769	15^{00}	3,596,535	799,230		4,39
3	MAT STEEL – f_y = GR.60	1,465	TONS	440^{00}	8	11,720	17^{00}	199,240	644,600		843,
						[illegible]		[illegible]	[illegible]		[illegible]
	TOTAL					880,979		13,313,300	4,520,420	23,000	17,865,

FORM 22-2110 REV 1

Stearns-Roger

ORDER OF MAGNITUDE ESTIMATE SUMMARY

CUSTOMER ATOMICS INTERNATIONAL
PROP NO.
LOCATION
JOB NO. 20325
PROJECT ADVANCED CENTRAL RECEIVER (400 METERS HEIGHT / 1,500 KIPS)
DATE 2-13-78
BY J. W. F.
REV. NO.
REV. DATE
BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	6 021	72 250	36 000	23 000	131 250
B	CONCRETE	874 994	13 241 660	4 485 740		17 727 400
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	881 015	13 313 910	4 521 740	23 000	17 858 650
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP					
	INDIRECT FIELD COST		70 % OF	DIRECT	LABOR	9 319 740
	TOTAL FIELD COST					27 178 390
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG. COST					
Q	SALES TAX 4% OF MAT'L COST					180 870
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½% OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					2 050 220
	SUB TOTAL					29 409 480
Y	FEE 5% OF SUBTOTAL					1 470 475
	TOTAL					30 879 955

Stearns-Roger
INCORPORATED

CLIENT Atomics International
ORDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-13-78

CCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS			LABOR	MATERIAL	OTHER	TOTAL
					UNIT	TOTAL	$/MH				
	TOWER :										
	HEIGHT: 400 METERS										
	RECV. WT 1,500 KIPS										
A	SOIL EXCAVATION	35,891	CY	–	.08	2,871	12^{00}	34,450	–	14,000	48,45
A	BACK-FILL (COMPACTED STRUCT)	9,000	CY	4^{00}	.35	3,150	12^{00}	37,800	36,000	9,000	82,80
						6,021		7[illegible]	[illegible]	23,[illegible]	[illegible]
3	TOWER CONCRETE – f'_c = 4000 psi	44,373	CY	30^{00}	13	576,849	15^{00}	8,652,735	1,331,190		9,983,92
3	TOWER STEEL – f_y = GR. 60	3,888	TONS	440^{00}	12	46,656	17^{00}	793,150	1,710,720		2,503,87
3	MAT CONCRETE – f'_c = 4000 psi	26,641	CY	30^{00}	9	239,769	15^{00}	3,596,535	799,230		4,395,76
3	MAT STEEL – f_y = GR. 60	1,465	TONS	440^{00}	8	11,720	17^{00}	199,240	644,600		843,84
						874,914		[illegible]	4,485,740		[illegible]
	TOTAL					881,015	-	13,313,910	4,521,740	23,000	17,858,65

FORM 22-288 REV 11/

Stearns-Roger

ESTIMATE SUMMARY

CUSTOMER ATOMICS INTERNATIONAL PROP NO.
LOCATION JOB NO. 20325
PROJECT ADVANCED CENTRAL RECEIVER DATE 2-13-78
(400 METERS HEIGHT / 3,000 KIPS) BY J. W. T.
REV. NO. REV. DATE BY

ACT	DESCRIPTION	CRAFT HOURS	LABOR	MATERIAL	OTHER	TOTAL
A	EARTHWORK	6 021	72 250	36 000	23 000	131 250
B	CONCRETE	874 838	13 239 010	4 480 020		17 719 030
C	BUILDINGS & STRUCTURES					
D	PROCESS EQUIPMENT					
E	PIPING					
F	ELECTRICAL					
G	PAINTING					
L	PLANT ITEMS					
N	INSTRUMENTS & CONTROLS					
P	INSULATION					
	DIRECT FIELD COST	880 859	13 311 260	4 516 020	23 000	17 850 280
H	FIELD EXPENSE					
H	ALL RISK, PR TAX, BOND					
K	CONSTRUCTION SUPPLIES					
M	STARTUP					
S	TEMPORARY FACILITIES					
V	CRAFT BENEFITS					
V	CONSTRUCTION CAMP.					
W	CONSTRUCTION EQUIP.					
	INDIRECT FIELD COST		70 % OF	DIRECT	LABOR	9 317 880
	TOTAL FIELD COST					27 168 160
J	ENGINEERING BY OTHERS					
	TOTAL FIELD & ENG. COST					
Q	SALES TAX 4% OF MAT'L COST					180 640
R	PREMIUM PAY NONE					
	ESCALATION CURRENT PRICES AND LABOR RATES					
	CONTINGENCY 7½ % OF TOTAL FIELD COST PLUS SALES TAX MINUS SUBCONTRACT					2 047 435
	SUB TOTAL					29 396 235
Y	FEE 5% OF SUBTOTAL					1 469 810
	TOTAL					30 866 045

Stear. s-Roger
INCORPORATED

CLIENT ATOMICS INTERNATIONAL
ORDER NO. 20325 LOCATION

SHEET NO. 1
BY J. W. F.
DATE 2-13-78

CCOUNT	ITEM AND DESCRIPTION	QUANTITY	UNIT	MAT'L UNIT COST	MANHOURS UNIT	MANHOURS TOTAL	MANHOURS $/MH	LABOR	MATERIAL	OTHER	TOTAL
	TOWER :										
	HEIGHT : 400 METERS										
	RECV. WT 3,000 KIPS										
A	SOIL EXCAVATION	35,891	CY	–	.08	2,871	12.00	34,450	–	14,000	48,450
A	BACK-FILL (COMPACTED STRUCT)	9,000	CY	4.00	.35	3,150	12.00	37,800	36,000	9,000	82,[illegible]
						6,021		[illegible]	36,[illegible]	23,[illegible]	[illegible]
3	TOWER CONCRETE – f'_c=4000 psi	44,373	CY	30.00	13	576,849	15.00	8,652,735	1,331,190		9,983,92
3	TOWER STEEL – f_y=GR.60	3,875	TONS	440.00	12	46,500	17.00	790,500	1,705,000		2,495,50
3	MAT CONCRETE – f'_c=4000 psi	26,641	CY	30.00	9	239,769	15.00	3,596,535	799,230		4,395,7
3	MAT STEEL – f_y=GR.60	1,465	TONS	440.00	8	11,720	17.00	199240	644,600		843,84
						874,83[illegible]		[illegible]	4,480,020		17[illegible]
	TOTAL					880859		13,311,260	4,516,020	23,000	17,850,2

FORM 22-203 REV 12/

APPENDIX J

A COMPARISON OF MECHANICAL AND ELECTROMAGNETIC SODIUM PUMPS

AT Letter 78AT-2995

Atomics International Division
D/198 Correspondence

LTR. NO.
78AT-2864

	LTR/ENC	
ANDERSON, S. H.		
ASHWORTH		
ASQUITH		
BALENT		
BARTO		
BAUMEISTER		
BOTTS	✓	✓
BRIGHTMAN		
BRINDLEY		
BUERGIN		
CARTER, E. H.		
COCHRAN, J. C.		
COCKERAM		
CRAWFORD		
DE LOS PRADOS		
DETTERMAN		
Di POL		
FEILER		
GYLFE		
HARRIS-WASH.		
HARTZLER		
HILLIG		
HOLBROOK		
IACOBELLIS		
JACOBSON, J.		
JANIS		
JETTER		
JOHLER		
JONES, R. G.		
JULIAN, M.		
KEATEN		
KITTINGER		
KOLIN	✓	✓
KUSTUDIA		
MARTIN, A. B.		
McCOURT	✓	✓
McDERMOTT, R. J.		
McDONALD, J. S.		
MEYERS, G. W.		
MURPHY, J. E.		
OLDENKAMP		
PARKINS		
PARRY		
PAULSON		
REINECKER	✓	✓
REMLEY		
ROBERTS, W. J.		
ROHLFS		
SANDERS		
SCHIRM, R.C.		
TINGER		
TOHER		
WALTER, J. H.		
WEISNER		
WHEELER		
WIESENECK		
WILLIAMS, R. O.		
KLAUS, P	✓	✓
KATZ, B	✓	✓
Johnson, T. L	✓	✓
THOMPSON W	✓	✓
FRANCIS, H	✓	✓
GLASGOW		
SPRINGER, T.H	✓	✓

R—C

N.E.I. CLASSIFICATION	LTR/ENC	
UNCLASSIFIED	X	X
CLASSIFIED		

LTR. APPROVALS

RDD 3-24

ORIG. & TYPIST INITIALS
ECS/Betty

IN REPLY TO LTR. NO.
1352
File [illegible]

FORM N 22 H REV. 11-77

APPENDIX J

Atomics International Division
8900 De Soto Avenue
Canoga Park, California 91304
(213) 341-1000

Rockwell
International

March 22, 1978

In reply refer to 78AT-2995

Technical Manager
Contract EG-77-C-03-1483
Solar Projects Division, 8132
Sandia Laboratories
Livermore, California 94550

Attention: Mr. Ed Cull

Reference: TWX 24 dated February 14, 1978, E. T. Cull to T. H. Springer, "Comments and Action Items from the First Quarterly Review for the Atomics International Advanced Control Receiver Program, at Atomics International, Canoga Park, on February 9, 1978"

Gentlemen:

Subject: Response to Action Item 4.2 of the Referenced TWX - "A Comparison of Mechanical and Electromagnetic Sodium Pumps"

Action Item 4.4

"AI will furnish a comparison of mechanical and electromagnetic sodium pumps by March 10, 1978."

Response

The enclosed document briefly describes typical large-scale electromagnetic and mechanical pumps, describes their characteristics, notes the advantages and disadvantages of each, and assesses their applicability to the Advanced Central Receiver Power System main sodium loops. The conclusions reached in this study are:.

1. The electromagnetic pump head-flow characteristics are not suited to the requirements of the receiver system sodium loop (P-1 pump).
2. The electromagnetic pump does meet the requirements of the steam generator sodium loop (P-2 pump).

3. The mechanical pump will meet all system requirements.

4. The calculated cost penalty to the use of electromagnetic pumps is $\$4.1 \times 10^6$ for the P-1 pump and $\$0.59 \times 10^6$ for the P-2 pump.

Very truly yours,

T. H. Springer

T. H. Springer
Project Manager
Solar Electric Systems
Atomics International Division

nth:3/3-4

Enclosure

cc w/enclosure: Mark Schanfein, DOE
G. C. Coleman, MDAC
W. Lang, S-R
S. Chalmers, SRP
G. Kaplan, DOE/DSE

Enclosure to
AI Letter 78AT-2995

CONTENTS

FIGURES

FIGURES

I. SUMMARY AND CONCLUSIONS

The performance characteristics and economics of electromagnetic pumps and mechanical centrifugal pumps were compared for application to the Advanced Central Receiver Power System main sodium loops. The larger size electromagnetic pumps appear to have a rising head flow characteristic which makes them less suitable than mechanical pumps for high lift variable flow applications. In all aspects, except efficiency, the electromagnetic pumps and the mechanical pumps are equally suited for application to the steam generator sodium system.

The lower pumping efficiency of the electromagnetic pumps imposes a cost penalty of \$4.1 x 10^6 for the P-1 pump and \$0.59 x 10^6 for the P-2 pump.

It is concluded that centrifugal pumps should be used in the conceptual design of the Advanced Central Receiver Power System main sodium loops.

II. OBJECTIVE AND PURPOSE

The objective of this study is to assess the operational benefits and cost differences between electromagnetic and mechanical pumps, as they apply to the Advanced Central Receiver System, in order to permit a selection between the two types. The pump type with the best cost benefit ratio will be selected for the receiver pump P-1 and the steam generator pump P-2 (see Figure 1).

III. DESCRIPTION AND PRINCIPLES OF OPERATION

A. ELECTROMAGNETIC PUMPS(1,2)

The pumping action of all electromagnetic pumps is due to body forces on the sodium, or other electrically conductive fluid, being pumped. An electric current in a magnetic field has a force exerted ~~in~~ it. If the current is flowing in a conducting material, the force is effectively exerted on the conductor. The total pressure developed is the integral of the flux density times the current density throughout the pump duct.

SODIUM ADVANCED CENTRAL RECEIVER

R-1
SODIUM COOLED RECEIVER
429 MW
(1.5 x 10^9 BTU/hr)

P-1
RECEIVER PUMP
305 m (1,000 ft) TDH
1.3 m^3/sec
(20 x 10^3 gpm)
4.7 Mw (6,300 hp)

T-1
LOW TEMPERATURE SODIUM TANK
288°C (550°F)
8,700 m^3 (2.3 x 10^6 gal)

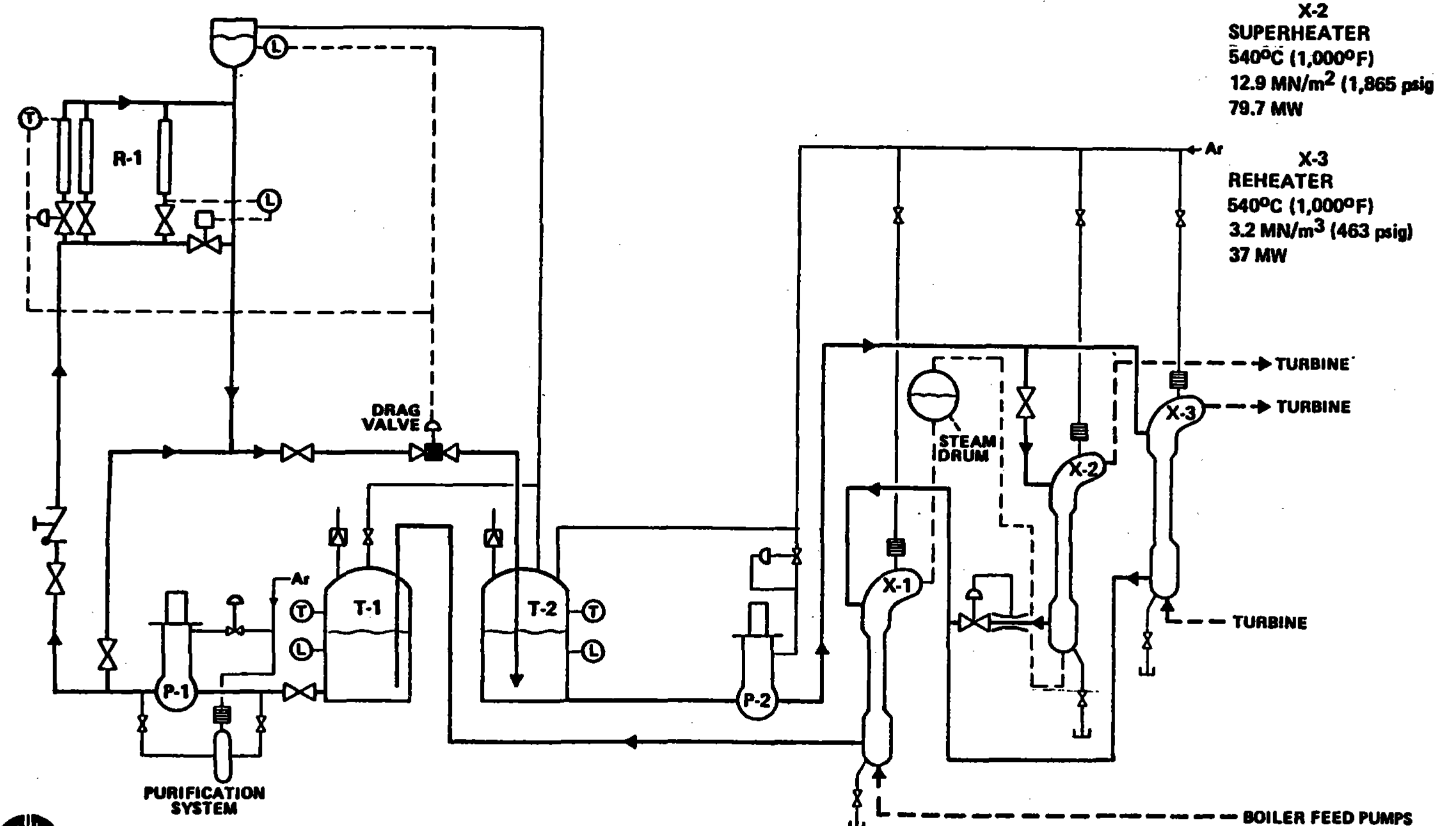
T-2
HIGH TEMPERATURE SODIUM TANK
590°C (1,100°F)
9,500 m^3 (2.5 x 10^6 gal)
3 hrs FULL POWER

P-2
STEAM GENERATOR PUMP
61 m (200 ft) TDH
1.0 m^3/sec (15 x 10^3 gpm)
0.7 Mw (900 H.P.)

X-1
EVAPORATOR
341°C (646°F)
15 MN/m^2 (2,200 psia)
156 MW

X-2
SUPERHEATER
540°C (1,000°F)
12.9 MN/m^2 (1,865 psig)
79.7 MW

X-3
REHEATER
540°C (1,000°F)
3.2 MN/m^3 (463 psig)
37 MW



Rockwell International
Atomics International Division

Figure 1. Advanced Central Receiver P&I Diagram

EM pumps can be made in an extremely wide variety of shapes limited only by the designer's ability to bring electric current into a magnetic field. In addition to direct acting pumps, impellerless centrifugal force can also be used to generate pressure in a conducting fluid which is being rotated by electromagnetic body forces.

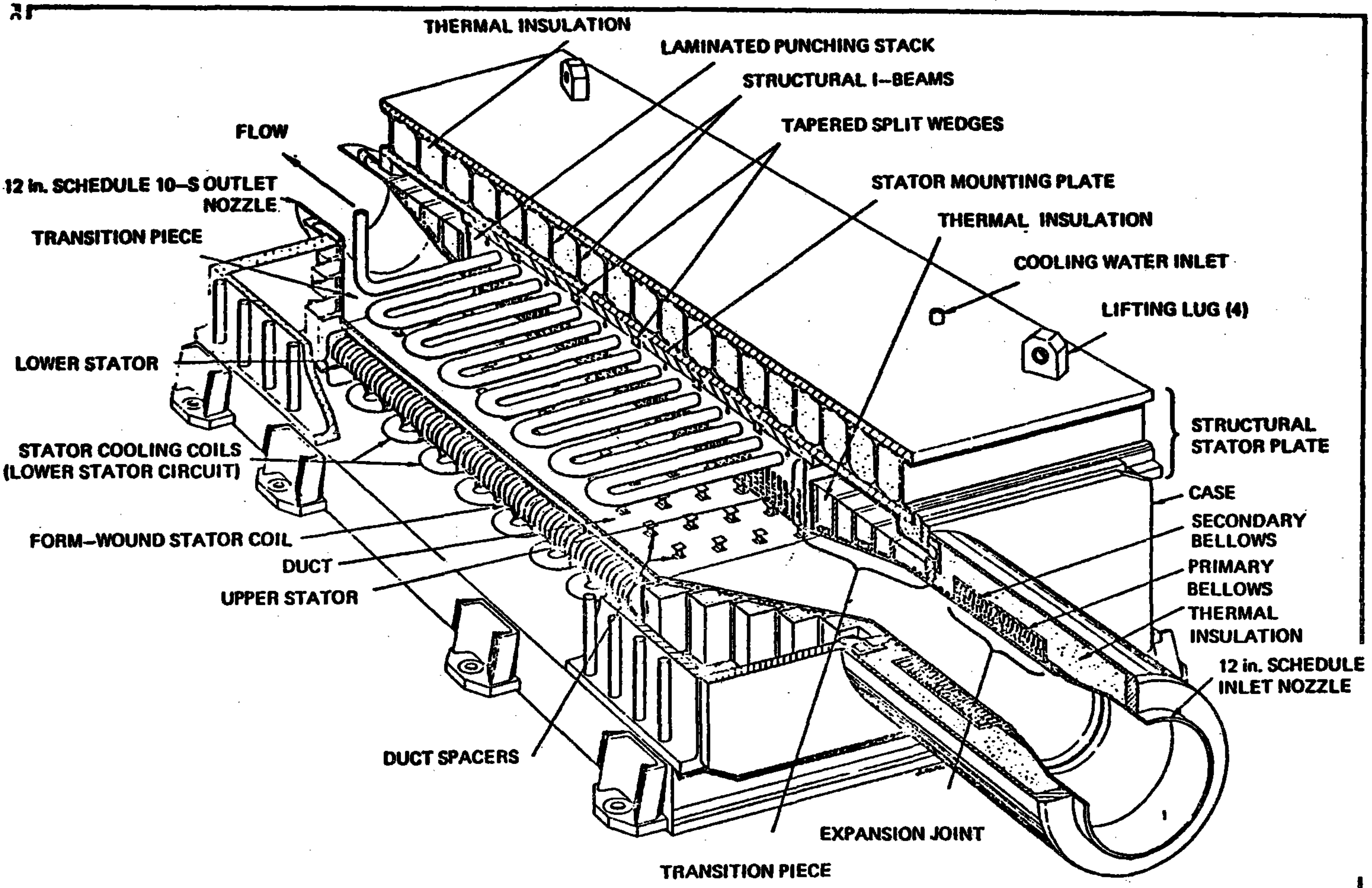
For small, low-cost, laboratory or test loop pumps, it is convenient to generate current outside the pump and pass it through the sodium by conducting it through the walls of the duct. This can be done by attaching bus bars to the duct, but since large currents at very low voltage are desired, the resistances must be kept extremely low. These types of pumps are conduction pumps. High currents present problems in large conduction pumps [∿500,000 amperes at 6.3 m^3/s (10,000 gpm)], so high-capacity units are usually of the type where current is induced in the fluid directly by the action of a time-varying magnetic field.

Within the group of pumps called induction pumps, the duct may have different shapes. The two shapes which have been developed and employed most often are flat and annular.

The basic principle of operation of a linear induction electromagnetic pump is the same as that of a polyphase, squirrel cage induction motor. In an induction motor, a moving magnetic field is produced by a distributed polyphase winding, wound on the inner periphery of a cylindrical magnetic structure (stator). The rotating field induces a voltage in conductors imbedded in the outer periphery of a second cylindrical magnetic structure (rotor). Interaction between the magnetic field and the currents resulting from the induced voltages produces a force on the magnetic structure of the rotor. Since the configuration is cylindrical, these forces produce a torque on the rotor.

1. Flat Linear Induction Pump — FLIP

In a flat linear induction electromagnetic pump (FLIP), shown in Figure 2, the stator structure is similar to that of a motor except that the windings are distributed in a flat rather than a cylindrical magnetic structure. Therefore, the motion of the field is linear (in a straight line) rather than circular



(Ref. GE Report GEAP-13965)

Figure 2. Secondary FLIP Pump

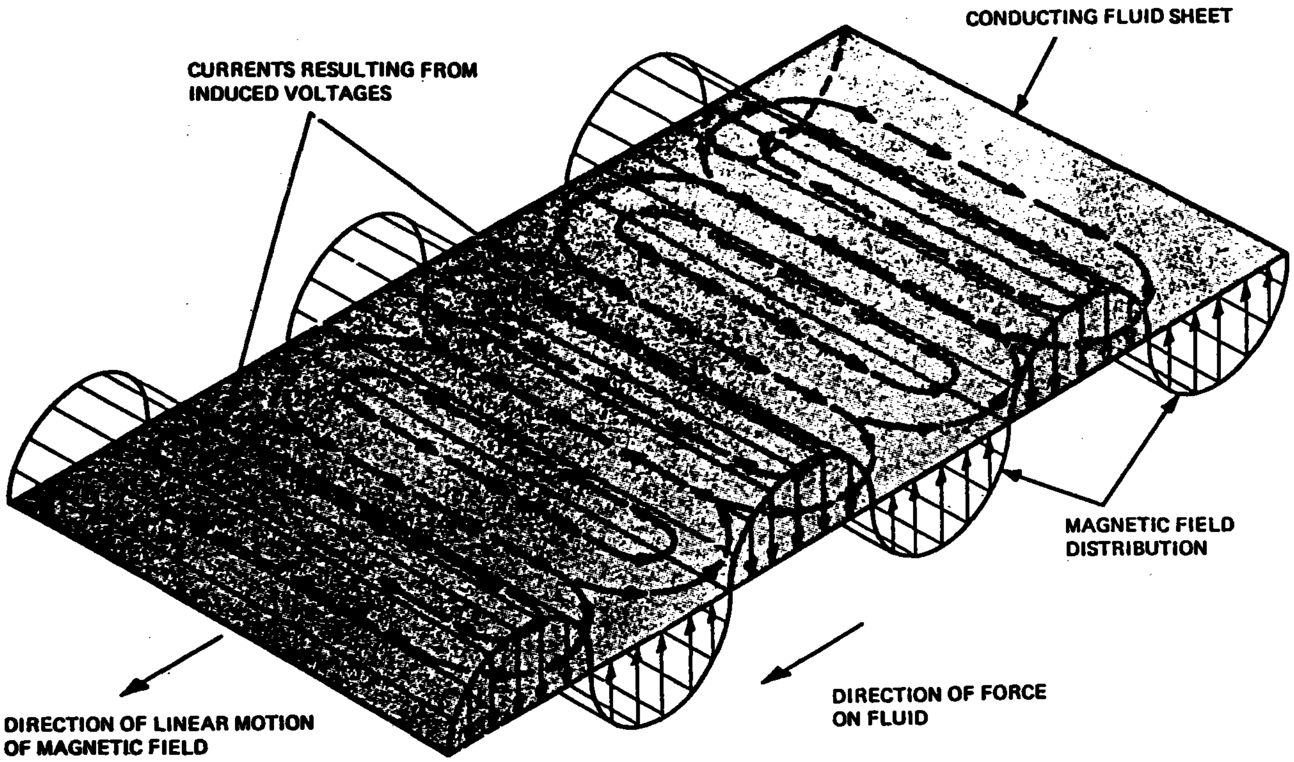


Figure 3. Principles of Operation — Linear Induction Pump

(revolving) as in a motor. The rotor is replaced by a layer of conducting fluid confined in a metal envelope of rectangular cross-section (pump duct). Voltages are induced in the fluid, and interaction of the resulting current with the field produces a force on the fluid. The integrated effect of this force along the length of the duct is the pressure developed by the pump. These principles are illustrated in Figure 3.

In FLIP design practice, two stator structures are used. These are placed on opposite sides of the layer of conducting fluid and connected so that the fields produced are additive. Note (Figure 3) that the induced currents flow across the duct perpendicular to the direction of the linear motion of the magnetic field. To complete their paths, the currents must flow for a short distance (one pole length, maximum) parallel to the direction of magnetic field motion. Some gain in efficiency is afforded by providing a low resistance path, such as a copper bar for these edge currents, but its attachment is a difficult design problem in practice, under the action of thermal shocks, and this feature is often omitted.

2. Annular Linear Induction Pump — ALIP

The required orthogonal relation of flux and current can be preserved in round and annular shapes. Flow in the annulus can be axial, helical, or tangential.

Figure 3 shows an arrow in the "direction of linear motion of magnetic field." If one imagines this arrow as an axis and rolls the flat duct into a thin, cylindrical annulus surrounding the axis, the result is the annular linear induction pump (ALIP) duct (Figure 4). The induced currents have circular paths in the sodium annulus and the currents flow in planes perpendicular to the axis. Current flow parallel to the axis is not present as it is in the FLIP.

Axial flow is used in the ALIP or annular linear induction pump. This pump was the subject of a patent filed in Germany in 1936 by Albert Einstein and Leo Szilard. The magnetic iron is laminated radially. This is convenient in the stator outside the annulus, where radial spaces between groups of punchings provide convenient channels for gas cooling the electric coils, but is complicates

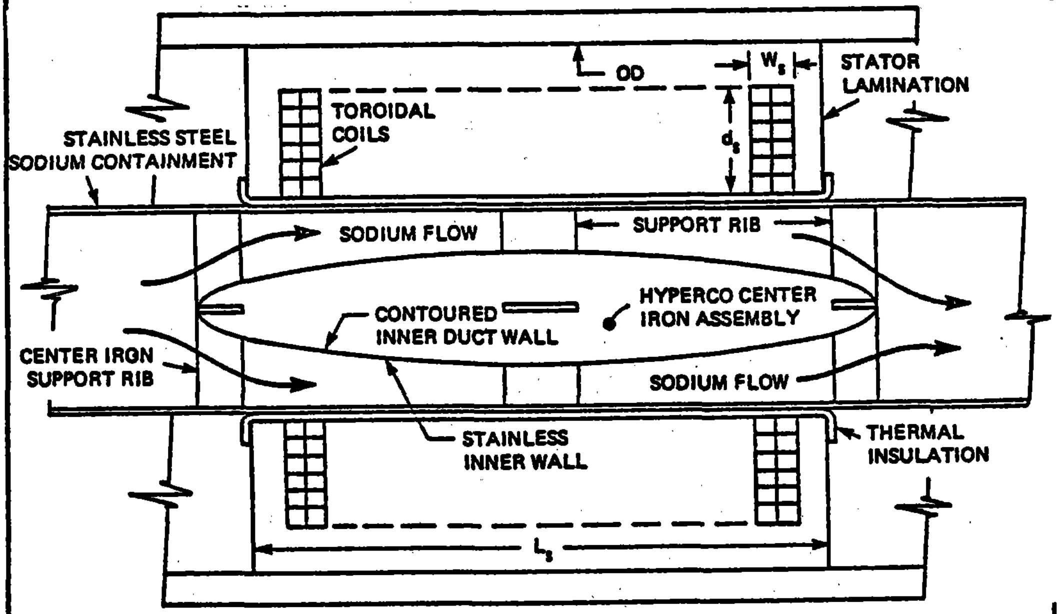


Figure 4. ALIP Conceptual Configuration ("Straight-Thru"Flow) (Ref. GE Report GEAP-13965)

the magnetic lamination structure inside the annulus. The electric coils of the ALIP are of uniform size, spirally wound, and shaped like a slice of canned pineapple. The currents induced in the sodium flow in circles concentric with the pump axis.

The larger the capacity, the more attractive the ALIP pump. As the diameter of the annulus increases, more space is available for coils and punchings inside the annulus. In small ALIP pumps, there is space for only the outer coils. This is analogous to a FLIP pump with a stator winding on only one side of the duct. The output of a given pump is less with one stator than two due to the greater magnetic leakage flux. Also, the slots in two stators can be smaller than would be required in the same capacity pump designed for a single stator, thereby reducing magnetic reluctance and leakage and producing improved power factor.

3. Annular Duct — HIP

Spiral flow through the annulus is used in the HIP or helical induction pump. The stator winding is of the same construction as for three-phase induction motors. The stator induces currents which flow in the sodium parallel to the pump axis. At the ends of the stator, the currents must flow circumferentially one pole width to their return path under the adjacent magnetic pole.

The interaction of the induced currents with the magnetic field causes the sodium to rotate tangentially the same as an induction motor rotor rotates. No net pumping action is produced so a spiral vane (or vanes) is provided in the annulus. The vanes cause the sodium to literally screw itself along the annulus at a rate determined by the rotational speed of the sodium and the pitch or helix angle of the spiral vane(s). Appropriate choice of helix angle allows a wide variation in the ratio of pressure to flow in the same annulus excited by the same stator. However, the HIP is usually applied where ratios of developed pressure-to-flow are much higher than required in LMFBR main heat transport systems.

Once the sodium has passed through the annulus in either HIP or ALIP pumps, it may take one of three paths. First, it may be ducted to the exit pipe directly by either a tapered axially oriented conical section as illustrated in

Figure 4, or collected in a toroidal section and fed to a tangential pipe nozzle. Or, if desired, the sodium can be returned to the entrance end of the pump through a central pipe coincident with the axis of the pump (see Figure 5). The pipe runs through a hole provided in the core magnetic laminations on the inside of the sodium annulus. This is possible because the flux return path stays near the outer circumference and the center is not needed for the magnetic circuit. In induction motors, this space is occupied by the shaft.

In the HIP, a third possibility is to return the sodium to the inlet end of the pump through a second annulus, adjacent to the first, with helical vanes at a negative angle with respect to the first pass. This is an appropriate design for very high ratios of pressure to flow, and is not possible in the ALIP.

4. Performance Characteristics

Typical pump curves for the FLIP and the SLIP "straight thru" and "center return flow" pumps are given in Figures 6, 7, and 8. It is to be noted that these pumps exhibit a raising head-flow characteristic up to nearly 100% design flow.

5. Advantages of EM Pumps

The principal advantages of the EM pumps are: (1) they have no moving parts and should, following the development period, exhibit a high reliability and a long life; (2) they do not require a penetration of the pressure boundary and do not require rotating seals or a cover gas; and (3) they have good control characteristics from 0 to 100% at full flow in systems with a predominant dynamic head-flow characteristic.

6. Disadvantages of EM Pumps

The principal disadvantages of EM pumps are:(1) a relatively low pump efficiency; and (2) the requirement that the pump throat section must be kept warm during shutdown, to keep from freezing the sodium in it, and simultaneously the stator must be kept cool to protect the winding insulation; (3) a drained pump risks burn-out of the pump throat section if the power is inadvertently turned on; and (4) EM pumps tend to have a raising head flow characteristic when the flow is somewhat less than the design point.

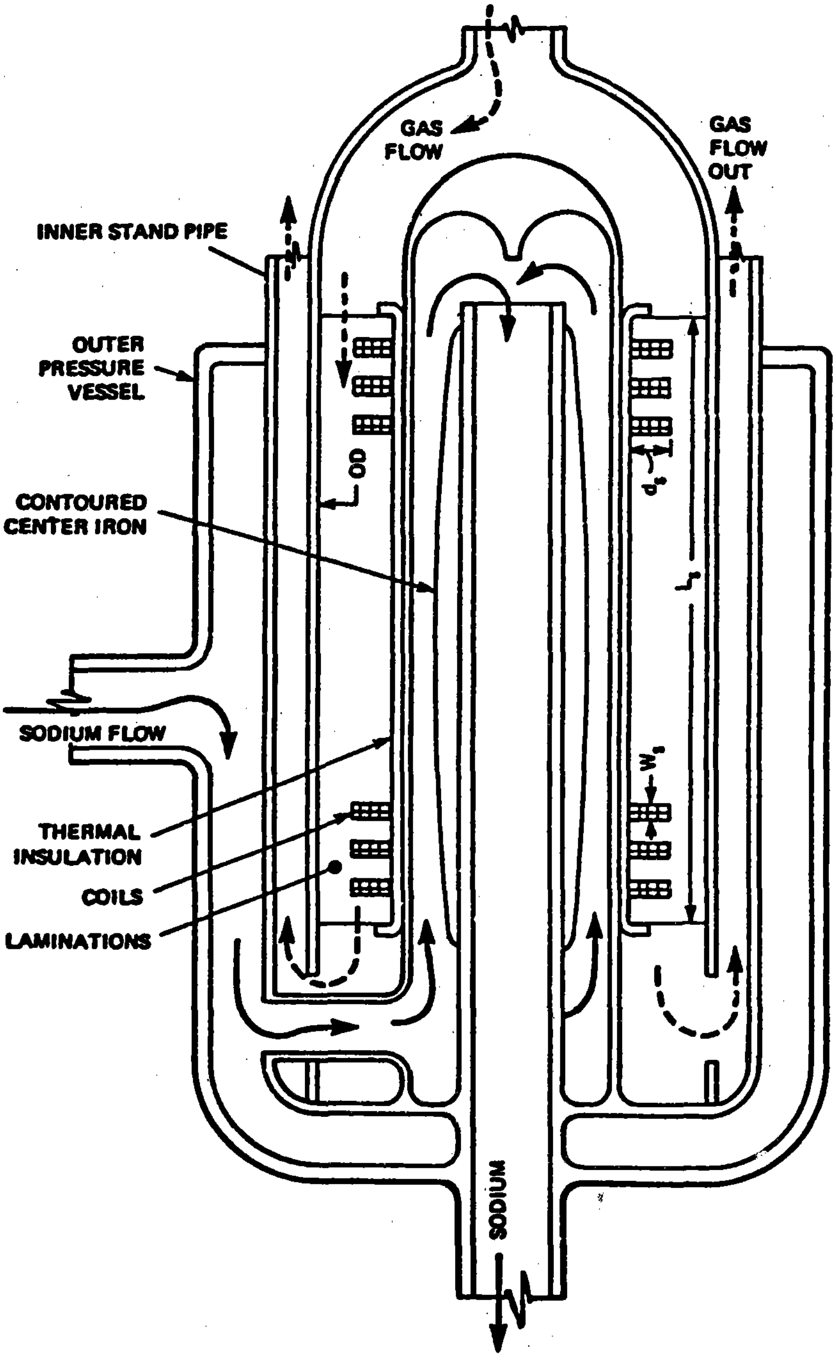
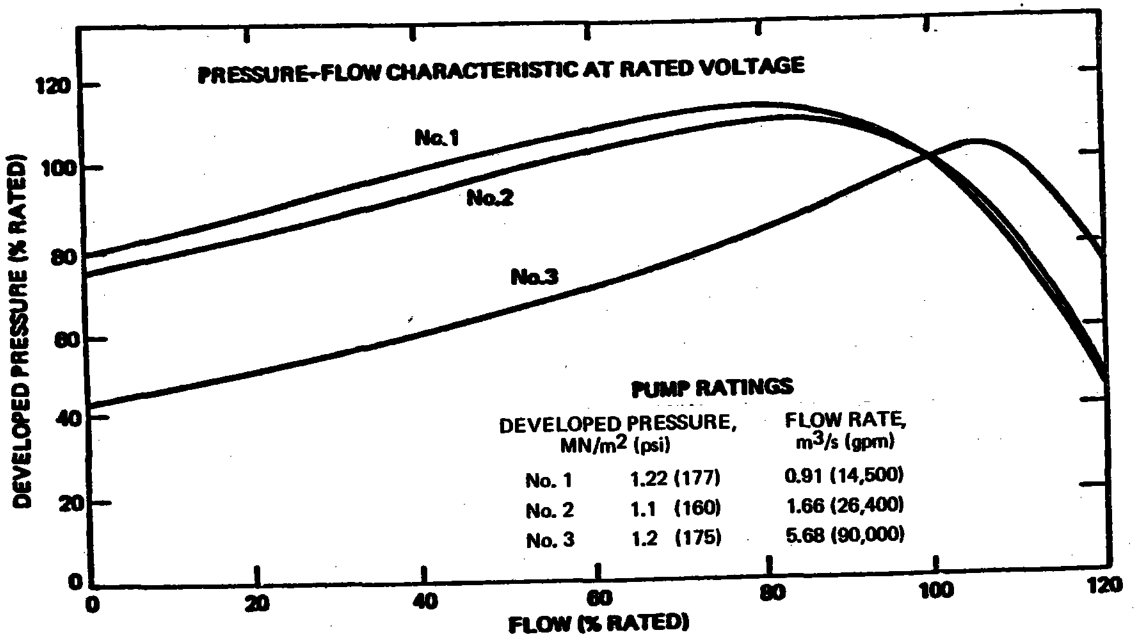


Figure 5. ALIP Conceptual Configuration Design (With "Center-Return" Flow)



	DEVELOPED PRESSURE, MN/m2 (psi)	FLOW RATE, m3/s (gpm)
No. 1	1.22 (177)	0.91 (14,500)
No. 2	1.1 (160)	1.66 (26,400)
No. 3	1.2 (175)	5.68 (90,000)

Figure 6. Flat Linear Induction Pump Pressure Flow
Characteristic at Rated Voltage
(Ref. G.E. Report GEAP - 13965)

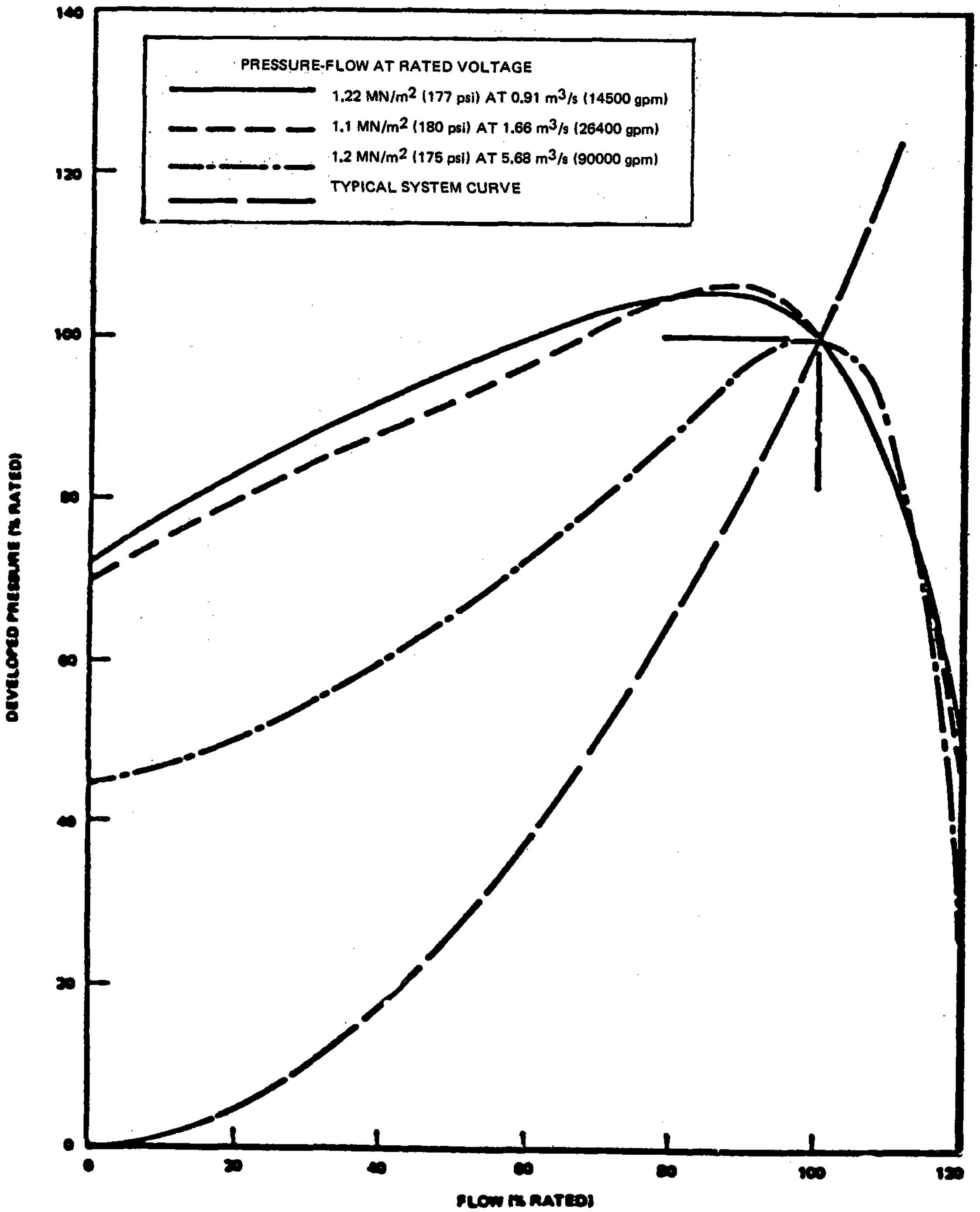


Figure 7. Annular Linear Induction Pump With "Straight Thru" Flow — Preliminary ALIP Designs

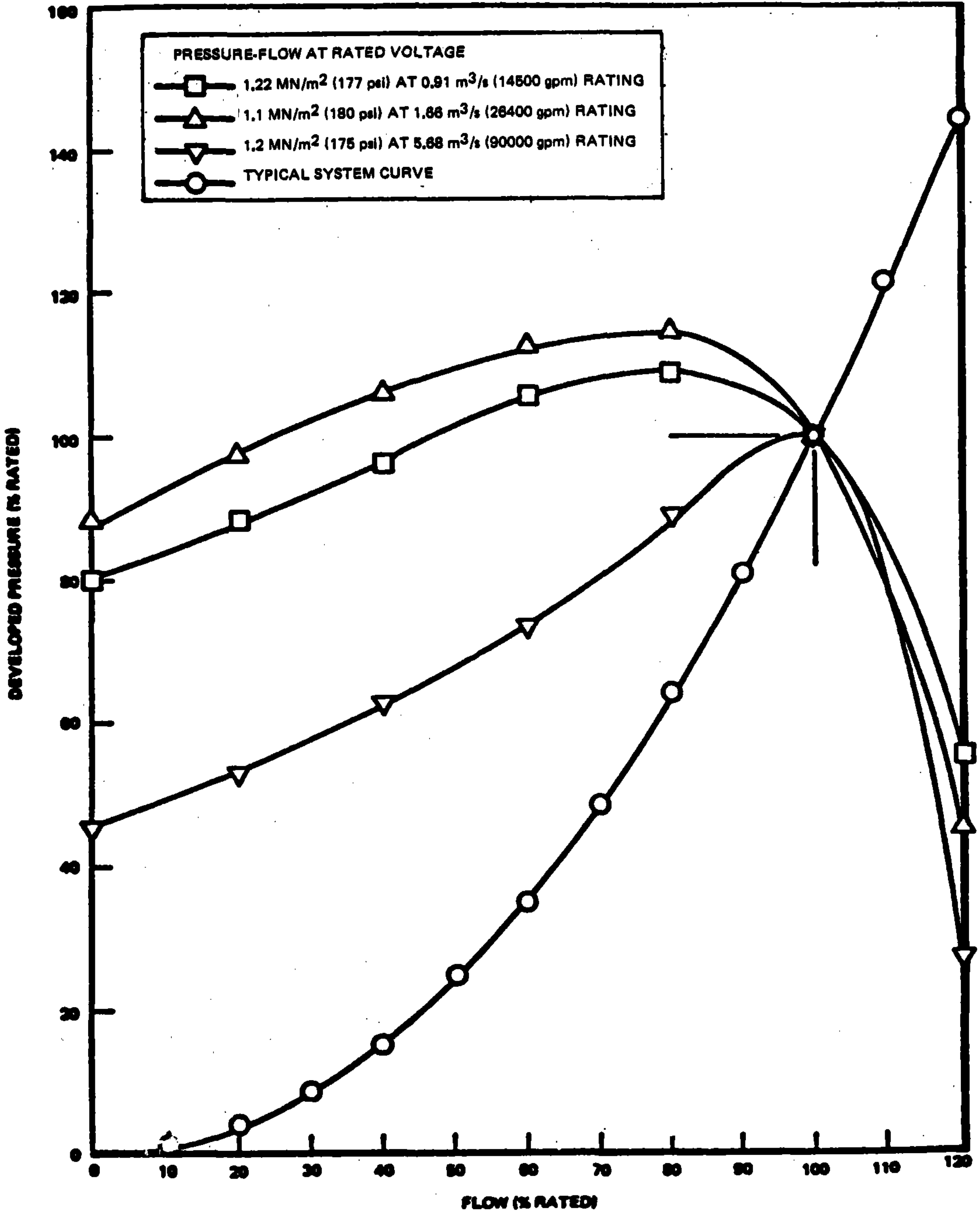


Figure* 8. *Annular Linear Induction Pump With "Center Return Flow" — Preliminary ALIP Designs

IV. MECHANICAL PUMPS DESCRIPTION AND PRINCIPLES OF OPERATION

Large sodium systems nearly always use centrifugal pumps for the main pumps and EM pumps for auxiliary services where pumping efficiency is not important. A typical pump for application to sodium systems is shown in Figure 9. The basic centrifugal pump theory, key components, and manufacturing techniques are similar to water pumps. One distinct difference is the requirement to provide a cover gas over the free surface of the sodium which is passive with respect to sodium and the materials of construction. (The cover gas is usually either argon or helium.) To conserve the cover gas and to preclude air from the pump ullage, a rotating shaft seal is required. The hydrostatic radial bearing that is used in these pumps is similar to those used successfully on water cooled nuclear reactor main circulation pumps. About one-half of the sodium that flows through the bearing flows into the pump barrel; the other part flows back to the backside of the impeller. Sodium pumps are normally designed to permit the rotating parts to be removed from the pump casing without cutting into the system which is the reason for the separate center barrel, fixed into the system, and the removable inner barrel which supports the rotating parts and the radial bearing. This removal feature necessitates a slip seal (labyrinth case seal, shown in Figure 9) between the high pressure plenum and upper part of the barrel which is at low pressure. Some sodium flows through this seal and adds to the sodium flowing from the bearing. This tends to fill the pump upper barrel. Pressuring the gas space over the sodium forces the sodium through the overflow connection back to the sodium supply tank.

A. ADVANTAGES OF MECHANICAL PUMPS

The principal advantages of the mechanical pumps are: (1) they have the highest pumping efficiency of any known alternative; (2) the technology is very well developed; (3) there are many proven design options which permit the pump characteristics to be closely fitted to system characteristics; and (4) the control characteristics of these pumps can be well matched to the system requirement.

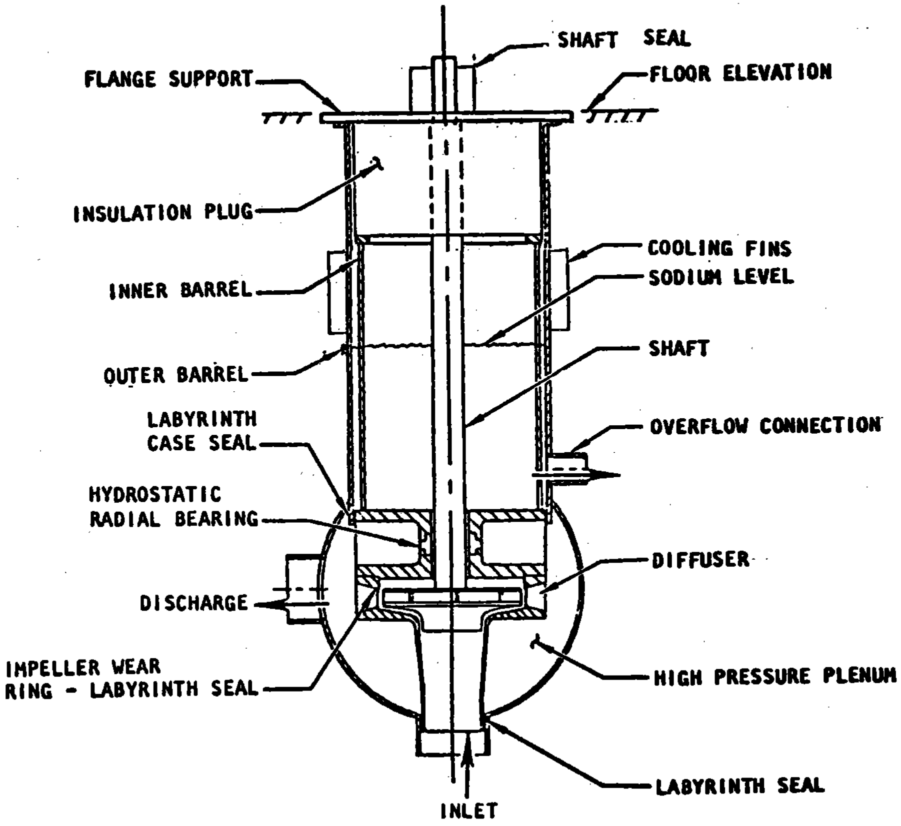


Figure 9. Typical Centrifugal Pump for Sodium Systems

B. DISADVANTAGES OF MECHANICAL PUMPS

For sodium systems, the disadvantages of mechanical pumps are: (1) they are subject to the usual problems of rotating equipment, rubbing, shaft binding and vibration; (2) they require a controlled free surface; and (3) they require a inert cover gas and a shaft seal where the shaft penetrates the pressure boundary.

V. APPLICATION OF EM vs MECHANICAL PUMPS

A. ADVANCE CENTRAL RECEIVER SYSTEM

The receiver pump (P-1) must provide a high static lift (92% of the total head) plus the normal dynamic head loss. This requirement is illustrated in Figure 10, which shows the system curves together with typical curves for EM and mechanical pumps. As can be seen from the curves for the EM pumps, the raising head flow characteristic tends to make the flow unstable as the trim valves close. (See Section III, Paragraph A-4 and Figures 6, 7, and 8.) For the mechamical pump, which has a falling head flow characteristic, the system is self regulating and the flow is stable.

For systems with a high static lift characteristic, variable speed pumps are not recommended for flow control because of the flat intercept between the pump curve and the system curve, the good flow control characteristics of the EM pump cannot be exploited for the P-1 pump application. See Paragraph III A-5

For the mechanical pump, the high head requirement can be achieved by using a two stage centrifugal pump.

The requirements on the Steam Generator Pump (P-2) are more conventional. Since 80% of the head is dynamic head, and flow control is required of this pump, the EM pump is more attractive in this application than it is for the receiver pump application.

VI. RELIABILITY COMPARISON

In Reference 3, p 30, if one uses the GEAP estimate for the mechanical pump and the current estimate for EM pump, p 31, then the mechanical pump appears to

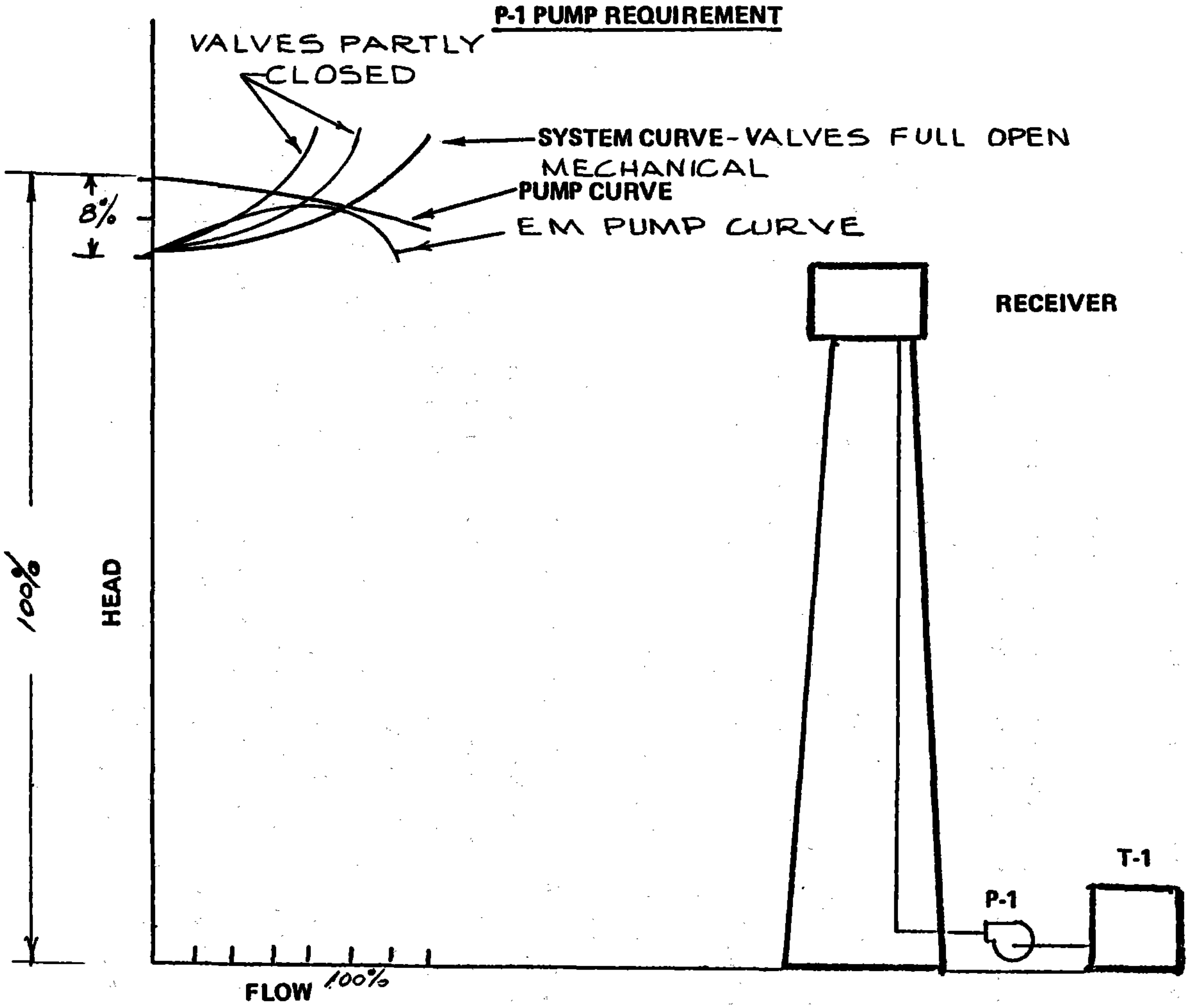


Figure 10. Receiver Pump Head Flow Requirement

be more reliable. If one takes the "Scientific Associates, Inc." estimate vs the GEAP estimate, then the EM pump is the more reliable. Taken either way, the relative reliability is within a factor of two which is not significant for this state of the design. The conclusion is that within our ability to estimate this quantity, the reliability factor is equal for both pumps.

VII. MAINTENANCE COMPARISON

No significant advantage has been found in terms of failure rates or repair times which would favor either pump.

VIII. ECONOMIC COMPARISON

Usually the five aspects of pump costs which are considered in pump economics are: (1) capital cost of the pump; (2) capital cost of the plant to provide the additional capacity to power the pump; (3) cost of the power used by the pump; (4) cost of plant downtime caused by pump failures; and (5) pump maintenance costs.

1. CAPITAL COST OF THE PUMPS

Reference (2), p 77, claims that the mechanical pump cost is approximately one-half to two thirds the cost of the EM pump. Reference (3), p 33H, claims a 23% advantage for the EM pump in the 4.1 m^3/s (67,5000 gpm) size. My assessment of the data given on p 33G, scaling down the cost of the 2.12m^3/s (33,700 gpm) CRBRP pump to 0.91m^3/s (14,500 gpm), gives about the same price for the EM and mechanical pumps (using a 0.6 scaling law). I conclude that, within our ability to estimate, the cost of the EM pump approximates the cost of the mechanical pump, if both pumps are made of the same materials. This is the same conclusion reached in Reference 4. Since we plan to make the P-1 pump out of mild steel, we expect to save at least the difference in the cost of the materials. Thus for the receiver pump the mechanical pump cost should be lower.

For the steam generator pump, P-2, both pumps must be made of stainless steel and the two pumps should cost about the same.

2. CAPITAL COST OF THE PLANT TO PROVIDE THE ADDITIONAL CAPACITY TO POWER THE PUMPS

Since pumps return energy to the system, this factor was considered in the analysis.

From Reference 1, p 2-14, the pump drive (M.G. set equipment) efficiency is given as 0.91. Page 3-13 (ibid) gives a 45% pump efficiency at the best efficiency point (B.E.P.), thus the overall efficiency is 40%. This requires 7.75 MW of electrical power be delivered to the pump. 2.1 MWe is recovered from the fluid energy input. From Reference 5, p 3, the mechanical pump efficiency is 82%, the motor efficiency is 95%. Thus, the overall efficiency is 78%. This requires 3.9 MW of electrical energy to the pump. The recovery is 1.47 MWe. The net difference is 2.95 MW electrical. This is 2.6% of the plant gross capacity.

The increase in plant size to accommodate this extra power, scaled to the 0.8 power, gives an increase of capital investment of \$2.42 x 10^6 for the P-1 pump and \$0.346 x 10^6 for the P-2 pump. The associated present worth of these two amounts is \$4.1 x 10^6 for the P-1 pump and \$0.59 x 10^6 for the P-2 pump.

3. COST OF THE POWER USED BY THE PUMP

Since there is no fuel charge in a solar energy system, the consumption of electricity difference cost was considered to be insignificant.

4. COST OF PLANT DOWNTIME

The Difference in the cost of plant down-time caused by the different pumps was considered to be negligible.

5. PUMP MAINTENANCE COSTS

The maintenance cost of the two pump types was determined to be approximately equal.

IX. REFERENCES

1. Collins, G. D. "Development of Large Electromagnetic Pumps for Main Heat Transport Systems of LMFBR's," GEAP-13965, June 1973

2. Brunings, J. E. and Larson, E. M. "PLBR Main Circulating Pump Type and Location Selection," AI Document N222TSR310001, March 29, 1976

3. General Electric Co., "Large EM Pump Program Review," January 23, 1976, ERDA-RDD Headquarters, Germantown, Maryland

4. Morabito, J. J., to Thorne, R. D., "Large EM Pump Development," 189 No. SG012; Report on Meeting of January 23, 1976 at ERDA, Germantown, Maryland

5. Pfouts, J. O. to Frangos, A. Z., Internal Atomics International Letter, "Preliminary Size and Cost Related Information for Pumps for a Solar System," dated January 16, 1978

APPENDIX K

PIPE ROUTING STUDY OF SODIUM DOWNCOMER

AI Technical Information

Document N272T1000001

APPENDIX ~~J~~K

Rockwell International
Atomics International Division

SUPPORTING DOCUMENT

NUMBER N272TI000001

REV LTR/CHG NO. SEE SUMMARY OF CHG

DOCUMENT TYPE Technical Information

KEY NOUNS Piping, Pipe Supports, Snubbers, Expansion Devices

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Conceptual Design of Advanced Central Receiver Power Systems

DOCUMENT TITLE
Pipe Routing Study of Sodium Downcomer

PREPARED BY/DATE W. J. Hughes/1-26-78 DEPT 731 MAIL ADDR LB14

W. J. Hughes

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APPROVALS DATE

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ABSTRACT

Four piping configurations were developed and studied to determine the simplest routing for a 20-in. sodium downcomer line from the receiver at 900 ft above grade to the hot storage tank at grade.

CONTENTS

CONTENTS
(continued)

STATEMENT OF REPORT

Given:

A single run of 20-in. A452, TP304H pipe with a fixed anchor at 900 ft above grade and the other end at grade. The operating temperature is 1100°F. The piping will be conventionally supported from an existing structure that will impose no unusual loadings on the pipe. There is no wind loadings on the pipe.

Find:

The simplest routing for the piping.

Data:

Allowable Stress S_A = 21,600 psi
Free End Expansion = 155.56 in. (9 ft - 7-1/2 in.)

INDEX OF TYPES

Type I:

Multiple U shape with equal tangents (Sketch 1).

Type II:

90^{0} turn (Sketch 2).

Type III:

Single tangent with multiple U bends at grade (Sketch 3).

Type IV:

Straight through with expansion device (Sketch 4).

SUMMARY

All four types are suitable for the intended purposes.

Type IV is the simplest routing for the piping, but it requires the use of a high-price expansion device.

Type II is a simple pipe routing. It requires about 15 compliance supports. These could be counterweight hangers. The cost will depend on a detailed study of a reference hanger design.

Type III is a little more complicated than Type II but it has the advantage of occupying less floor space and using fewer snubbers. It could also be rerouted to fit the contour of a 150 ft diameter building.

Type I is the most complicated pipe routing. It uses the more common pipe fittings and supports; therefore, it would be the easiest to set its construction cost. It could be used as a basis for evaluating the other types.

MAINTENANCE

All the piping will require access maintenance the full height of the tower with platforms at frequent intervals (30 ft). The rigging supports used for construction should be left in place for major maintenance.

The frequency of maintenance will vary. Type I should require only the visual inspection for leakage and hanger engagement.

Types II and III will require additional checks to insure movement of compliance supports.

Type IV will require instrumentation to indicate movement.

ENGINEERING

Type IV will require testing and qualifying of the bellows component. If a detailed stress analysis of the bellows is required, this cost could be an open end item.

Types II and III will require design evaluation of the compliance supports. The space, structure, and mechanical devices required for free movement of the pipe and pipe supports will have to be developed.

Type I will not require any special engineering studies.

CONCLUSION

There are more types and variations of piping arrangements than the four discussed in this report. But within the limitations of these four I would recommend the multiple U shape with equal tangents (Type I). It is the highest in piping material costs, but this would be more than offset by lower engineering and maintenance costs. It is the highest in normal operating costs, but it would also be the most reliable.

The 90^0 turn (Type II) and the single tangent with multiple U bends at grade (Type III) are roughly equivalent. The only reason I do not recommend either of them ahead of the Type I is because of some doubt as to the reliability of the counterweight supports.

The straight through with expansion device (Type IV) would encounter the usual resistance and analysis costs associated with all bellows.

TYPE I

Type I is the most conventional configuration from a pipe routing standpoint. It is similar in design to the high-temperature steam piping used in petro-chem and large process plants. The principal difference is the steam piping is usually in a horizontal plane. The Advanced Central Receiver (ACR) downcomer is principally in a vertical plane. This does not effect the thermal loadings, the anchor locations, or the restraint locations, but it does effect the weight supports. The steam piping lateral restraints are the weight support elements. The ACR downcomer weight can be carried by the anchors and rod supports at points of zero vertical movement (see Sketch 1).

The distance between anchors and the U shape can be optimised to give the best support arrangement. The configuration can be altered to follow the tower support structure. Rod supports and anchors require minimum maintenance.

Reference Design

Distance between anchors = 90 ft

Offset of U bend = 25 ft

This configuration had a maximum stress of 19,353 psi and required only rod hangers and anchors for weight support.

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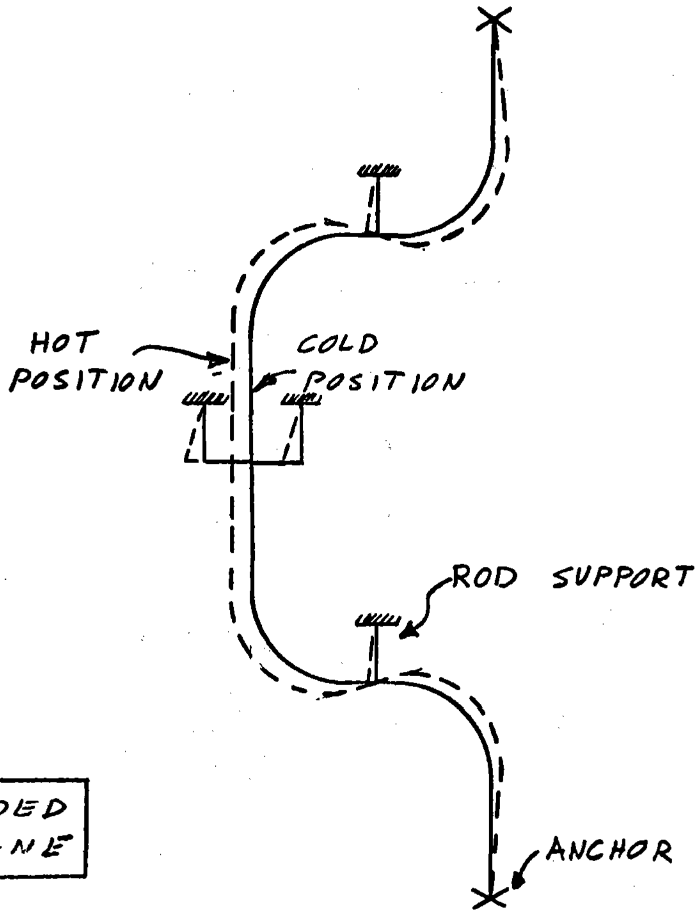
TYPE I - SUPPORT DIAGRAM



RIGID GUIDED OUT OF PLANE

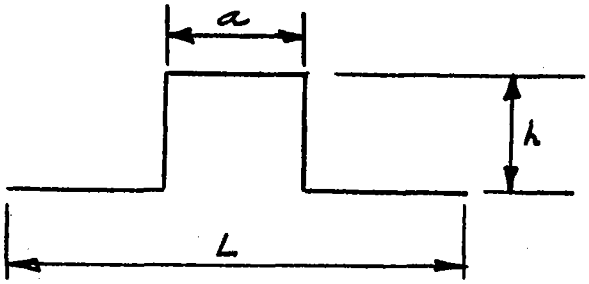
SKETCH 1

M 157-R-2 REV 8-73

Type I

(Ref. Grinnell - Piping Design and Engineering)

U Shape with equal tangents



Maximum Bending Stress, $S_B = k_b \, c \, \frac{D}{L}$

assume $S_B = 20{,}000$ psi

$D = 20''$

$c = 2036$

$$\frac{L}{k_b} = \frac{c\,D}{S_B} = \frac{2036\,(20)}{20{,}000} = 2.036$$

$$\text{If } L = 90': \quad K_b = \frac{90}{2.036} = 44.2 \begin{cases} L/a = 2,\ \overset{*}{3},\ 4,\ 5,\ 6 \\ L/h = 4.4,\ 3.5,\ 3.1,\ 2.9,\ 2.7 \end{cases}$$

$a = 45, 30, 22.5, 18, 15$

$h = 20.5, 25.7, 29, 31, 33$

TYPE II

This configuration uses less pipe than Type I. There is no penalty in pipe weight even if we assume most of the weight is supported from the top. The problem here is the large pipe movement (approximately 10 ft) at the bend. This will require compliant restraints and supports. This excludes spring hangers and sway braces in the vicinity of the bend. The design of roller restraints and counterweight supports present no special problem. The analysis and maintenance of compliant devices would require special consideration.

Pipe rolls are, in general, used in tunnels and enclosed areas. In a controlled environment, they should present no special problems. In an outdoor environment they have been known to freeze up.

The large pipe movements will require an exclusion area. This area will have to be sealed off or monitored to prevent interferences.

Reference Design

Long leg = 900 ft; Short leg = 250 ft

Maximum stress 21,945 psi for an unguided arrangement.

A partially guided arrangement would require a longer "short leg" but should result in an overall cost reduction.

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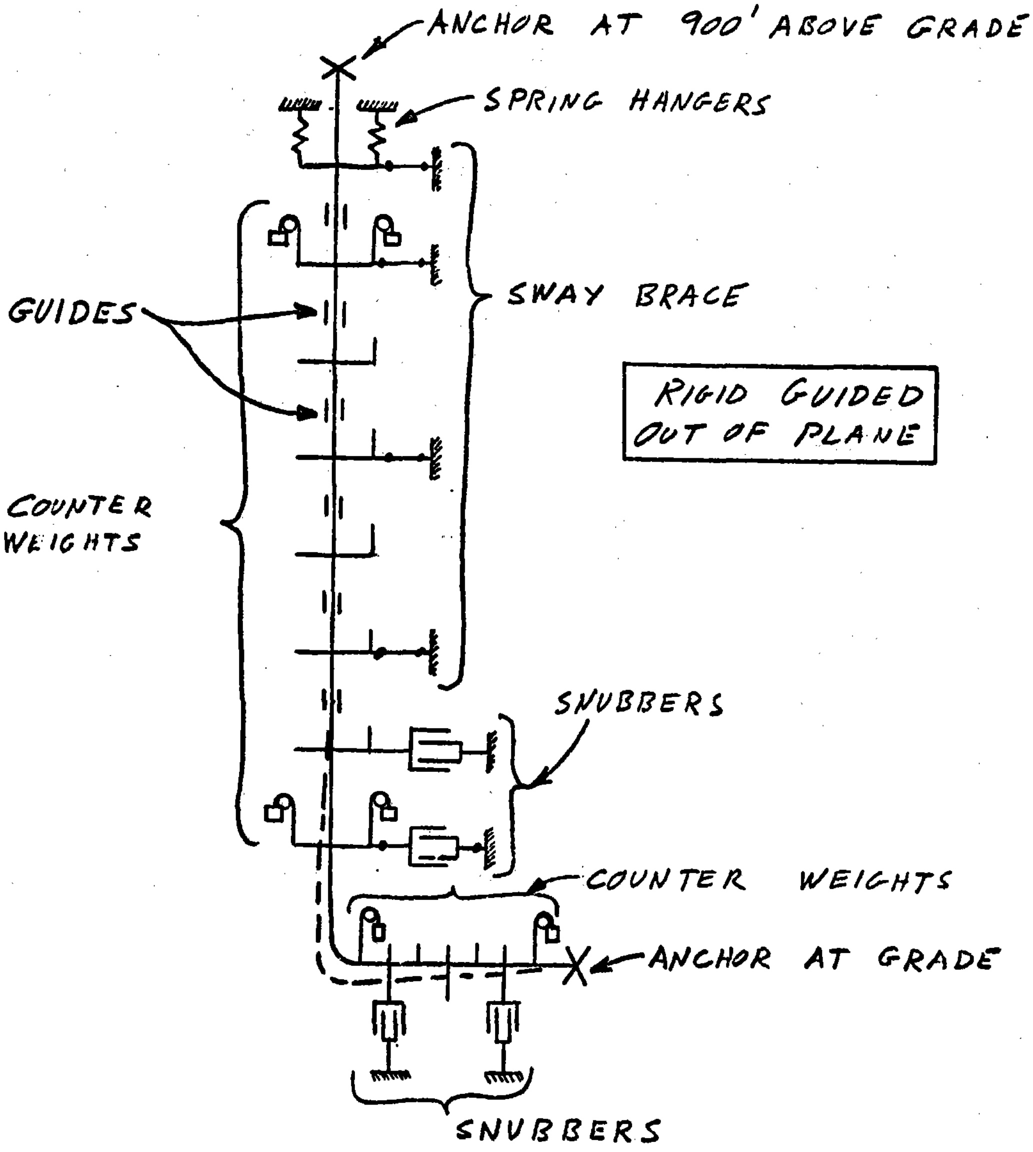
TYPE II - SUPPORT DIAGRAM



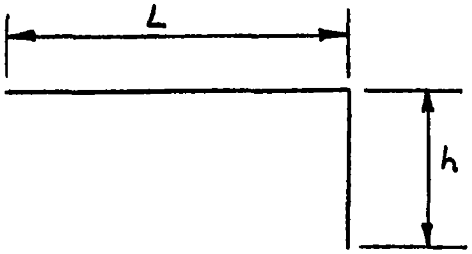
SKETCH 2

N 133-B-3 REV 6-73

Type II

(Ref. Grinnell - Piping Design and Engineering)

90° turn



Maximum Bending Stress $S_B = k_b \, c \, \frac{D}{L}$

Assume $S_B = 20,000$ PSI

$D = 20''$

$c = 2036$

$L = 900'$

$$k_b = \frac{S_B \, L}{c \, D} = \frac{20,000(900)}{2036\,(20)} = 442$$

$4.6 - 456$

$\underline{4.4} - \underline{406}$

$.2 - 50$

$\frac{42}{50} \times .2 = 1.68$

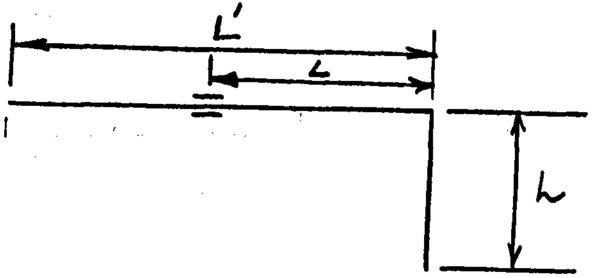
$$\frac{L}{h} = 4.568$$

$$h = \frac{900}{4.568} = 197$$

Use $h = 250'$

Type II

90° Turn, Guided



Maximum Bending Stress $S_B = k_b \, c \, \frac{D}{L}\left(\frac{L'}{L}\right)$

Assume $S_B = 20{,}000$ PSI, $D = 20''$, $c = 2036$, $L' = 900$

$$k_b = \frac{S_B L}{c D}\left(\frac{L}{L'}\right) = .491\left(\frac{L^2}{900}\right) = .000546 \, L^2$$

L	K_b	L/h	h
450	110	2.1	214
225	27	<1	

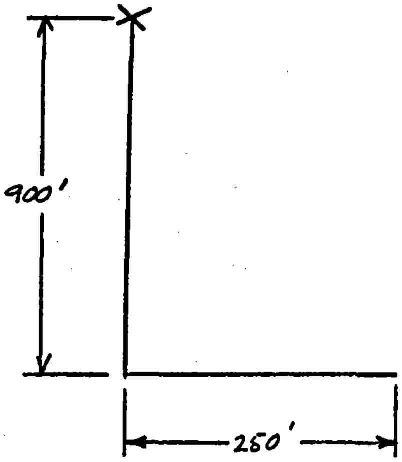
$$S_B = 36(2036)\frac{20}{250}\left(\frac{900}{250}\right) = 21{,}109$$

$$\boxed{\text{Minimum } L = h = 250'}$$

Type II

SUPPORT WEIGHT

① PRESSURE OF 900' COLUMN OF SODIUM



DENSITY AT 212°F = 57.9 #/FT^3

DENSITY AT 482°F = 55.7 #/FT^3

USE DENSITY OF 62.4 #/FT^3

150' = 64.97 PSI

900' = 389.82 Say 400 psi

USE 20" x 0.500" PIPE

WEIGHT = 170.93 #/FT, SAY 200 #/FT

TOTAL WEIGHT = 1150 x 200 = 230,000 #

SUPPORT STRESS = $\frac{230,000}{30.6}$ = 7516 PSI

ALLOWABLE AT 1100°F = 7400 PSI

THIS IS OK IF WE ASSUME 20% OF THE WEIGHT IS CARRIED BY LOWER LEG SUPPORTS.

TYPE III

This configuration is similar to Type II except that it does not require compliant restraints on the tangent but it does require an extra 50 ft of pipe in the U bend and two extra elbows. The comments on restraints and supports for Type II apply to Type III.

Reference Design

A 150 ft offset by 50 ft U shape, guided at 150 ft above grade.

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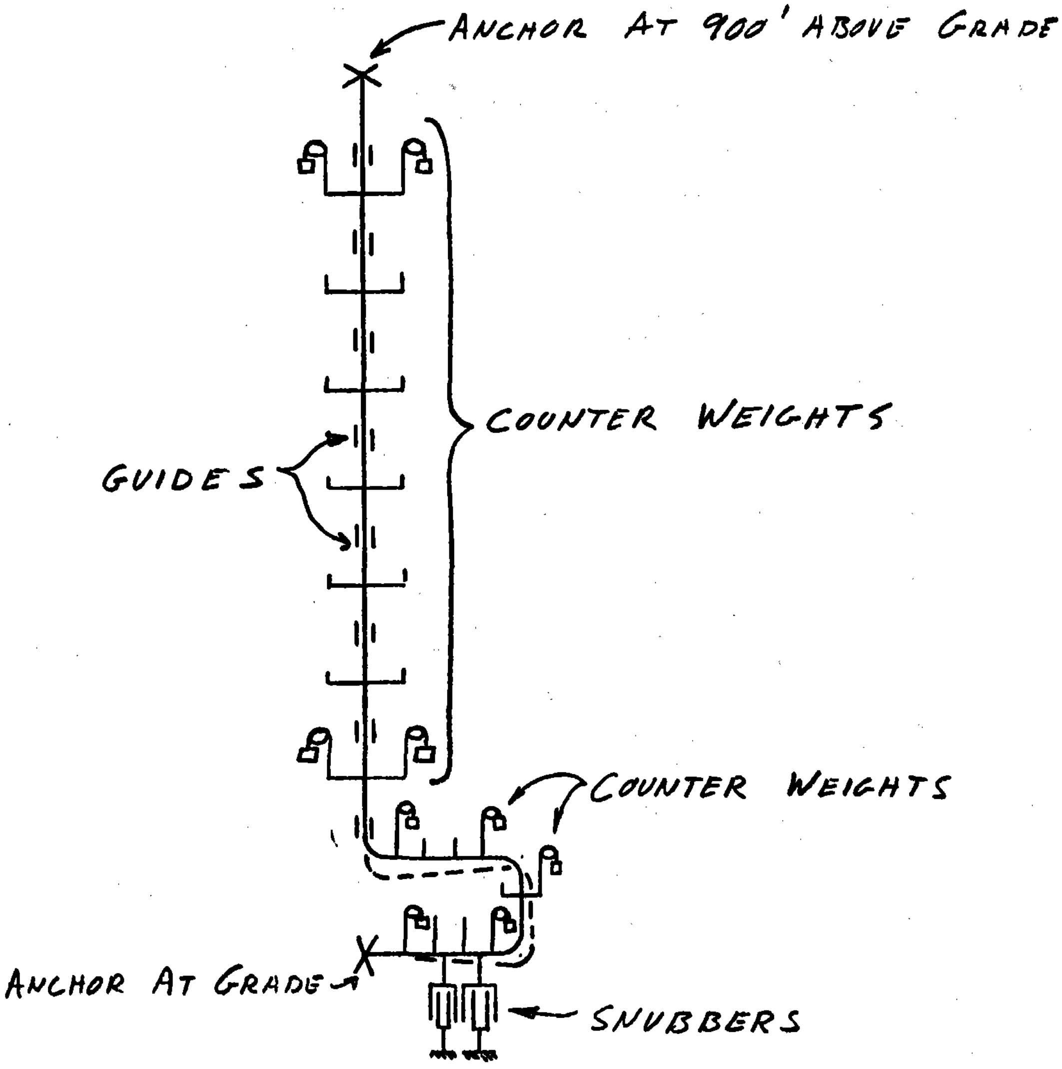
TYPE III - SUPPORT DIAGRAM



SKETCH 3

type III

(Ref. Grinnell - Piping Design and Engineering)

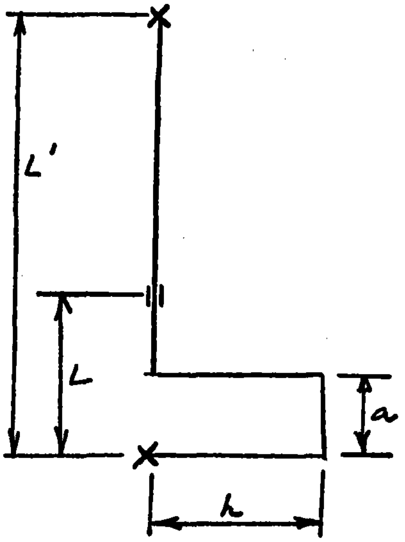
U shape with single tangent

Maximum Bending Stress (S_B)

$$S_B = k_b\, c\, \frac{D}{L}\left(\frac{L'}{L}\right)$$

$$k_b = \frac{S_B L^2}{c\, D\, L'} = \frac{20{,}000\ L^2}{2036(20)\ 900}$$

$$k_b = 0.000546\ L^2$$



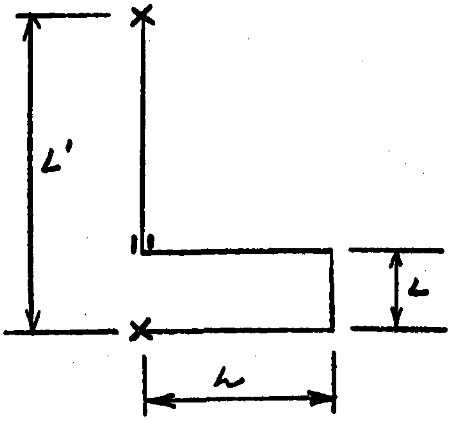
L	Kb	L/a	L/h	a	h
250	34	1.5	2.0	166	125
"	"	2	1.9	125	132
"	"	3	1.7	83	147
"	"	4	1.8	63	138
200	22	4	1.3	50	154
150	12	4	1	50	150

Type III

U shape - equal legs

$K_b = 0.000546 L^2$

L	K_b	L/h	h
100	5.46	0.65	153
50	1.37	0.3	166



TYPE IV

There are two types of expansion devices in general use, a slip joint and a bellows joint. This application would probably use a combination of the two - a slip joint for alignment and side loading and a bellows for pressure loading.

The 10-ft pipe movement presents a special problem. The simplest solution would be to break up this movement into, say, ten one-ft movements. Then, a commercial expansion device could probably be found that would suit this requirement.

Reference Design

Nine units equally spaced.

Axial-movement type expansion joints are quite similar in detail to their counterpart in packed joints, with the substitution of a bellows seal for the packing. When constructed with machined parts, this type of design is obviously expensive and can be justified only for special cases where installed location and general system arrangement make it difficult to achieve effective guiding by other means, or where a large amount of axial movement must be provided and guiding of the bellows assembly against lateral buckling is necessary. With an internal arrangement it is also possible to secure maximum confinement of the bellows against abrupt release of contents, and sometimes an auxiliary packed joint is provided to further minimize this hazard particularly for toxic content services. Sometimes joints of this type are fabricated to reasonably close forming tolerances, without machining; however, without lubrication, binding is much more likely to occur.

TYPE IV

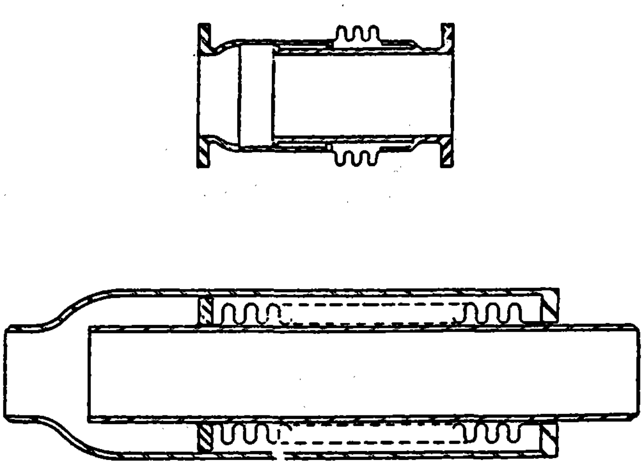


FIG. 7.11 Axial movement type expansion joints.

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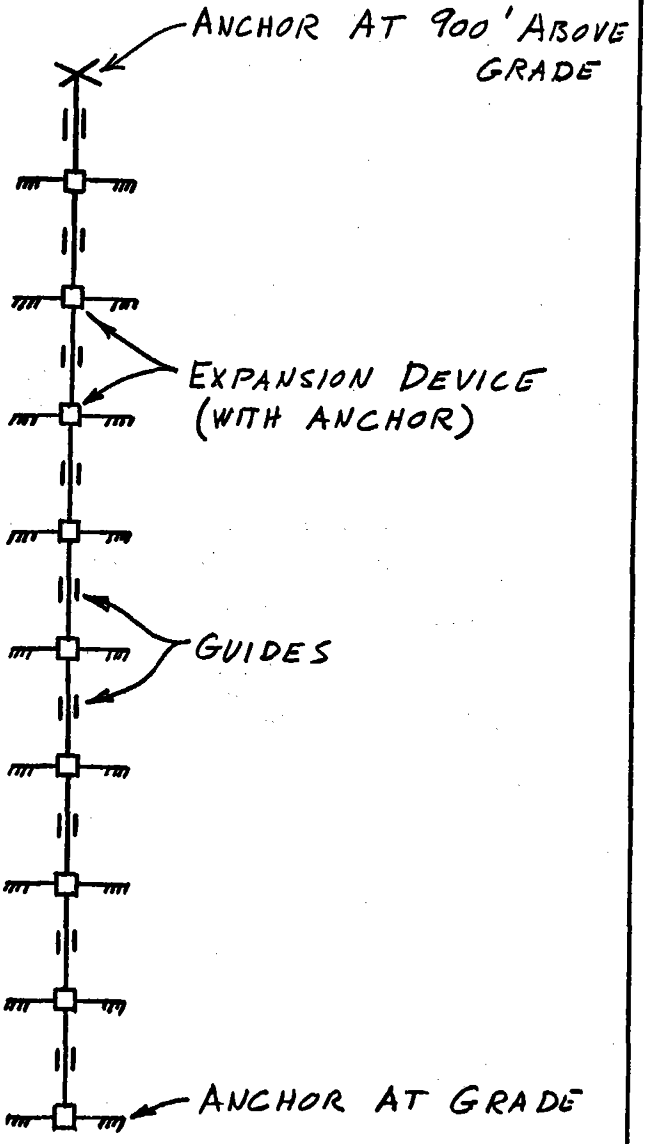
TYPE IV - SUPPORT DIAGRAM



SKETCH 4

N 131-8-2 REV. 6-73

APPENDIX L

SODIUM-COOLED ADVANCED CENTRAL RECEIVER SYSTEM SIMULATION MODEL

AI Technical Information

Document N272TI00000

Rockwell International
Atomics International Division

SUPPORTING DOCUMENT

NUMBER N272TI000006

REV LTR/CHG NO. SEE SUMMARY OF CHG

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KEY NOUNS Advanced Central Receiver Simulation Model

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ABSTRACT

A mathematical model describing the dynamic behavior of the sodium-cooled advanced central receiver power system has been written and used to verify the receiver control methodology and simulate the receiver system under various transients of interest. The control methodology of individual panel control has been verified for controlled situations with receiver mixed outlet temperatures varying less than 8°F over the range of controlled transients examined. However, active heliostat steer-off is required during transients in which the receiver pump trips.

FORM 734-C REV. 11-77

CONTENTS

APPENDICES

I. INTRODUCTION

A. ADVANCED CENTRAL RECEIVER SYSTEM DESCRIPTION

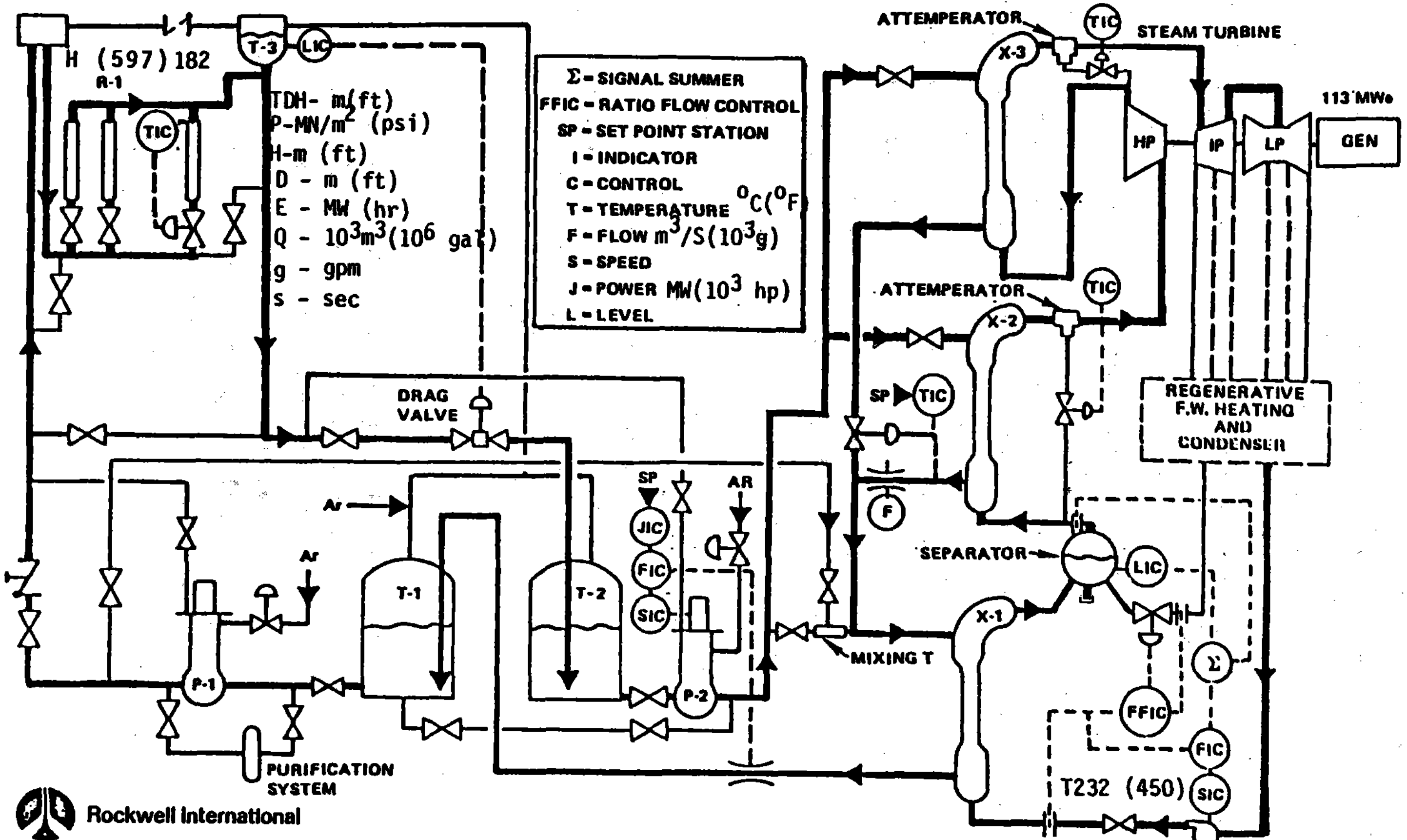
A simplified flow and control diagram of the baseline conceptual configuration of a 100-MWe Sodium-Cooled Advanced Central Receiver Power System is shown in Figure 1. In this system, liquid sodium is circulated from a cold tank (T-1) through 24 panels located on the surface of a right circular cylinder receiver, located on top of a tower, to a hot tank (T-2) by a centrifugal pump (P-1). Sodium is heated in the receiver by solar insolation reflected by a large number of heliostats which surround the receiver tower. From the hot tank, sodium is circulated by a second pump (P-2) through a superheater (X-2) and reheater (X-3), configured for parallel sodium flow, to an evaporator (X-1) and finally back to the cold tank. Under conditions of full solar insolation, the flow through the steam generators (evaporator, superheater, reheater) is about 2/3 of the receiver flow. Thus, 1/3 of the receiver flow accumulates in the hot tank during the day for use at night. Steam, generated by sensible heat released by the sodium in the steam generators, is used to drive a conventional three-stage steam turbine in conjunction with a conventional Rankine cycle. A more detailed description of the sodium-cooled advanced central receiver system is contained in Reference 1.

B. MODEL SCOPE

For purposes of developing a meaningful representation of the Sodium-Cooled Advanced Central Receiver Power System, only the normally active sodium components physically located in the flow stream between the cold and hot tanks, including the cold and hot tanks, are included in the model. The steam generator and Rankine cycle equipment have been previously simulated in various LMFBR programs(2), and their response to a large number of transients is well known. More importantly, the large mass

ADVANCED CENTRAL RECEIVER
(100 MWe)

P-1 RECEIVER PUMP	T-1 & T-2 STORAGE TANKS	P-2 ST.GEN.PUMP	X-1 EVAPORATOR	X-2 SUPERHEATER	X-3 REHEATER
TDH-220 (722)	D - 305 (100)	TDH-76 (250)	T-341(646)	538 (1000)	538 (1000)
F - 1.3 (20)	H - 13.6 (45)	F - 1.0 (15)	P-17 (2400)	15 (2200)	6.9 (1000)
J - 3.35 (4.5)	Q - 9.4 (2.5)	J - .53(.706)	J-155	76	37
D/H 1.9/3.5 (6.4/11.3)		D/L-1.2/2.7(4/9)			



Rockwell International
Energy Systems Group

Figure 1. Simplified Flow and Control Diagram

capacity of the hot and cold tanks effectively isolates the receiver and its associated components from the steam generation equipment. Consequently, it is cost effective to consider the receiver and its equipment separately since the outlet temperature variation of the hot tank and cold tank are insignificant.

The components comprising the model include: the cold tank, receiver pump, riser check valve, riser piping, panel control valves, 24 receiver panels and associated manifolding, panel flow controllers, receiver outlet surge tank, surge tank level controller, downcomer piping, drag valve and hot tank. Pipes and valves used for filling or draining receiver equipment have been omitted from the model but can be inserted if required.

II. MODEL DESCRIPTION

A. CSMP

The Advanced Central Receiver (ACR) Sodium-Cooled Solar Electric Power Plant was modeled using International Business Machine's Continuous System Modeling Program (CSMP).(3) CSMP solves coupled sets of first order differential equations. If a system of differential equations is expressed in terms of time, then CSMP will simulate the response of the systems to various perturbations in boundary and initial conditions, much like an analog computer.

A variety of integration routines are available to the CSMP user ranging from rectangular to fourth order Remge-Kutter methods. Naturally, for simple models, the more stable, sophisticated methods require more computer time per solution and are, consequently, more expensive. This common dilemma requires that the user trade off model accuracy against simulation cost. The size of the ACR model, in terms of finite element nodes, required that the integration method be among the least sophisticated so that reasonably low computer costs result.

The CSMP format requires that the model be expressed in three parts. Boundary and initial conditions are input directly or calculated in the first section called "INITIAL." The coupled differential equations and intermediate calculations are contained in a section entitled "DYNAMIC." Solution monitoring, time step changes and output instructions are located in the "TERMINAL" section. Subroutines, called MACRO's in CSMP, are physically located prior to the INITIAL section and can be called from either the INITIAL or DYNAMIC sections as required. CSMP also has a table look-up capability with several interpolation options. A full description of CSMP is well beyond the scope of this report. The interested reader is referred to Reference 3 for more detailed CSMP information. It is hoped that the foregoing discussion will allow a reasonable understanding of CSMP such that the code listing in Appendix A will be understandable.

B. MODEL FEATURES, GENERAL DESCRIPTION AND ASSUMPTIONS

For purposes of thermal analyses, certain large components of the ACR system, contained within the previously described scope, are divided into finite elements, and each element represented by a node. A nodal diagram is shown in Figure 2. The components which are so divided include the receiver, the receiver riser piping, and the receiver downcomer piping. The hot and cold storage tanks, the receiver outlet tank, the receiver pump, and suction pipe and the drag valve and its discharge pipe are all treated as single nodes for purposes of thermal analyses.

The receiver riser pipe is divided into 10 equal axial sodium nodes which are considered to be ideally insulated. Each axial node's response is determined by first order dynamics and is subject to input only from the upstream sodium node.

The receiver downcomer is similarly divided into five axial sodium nodes. The characteristic time constants of the riser and downcomer nodes are variable as the hydraulic conditions of the system change.

The receiver section of the model is more complicated. In the riser and downcomer, flow is considered possible only in one direction. The receiver panels, each of which is modeled, can experience flow reversals if the receiver is isolated from the pump and hot tank. Thus, each receiver panel model subsection has reverse flow thermal as well as hydraulic capabilities built in. Each panel is considered to be thermally independent (i.e., ideally insulated back side) along its length, but is hydraulically coupled at each end. Thus, panel thermal interaction is due totally to hydraulically coupled perturbations.

Each panel is divided into three axial sections, each section consisting of a tubing or wall node and sodium node. The differential equation describing each node's temperature is derived from an energy balance taken around each node. Thermal losses from the wall nodes

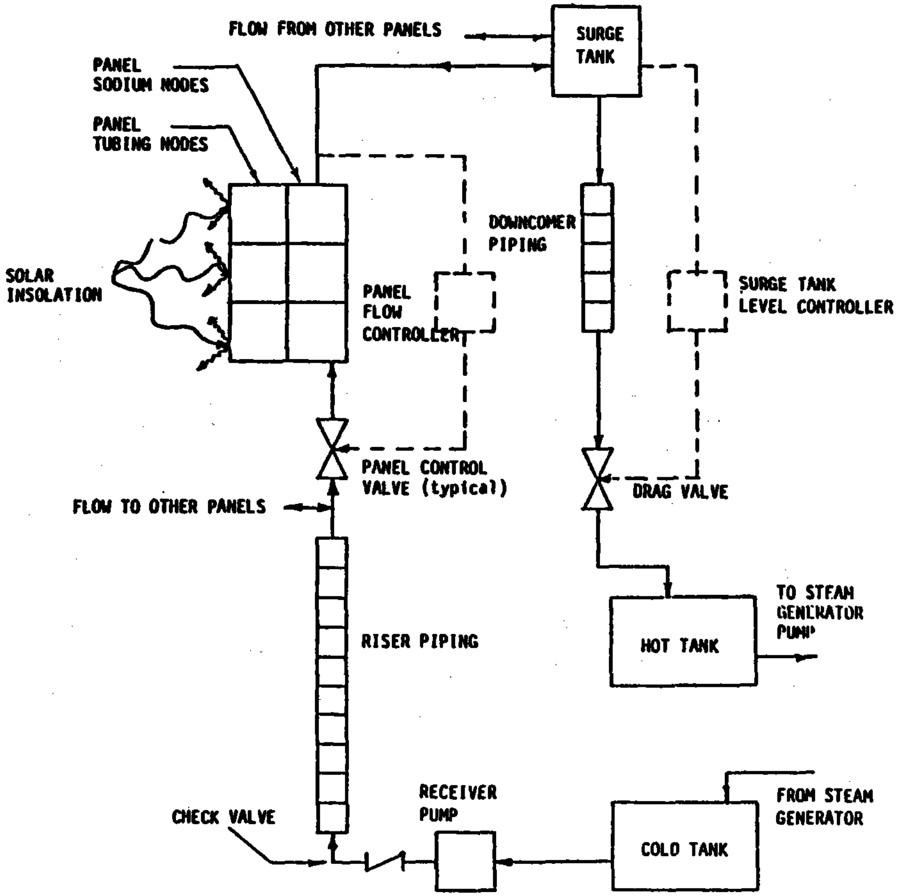


Figure 2. Advanced Central Receiver Transient Model Schematic

include reflection, reradiation to ground and sky, and convection to air. The film coefficient of the convection loss term can be circumferentially and time varied to simulate the receiver boundary conditions due to wind variation, if required. The incident receiver flux can also be circumferentially, axially, or time varied so simulate heliostat field design variations, cloud cover passage, or the effect of various aim point strategies. Panel wall node physical properties are assumed constant, but sodium properties and film coefficients are allowed to vary with temperature.

Each receiver panel is assumed to empty into the receiver outlet tank, and the tank is a small enough volume that it is assumed to mix ideally. Ideal mixing is also assumed for the hot and cold tanks.

Temperature rises of the sodium due to inefficiencies in the receiver pump and pressure drop in the drag valve are considered and included in the model. Changes in these rises are assumed to occur instantaneously.

For purposes of hydraulic simulation, three flow sections are considered. The first section runs from the cold tank surface to the point where the sodium flow splits to each panel. The second section runs from where the receiver panels diverge to where they converge. The third section includes the sodium from the receiver outlet tank surface to the hot tank surface.

For each section, the derivative of flow is determined from a force balance around that section. This method can accommodate reverse flow without methodology modification. One force balance is required for each panel as well as the receiver downstream and upstream sections. At the interface of the receiver and its upstream section (i.e., the receiver inlet manifold), no free surface and, therefore, no arbitrary pressure exists. Therefore, the continuity equation must be utilized to obtain pressure. Pressure drops are neglected in the receiver inlet and outlet manifolds.

For purposes of panel flow and receiver outlet tank level control, Proportional plus Integral (reset) plus Derivative control schemes are built in. Any combination of the above can be selected. The problem of integral wind-up, wherein the demanded valve position is greater than open or less than closed is resolved in the model through the use of appropriate logic. Valve pressure drop is calculated by means of standard equations developed by Kern.(4)

C. SPECIFIC EQUATIONS

1. Thermal (Section 3.3)

All temperatures are derived by integrating the time derivative of the temperature developed from a first law or energy balance equation for each node generally given by

$$\left\{\begin{matrix}\text{Accumulation of}\\ \text{energy within}\\ \text{the system}\end{matrix}\right\} = \left\{\begin{matrix}\text{Transfer of energy}\\ \text{into the system through}\\ \text{system boundary}\end{matrix}\right\} - \left\{\begin{matrix}\text{Transfer of energy}\\ \text{out of the system}\\ \text{through system boundary}\end{matrix}\right\}$$

$$+ \left\{\begin{matrix}\text{Energy generation}\\ \text{within the system}\end{matrix}\right\} - \left\{\begin{matrix}\text{Energy consumption}\\ \text{within the system}\end{matrix}\right\}^{(5)} \qquad (1)$$

Since there is no significant internal generation or consumption in any of the nodes, the last two terms zero out. For a given node the term on the left side of the equation becomes

$$\text{Accumulation} = dMTCp/dt \qquad (2)$$

where M = mass of node*
T = temperature of node
Cp = heat capacity of node
t = time

In all cases, the Cp of the node is assumed constant for at least each time step, thus Equation 2 becomes

$$\text{Accumulation} = CpdMT/dt \qquad (3)$$

*Units are defined in the variable index in Appendix A

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In most cases, the volume of the node is fixed and the density assumed to be constant over the time interval of interest. Hence, Equation 2 becomes

$$\text{Accumulation} = MCpdT/dt \quad (4)$$

The exception to this is the tanks, which are either draining and filling and, therefore, subject to changing volume and mass, in which case Equation 2 become

$$\text{Accumulation} = Cp(TdM/dt + MdT/dt) \quad (5)$$

The right hand terms of Equation 1 including energy transfer to and from the system depend upon the node at hand and will be considered on an individual basis below

a. Receiver Tube Nodes (Section 3.3.1.1)*

Solar energy absorbed by the nodes is given by

$$Qa = Qi\alpha - Qr - Qc \quad (6)$$

where

Qa = Incident power absorbed
Qi = Incident power
α = Tube Absorbtivity (constant)
Qr = Reradiated power
Qc = Convection power losses

Qi is determined by

$$Qa = P_p \times P_f \quad (7)$$

---

*Refers to numbering system of Code in Appendix A where

P_p = Circumferential varying panel power
$P_p = R_p \times N_{pp}$ (8)
R_p = Total receiver power
N_{pp} = Panel power fraction
P_f = Axial position power fraction

$$Qr = (\alpha\sigma A_{rr}[(T^4 - T_g^4) + (T^4 - T_s^4)]\ )/s \tag{9}$$

where

σ = Stephan/Boltzman Constant
A_{rr} = Node reradiation area
T_g = Ground temperature
T_s = Sky temperature

Note that a view factor of 1/2 was used for sky and ground, respectively.

$$A_c = HFA \times A_{rr}\ (T - T_A) \tag{10}$$

where

HFA = Receiver outside surface film coefficient
T_A = Ambient Air Temperature

Energy transferred from the tube nodes to the sodium is given by

$$\text{Energy transferred} = HARN\ (T - T_N) \tag{11}$$

where

HARN = Sodium film coefficient (variable) x tube sodium side area (calculated from the Seban-Shimiyaki correlation in a macro)
T_N = Sodium temperature

Combining Equations 4, 6, and 11 yields the equation for the derivative of tube wall temperature

$$dT_W/dt = (Qa - HANR\ (T_W - T_N))/(MCp) \qquad (12)$$

where

T_W = Temperature of the tubing wall

b. Receiver Sodium Node Temperature (Section 3.3.1.2)

The energy transferred to a receiver sodium node is equal to the energy transferred from the adjacent receiver tubing node and is described by Equation 11.

Energy is transferred from the sodium node by sensible heat gain of the sodium leaving the node.

$$\text{Energy transferred from system} = |\dot{m}|\ Cp\ (T_{NI} - T_{NO}) \qquad (13)$$

where

$|\dot{m}|$ = Absolute value of flow of sodium through node
Cp = Sodium heat capacity
T_{NI} = Sodium node inlet temperature
T_{NO} = T_N=Sodium node outlet temperature

If the flow direction in any panel reverses, the physical inlet to the node changes. To accommodate this, the inlet temperature of each sodium node is selected by an input switch function depending on the flow direction. Each sodium node is assumed to mix ideally, resulting in a uniform node temperature equal to the outlet temperature. Utilization of the absolute value of flow keeps the sense of direction of energy flow correct since the inlet-outlet temperature difference provides the driving potential and energy direction sign.

Combining Equations 4, 11, and 13 yields the expression for the derivative of a receiver sodium node.

$$DT_N/dt = (HANR\ (T_W - T_N) + |\dot{M}|\ Cp\ (T_{NI} - T_N))/(V_N \rho_N Cp) \qquad (14)$$

where

V_N = Volume of the sodium node
ρ_N = Sodium density
Cp = Sodium heat capacity
T_N = Sodium temperature

c. Riser Piping (Section 3.3.2.2)

The equation describing the derivative of the outlet temperature of each riser piping node is:

$$dT_{NR}/dt - |\dot{M}|\ /M\ (T_{NRI} - T_{NR}) \qquad (15)$$

where

T_{NR} = Riser node sodium outlet temperature
T_{NRI} = Riser node sodium inlet temeperature

This is the classical equation describing a first order lag-type dynamic situation; however, the time constant is allowed to vary with the flow. This provides a more accurate picture of the riser dynamics.

d. Receiver Pump (Section 3.3.2.3)

The temperature rise due to viscous heating is assumed to be a quasi-steady-state phenomenon. The equation describing the outlet temperature is:

$$T_{RP0} = T_{RPI} - H_{RP}/\rho Cp \; (1 - 1/\eta) \qquad (16)$$

where

T_{RP0} = Receiver pump outlet temperature
T_{RPI} = Receiver pump inlet temperature
η = Receiver pump hydraulic efficiency

The receiver pump efficiency is assumed to be .75 of the normalized pump sodium flow.

e. Cold Tank to Receiver Pump (Section 3.3.2.4)

The cold tank-to-receiver pump piping temperature dynamics are similar to the riser dynamics. The equation describing the dynamics is similar to Equation 15.

f. Cold Tank

Since the level of the cold tank is variable, the changing mass of the cold tank must be accounted for as noted in Equation 5. The equation for the cold tank outlet temperature derivative is:

$$dT_{CT}/dt = (\dot{M}_i T_i - \dot{M}_o T_{CT} - dM/dt T_{CT})/MCp \qquad (17)$$

where

T_{CT} = Cold tank temperature
$\dot{M}_i$ = Cold tank sodium inlet flow
T_i = Cold tank sodium inlet temperature
$\dot{M}_o$ = Cold tank sodium outlet flow

dM/dt is determined from the continuity equation.

g. Downcomer Piping (Section 3.3.2.6)

The downcomer piping node temperature equations are the same as the riser equation. See Equation 15.

h. Pressure Reducing Device (Section 3.3.2.7)

The viscous heating of sodium due to pressure drop across the drag valve is assumed to be quasi-steady-state process similar to the rise across the receiver pump. However, in this case all of the pressure drop is converted to heat by the equation

$$T_{DVO} = T_{DVI} + P_{DV} \times 144/(778 \rho Cp) \qquad (18)$$

where

T_{DVO} = Drag valve outlet temperature
T_{DVI} = Drag valve inlet temperature
P_{DV} = Drag valve pressure drop

i. Pressure Reducing Device to Hot Tank (Section 3.2.1.8)

The hot tank inlet temperature piping equation is similar to the riser piping temperature equation. See Equation 15.

j. Hot Tank (Section 3.2.1.9)

The hot tank temperature derivative equation is similar to the cold tank equation. See Equation 17.

k. Sodium Film Coefficients and Properties (Section 3.1)

The sodium film coefficients for all sodium convective heat transfer in the receiver is determined by the Seban-Shimazaki correlation:

$$Nu = 5.0 + 0.025(RePr)^{.8} \qquad (19)$$

where

Nu = Nusselt Number

$$Nu = \frac{H. \times D}{K}$$

H. = Film coefficient
D = Tube diameter
K = Sodium thermal conductivity
Re = Reynolds Number
Pr = Prandtl Number

This correlation includes thermal conductivity and is useful at low flows. Sodium properties are determined from correlations supplied by Reference 6. The correlation for heat capacity is:

$$Cp = 0.364 - 0.792 \times 10^{-4}T + 0.341 \times 10^{-7}T^2 \qquad (20)$$

The correlation for thermal conductivity is:

$$K = 54.306 - 0.01878T + 2.09 \times 10^{-6}T^2 \qquad (21)$$

The correlation for viscosity is:

$$\text{Log}_{10}\,\mu = 1.0203 + 397.17/T - 0.4925 \log_{10}T \qquad (22)$$

All of the above correlations are handled as macros which are called as required from the DYNAMIC sections. These macros are physically located in Section 1.0.

2. Hydraulics (Section 3.2)

The flow in a given flow channel is determined by integrating flow acceleration as determined by a force balance between two points in the flow path. The general equation is:

$$\Sigma F = Ma \tag{23}$$

where

ΣF = Summation of the forces exerted on the fluid
M = Mass of Sodium between Points 1 and 2
a = Acceleration of fluid between Points 1 and 2 which is given by

$$a = dV/dt \tag{24}$$

Instantaneous velocity is given by:

$$V = \dot{M}/\rho A \tag{25}$$

noting that the mass of the fluid accelerated is given by:

$$M = \rho AL \tag{26}$$

where

V = fluid velocity
A = Flow area
L = Flow path length

and combining Equations 23, 25, and 26 yields

$$\rho ALd(\dot{M}/\rho A)/dt = \Sigma F \tag{27}$$

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ρ and A are assumed constant and Equation 27 becomes

$$L dm/dt = \Sigma F \qquad (28)$$

dividing by gA to convert to force per unit flow area and lbf to lbm yields the expression for flow acceleration

$$d\dot{M}/dt = (gA/L\Sigma F \qquad (29)$$

where

g = acceleration due to gravity

it is often numerically convenient to express the flow referenced to steady-state as a fraction

$$\dot{M}_f\dot{M}_0 = \dot{M} \qquad (30)$$

where

$\dot{M}_f$ = Fraction of reference flow
$\dot{M}_0$ = Reference flow

Substituting Equation 30 into 29 and dividing through by $\dot{M}$ yields the form of Equation 29 used in the model.

$$d\dot{M}f/dt = (gA/L\dot{M}_0)\Sigma F \qquad (31)$$

g, A, L and $\dot{M}_0$ are all easily calculated constants or initial conditions and are lumped into a term called the flow inertia.

$$I_f = \dot{M}_0 L/gA$$

where

I_f = Flow inertia.

a. Receiver Panel and Riser Flow (Section 3.2.1.1.1)

For any receiver panel, the inlet pressure is the same as any other panel since all panels start from a common point and manifold losses are assumed to be negligible. The same is true for the receiver outlet pressure. The equation for the ith panel is:

$$d\dot{M}f_i/dt = (PIR - POR - FH_i - DPCV_i - SH_i)/I_{f_i} \quad (32)$$

where

PIR = Common panel inlet pressure
POR = Common panel outlet pressure
FH_i = Panel i friction head
$DPCV_i$ = Panel i control valve head
SH_i = Panel i static head
$\dot{M}f_i$ = Panel i flow

POR is determined from the static head in the receiver outlet tank.

Each panel friction head is approximated by

$$FH_i = KF_i \; |\dot{M}_{f_i}| \times \dot{M}_{f_i} \quad (33)$$

where

KF_i = steady-state flow friction drop. The absolute value function causes the sign of the friction drop to automatically change during panel flow reversal.

The expression for control valve head is given by:

$$DPCV_i = \frac{\rho}{\rho_w} Q\,|Q|/CVC^2 \quad (34)$$

where

ρ/ρ_w = Specific gravity of sodium

Q = Sodium volumetric flow
CVC = Control valve flow coefficient
(See control model description)

The equation for panel static head is:

$$SH_i = (E_o - E_i)\,\bar{\rho}/144 \tag{35}$$

where

E_o = Panel outlet elevation
E_i = Panel inlet elevation
$\bar{\rho}$ = Average panel density

The riser flow equation is written in a manner similar to the panel flow equations. However, only one equation is required. The equation is:

$$\frac{d\dot{M}f}{dt} = (POCT - PIR + (E_i - E_o)\bar{\rho}/144 - \dot{M}_f\,|\dot{M}_f|\,KFH_R + H_{RP})/I_R \tag{36}$$

where

POCT = Ullage pressure of cold tank
E_i = Cold tank level elevation
E_o = Receiver inlet elevation
KFH_R = Steady-state riser friction drop
H_{RP} = Receiver pump head
I_R = Riser inertia

b. Receiver Outlet Tank and Cold Tank (Sections 3.2.1.1.2 and 3)

In these sections the time varying inventories and levels are determined by a simple integration of the continuity equation

$$dm/dt = \Sigma\dot{M}_i - \Sigma\dot{M}_o \tag{37}$$

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c. Receiver Pump (Section 3.2.1.1.4)

The receiver pump speed is determined by integrating the equation

$$dN/dt = K_{RP}(\tau_m - \tau_p) \tag{38}$$

where

N = Receiver pump speed (normalized)
K_{RP} = 1/receiver pump inertia
τ_m = Receiver pump motor output torque (normalized)
τ_p = Receiver pump torque required (normalized)

The expression for required receiver pump torque was determined by fitting the speed-torque-flow curves for a typical sodium pump. The expression is

$$\tau_p = C_1N^2 + C_2\dot{M}_fN + D_3\dot{M}_f^2 \tag{39}$$

where

C_1, C_2, and C_3 are the coefficients required to fit the speed-torque-flow curve. Similarly, the expression for receiver pump head is

$$H_{RP} = C_1N^2 + C_2N\dot{M}_f + C_3\dot{M}_f^2 \tag{40}$$

where

C_1, C_2, and C_3 are the coefficients required to fit the speed-flow-head curve characteristics of the modeled receiver pump. Receiver pump head is limited to 120% of the design head.

d. Riser Pressure (Section 3.2.1.1.5)

Determining the riser outlet/receiver inlet pressure is critical to the solution of Equations 32 and 36. This pressure is determined from the derivative of the continuity equation:

$$\dot{M}_R = \sum_{i=1}^{24} \dot{M}_i \qquad (41)$$

where

$\dot{M}_R$ = Riser flow
$\dot{M}_i$ = Panel i flow

taking the derivative of Equation 41 yields

$$d\dot{M}_R/dt = d\left(\sum_{i=1}^{24} \dot{M}_i\right)/dt = \sum_{i=1}^{24} d\dot{M}_i/dt \qquad (42)$$

The left side of Equation 42, when expanded is similary to Equation 36. When expanded, the right side of Equation 42 is similar to Equation 32. The differences are due to Equations 32 and 36 being expressed as normalized flow. When Equations 32 and 36 are multiplied through by the reference flow and substituted into Equation 42, the result is:

$$(POCT + (E_i - E_o)\bar{\rho}/144 - \dot{M}_f \, |\dot{M}_f| \, KFH_R + H_{RP})/LOGAR = \sum_{i=1}^{24} (PIR - POR - FH_i - DPCV_i - SH_i)/PLOGA \qquad (43)$$

where

$$LOGAR = I_R \dot{M}_{ro} \qquad (44)$$

and

$$PLOGA = I_{f_i} \dot{M}_{io} \qquad (45)$$

Solving Equation 43 for the receiver inlet pressure yields:

$$PIR = ((24 \times POR + \sum_{i=1}^{24} SH_i + FH_i + DPCV_i)/PLOGA +$$

$$(POCT + (E_i - E_o)\bar{\rho}/144 - \dot{M}_f|\dot{M}_f|KFH_R + H_{RP})/LOGAR/$$

$$(24/PLOGA + 1/LOGAR) \qquad (46)$$

which is the form used in the model. Equation 46 is not used at very low or zero riser flow due to numerical methods considerations. At low flow, Equation 46 is simplified to:

$$PIR = (\sum_{i=1}^{24} FH_i + SH_i + DPCV_i)/24 + POR \qquad (47)$$

e. Downcomer Flow (Section 3.2.1.1.6)

The force balance used to describe the downcomer flow is taken between the receiver outlet tank surface and the hot tank surface. The expression is

$$d\dot{M}_{fDC}/dt = (POROT - POHT - FH_{DC} - DP_{DV} - SH_{DC})/I_{DC} \qquad (48)$$

where

$\dot{M}_{fDC}$ = Downcomer fractional flow
POROT = Receiver outlet take ullage pressure
POHT = Hot tank ullage pressure
FH_{DC} = Downcover friction head
DP_{DV} = Drag valve head
SH_{DC} - Downcomer static head

The equations describing the friction, static and drag valve heads are the same as those used in the panel friction, static, and control valve heads.

f. Hot Tank (Section 3.2.1.1.7)

See "Receiver Outlet Tank and Cold Tank."

3. Plant Protection and Control System (Section 3.4)

The plant protection and control model consists of receiver panel controllers and a drag valve controller. Each controller model has the capability of simulating any combination of all three control nodes (proportion, integral, or derivative).

a. Receiver Panel Controllers

The valve position demanded by a given controller is fundamentally expressed as a function of receiver outlet panel temperature error is:

$$VPOX_i = \int_0^t EIR_i \times KC_i/\tau_i \, dt + K_C \tau_{D_i} dT_i/dt + K_C ET_i \qquad (49)$$

where

$VPOX_i$ = Valve position demanded by controller for Panel i
EIR_i = integral error of Panel i
= ET for $0<VPOX_i<1$
= 0 for $1<VPOX_i<0$
(prevents integral windup)
KC_i = Proportional constant for Panel i controller
τ_i = Integral time (1/reset rate) Panel i controller
τ_{Di} = Derivative time, Panel i controller
T_i = Panel i outlet temperature
ET_i = Panel i outlet temperature error.

In addition to Equation 49, the outlet temperature of each panel is processed by first order dynamics to simulate thermocouple signal lag. Also, the demanded valve position is also processed by first order dynamics to simulate the valve actuator. The flow coefficient for each valve is determined from the equation:

$$CVC = .025^{(3.67 \, x \, VP_i)} CV \qquad (50)$$

where

VP_i = Actual valve position, Panel i
CV = Design valve flow coefficient, Panel i

Note the equal percentage valves are used and Equation 50 is a curve fit from Reference 7 describing flow coefficient as a function of valve position. The values of KC_i τ_i and τ_{Di} were determined from the methodology outlined in Reference 8 and are considered optimum.

b. Pressure Reducing Device Controller (Section 3.4.2)

The equations describing the drag valve controller response are similar to those describing the panel valve controllers. The only difference is that the error is provided by the level of the receiver outlet tank. Again, the constants K_c, τ, τ_D were determined by the methodology of Reference 8.

4. Boundary and Initial Conditions (Section 2)

This section inputs known constants and calculates boundary and initial conditions. Initial conditions used in integrals in the dynamic section are calculated using equations similar to the various differential equations but with the derivatives set to zero. For example, a typical receiver tubing node temperature is:

$$T_W = Q_a/HARN + T_N \qquad (51)$$

In this example, the associated sodium node temperature, T_N, must be known. This requires an iterative solution in this case. Guesses of sodium node temperatures are input and the true values are determined by converging on the correct value of Q_a. In most cases, iterative processes are not required to determine boundary and initial conditions since the required inputs have been previously determined. The numbering system of the initial section is keyed to that of the dynamic section. Hence, the boundary and initial conditions required by Section 3.3.2.6 are contained in Section 2.3.2.6. A listing of the model followed by a variable and function index, defining all variable and function names and units, is located in Appendix A.

III. RESULTS

The transients examined using the ACR model included: A 10% step change in incident flux, a cloud cover transient, 25% step-ramp changes in incident flux, loss of receiver pump power, accidental drag valve function, and an emergency shutdown incident flux ramp. The Cathode Ray Tube (CRT) output for each transient is presented in Appendix B-G, respectively. The response of the model to each of these perturbations will be discussed individually. For each of the transients examined, except for cloud cover, the following parameters were graphed as functions of time: incident power, absorbed power, riser flow, receiver outlet tank temperature, cold tank temperature, pump inlet and outlet temperature, receiver inlet temperature; south, east-west and north panel incident power, valve position, flow, outlet temperature, and mid-plane tube temperature, drag valve inlet temperature, drag valve outlet temperature, hot tank inlet and outlet temperatures, drag valve position, downcomer flow, receiver outlet tank level and error, normalized pump speed and head, receiver inlet and outlet pressures, and hot and cold tank levels. The CRT's for each run are presented in the previously indicated order with a legend at the top of each defining variable names and units.

Due to computer perversity, the CRT output for the cloud cover transient was not generated. The graph presented for this run is a hand-drawn plot of digital information obtained from the printed output. The significant response parameters for all runs are summarized in Table I.

A. RESPONSE TO 10% STEP CHANGE IN INCIDENT FLUX

The purpose of this run was to test the response of the panel control system. A 10% step change in control system input is a standard perturbation used to test the response of the control system. It is important to note that with the ACR system such a transient would never occur due to limitation on heliostat steer-off rates. The transient was

TABLE I - TRANSIENT PARAMETER SUMMARY

Transient	10% Step	Cloud Cover	25% Step	Pump** Trip	Drag Valve Failure	Emergency Shut-Down
Receiver Outlet Variation (°F)	6	5	6	7400	NA	8
Panel Outlet Variation (°F)	12	NA	25	7500	NA	12
Tube Ramp* (°F)	8	NA	20	7160	NA	5
Max. Receiver Inlet Pressure (psia)	100	NA	150	70	70	170
Receiver Outlet Tank Level Variation ft	.4	NA	2.5	.2	5	1
Minimum Receiver Inlet Pressure (psia)	70	70	70	33	70	70

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*All controlled tube ramps lasted less than 100°F
**Uncontrolled transient

hgw:5/1

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initiated at 5 seconds, and a total of 100 seconds of system response was examined. The Cathode Ray Tube (CRT) graphs of the system response are shown in Appendix B. The overall system response, shown on the first sheet, indicates a receiver outlet tank temperature variation of less than 6°F. Representative panel responses (Sheets 3-5) show overall panel outlet temperature variations of less than 8, 10, and 12°F, respectively. Ring down of all controlled panel temperatures occurs in less than 3 cycles. This indicates that the panel response is satisfactory and the control settings for gain, derivative time, and reset rate are optimum. The maximum wall temperature variation is approximately 20°F in 3 seconds. However, it should be noted that actual step changes in flux are impossible and that these ramps represent the worst case situation. Most realistic runs show wall ramps of lower magnitude. The remaining system variations in temperature were of an insignificant magnitude. The response of the receiver outlet tank indicated sluggish drag valve function. This was corrected by increasing the drag valve controller integral reset rate. Due to the closing of the panel valves, the receiver inlet pressure increased from 70 to 100 psia.

B. RESPONSE TO CLOUD COVER TRANSIENT

The purpose of this run is to verify adequate system response to a typical cloud cover. The cloud was approximated by a 1%/sec ramp to zero incident power initiated at 5 seconds. The inverse ramp of 1%/sec to 100% power was started at 105 seconds. Total run duration was 250 seconds. The overall response of the system was smooth, with the absorbed power going negative at low incident power due to reradiation and reflection losses. The riser flow follows the ramp and overshoots on return to 100% power due to control valve travel limitations. The maximum variation in receiver outlet tank temperature was 5°F, indicating an acceptable control response.

C. RESPONSE TO 25% STEP (STEEP RAMP CHANGES)

The purpose of this run was to demonstrate the ability of the system to follow incident power changes of the type that might be imposed by electrical load variations. The ramp rate was 25% power in 15 seconds or 1-2/3%/second. A total of four changes were applied, two negative, followed by two positive. Each change was followed by 50 seconds of no change to allow the system to recover. The first change was initiated at 5 seconds. Total run time was 265 seconds. The CRT's are shown in Appendix D. The overall response of the system was satisfactory, with slight overshoots in riser flow and a maximum receiver outlet temperature variation of 6^{o}F.

The pump outlet temperature increases approximately 7^{o}F at 50% incident power due to increased head and decreased flow. The maximum panel outlet temperature variation was less than 25^{o}F and occurred in the north panel due to the panel valve opening completely during the last positive ramp. This indicates panel interaction can cause non-linearities in certain circumstances. However, the magnitude of the overshoot is acceptable. Wall temperature variations were severe in this transient, with the maximum variation occurring in the south panel. However, the ramps are not carried more than 100^{o}F, so they are acceptable. All other system temperature variations were insignificant. The drag valve followed the changes and limited receiver outlet tank level error to ±2.5 ft. The maximum receiver inlet pressure achieved was 150 psia.

D. RESPONSE TO LOSS OF RECEIVER PUMP POWER

The purpose of this simulation was to explore the possibility of allowing passive heliostat defocusing during emergency conditions. The pump motor was tripped at 5 seconds, and the flux allowed to follow a decay curve, supplied by the heliostat subcontractor, representative of a solar image drift-off due to heliostat power failure.

It was assumed that during this transient the drag valve would fail closed and the panel valves fail open. With the receiver isolated by a check valve soon after pump trip, natural circulation induced reverse flow in the cooler panels. The gradual power decay of the image drift-off is shown in the first sheet of Appendix E. Due to the large static head of the riser, riser flow decays to zero within 5 seconds of pump trip. Due to recirculation, the receiver outlet tank temperature rises to about 1500^{o}F during the run duration of 100 seconds. The pump outlet temperature experiences a 30^{o}F spike during pump trip. The receiver inlet manifold sodium boils 80 seconds after pump trip.

The model does not include latent heat transfer. Hence, it is invalid past boiling temperatures. However, the model is adequate for purposes of showing the response of the system up to boiling.

The response of the south panel shows a rapid flow decay and flow reversal at 4 seconds from pump trip. The sodium in this panel does not boil. The east-west panel flow also reverses, although not to the same magnitude as the south panel. The sodium in this panel also does not boil. The north panel flow does not reverse, but the sodium boils 15 seconds after pump trip. The tubing temperature plots rise rapidly to 1600^{o}F and are meaningless past this point. The remaining system temperature variations are insignificant. The minimum receiver inlet pressure is 33 psia.

Clearly, passive defocusing is inadequate to prevent boiling in the receiver, an undesirable condition. As will be shown later, active defocusing is adequate. Another possibility is to provide an inventory of cold sodium to prevent boiling. Preliminary calculations indicate that 5,000 gallons of sodium heated from 550 to 1500^{0}F would suppress all receiver boiling. It should be noted receiver control is effectively lost when the pump does not supply adequate receiver inlet pressure.

E. RESPONSE TO ACCIDENTAL DRAG VALVE FUNCTION

The purpose of these runs was to determine the time available to take action following a drag valve failure. Two cases were considered: drag valve failed open and closed. Each failure was initiated at 5 seconds.

1. Drag Valve Fails Open

Over the run duration of 100 seconds, the temperature and flow variations were insignificant, and after 100 seconds about 1 foot of sodium remained in the receiver outlet tank. Even if no action were taken, the tank would merely drain. This would only present a problem if the pump failed subsequent to tank draining. The mild response of this transient is due to the nearly open steady-state valve position.

2. Drag Valve Fails Closed

The run duration was 30 seconds. Again, the temperature and flow variations were insignificant. However, the receiver outlet tank filled in 25 seconds. Clearly, active steer-off and pump trip measures must be initiated within 20 seconds of drag valve closure if receiver flow stoppage is to be avoided.

F. RESPONSE TO EMERGENCY SHUTDOWN

This transient was initiated at 5 seconds and included a 15 second ramp from 100 to 0% incident power (6-2/3%/sec). The run duration was 20 seconds. Pump trip was initiated at 20% riser flow.

The maximum temperature variation of the receiver outlet tank was $8^{\circ}F$, maximum panel outlet temperature variation was $30^{\circ}F$ with the worst ramp, $12^{\circ}F$/sec carried for less than $20^{\circ}F$. Tube temperature ramps of $5^{\circ}F$/sec were experienced for less than $50^{\circ}F$. This response is acceptable. All other temperature variations were insignificant. Receiver outlet tank level variation was 1 foot. Maximum receiver inlet pressure was 170 psia.

IV. CONCLUSIONS AND RECOMMENDATIONS

Over the range of transients examined, the controlled receiver outlet tank temperature varied less than 8°F. The maximum panel sodium temperature variation was 30°F, less than 6% of the total panel rise. The maximum real life tube temperature ramp experienced in a controlled transient was less than 15°F/second. In no controlled case were these ramps carried for more than 50°F.

It was found that passive heliostat defocusing is inadequate in an emergency situation. Emergency power must be available for active heliostat steer-off. As an alternative, a cold sodium supply could be used to cool the receiver during a pump failure.

The control methodology of individually controlled panels is adequate for purposes of receiver control over the range of transients studied.

V. REFERENCES

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4. Kern, Robert, "Control Valves in Process Plants," Chemical Engineering, April 14, 1975

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6. TDT 12083 (WHAN-D-3), "Standard FFTF Values for the Physical and Thermophysical Properties of Sodium," W. H. Yunker, Westinghouse Electric Corporation, Richland, Washington

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APPENDIX A

ADVANCED CENTRAL RECEIVER SIMULATION MODEL COMPUTER CODE LISTING AND VARIABLE INDEX

```
$$$CONTINUOUS SYSTEM MODELING PROGRAM  III    V1M3   TRANSLATOR OUTPUT$$$

TITLE          ADVANCED CENTRAL RECEIVER, SODIUM COOLED SOLAR/ELECTRIC
TITLE          POWER PLANT SIMULATION MODEL
TITLE          RUN 04-07 CLOUD COVER SIMULATION, 200 SECONDS

*          CURRENT VERSION DATE  JULY 13, 1978, DSN ACRPTM7.DATA


FIXED   KEEP,I,J,II,JJ,K,M,N,KK,L,LL,MM,NN,IJ,JI,JK,KJ,IK,KI,KL


*1.0                  MACRO STATEMENTS

*1.3.3.1              SEBAN-SHIMAZAKI EQUATION FOR SODIUM FILM COEFF. `

MACRO   CP,HA=LKEQ(MDOT,T,AFLOW,D,A)
        TR=T+460.
        MULOG=1.0203+397.17/TR-0.4925*ALOG10(TR)
        MU=10.**MULOG/3600.
        RED=MDOT*D/AFLOW/MU
        KNA=(54.306-0.01878*T+2.0914E-06*T**2)/3600.
        CP=0.34574-0.79226E-04*T+0.34086E-07*T**2
        PR=CP*MU/KNA
        NUN=5.0+0.025*(RED*PR)**.8
        H=NUN*KNA/D
        HA=H*A
ENDMACRO

MACRO   RHON=RHONA(TNA)
        RHON=59.566-7.9504E-03*TNA-.2872E-06*TNA**2+.06035E-09*TNA**3
ENDMACRO

MACRO   CPSOD=CPNA(TSOD)
        CPSOD=0.34574-0.79226E-04*TSOD+0.34086E-07*TSOD**2
ENDMACRO



*2.0                  CONSTANTS RUN PARAMETERS AND INITIAL CONDITIONS

*2.0.1                ARRAY DIMENSIONS
```

```
STORAGE WNRR(24),HFA(24),NPP(24),HANR1(24),HANR2(24),HANR3(24),          ...00000420
        QI1(24),QI2(24),QI3(24),PP(24),TNR10G(24),TNR20G(24)            ....00000430
        TNR30G(24),SH(24)                                 ....            00000440
        QA1(24),QA2(24),QAI(24),CPMEAN(24),NQA1(24),NQA2(24)            ,...00000450
        QA3(24),WNRA(24),CP1(24),CP2(24),CP3(24),RHO1(24),RHO2(24),      ...00000460
        RHO3(24),IR(24),NQA3(24),CV(24),VPOX(24)        ,...              00000470
                                  KC(24),TAU(24)            ,.           ...00000480
        TAUD(24),KFH(24),KFHC(24),FH(24),DPCV(24)                         00000490
                                                                          00000500
*2.1          INPUT AND BOUNDARY CONDITIONS                               00000510
                                                                          00000520
INITIAL                                                                   00000530
                                                                          00000540
PROCEDURE WNRR,TNR10,TNR20,TNR30,TRW10,TRW20,TRW30=INITC(TNR10G,         ...00000550
          TNR30G,NPP,RPI,PF1,PF2,PF3,AREEF,MWBTUS,AFLO,DRTUBE,HART,      ...00000560
        HFA,ALPHA,ASRA,TG,TS,TA,AR,TNR20G,TNRIO)                          00000570
      DO 10 KK=1,24                                                       00000580
       TNR10(KK)=TNR10G(KK)                                               00000590
       TNR20(KK)=TNR20G(KK)                                               00000600
       TNR30(KK)=TNR30G(KK)                                               00000610
       CPMEAN(KK)=.30296                                                  00000620
       PP(KK)=NPP(KK)*RPI                                                 00000630
       QI1(KK)=PP(KK)*PF1*MWBTUS                                          00000640
       QI2(KK)=PP(KK)*PF2*MWBTUS                                          00000650
       QI3(KK)=PP(KK)*PF3*MWBTUS                                          00000660
       QA1(KK)=QI1(KK)*AREEF                                              00000670
       QA2(KK)=QI2(KK)*AREEF                                              00000680
       QA3(KK)=QI3(KK)*AREEF                                              00000690
    10 QAI(KK)=QA1(KK)+QA2(KK)+QA3(KK)                                    00000700
    15 DO 20 LL=1,24                                                      00000710
       WNRR(LL)=QAI(LL)/CPMEAN(LL)/550.                                   00000720
       CP1I,HANR1I=LKEQ(WNRR(LL),TNR10(LL),AFLO,DRTUBE,HART)              00000730
       TNR10(LL)=QA1(LL)/WNRR(LL)/CP1I+TNRIO                              00000740
       TRW10(LL)=QA1(LL)/HANR1I+TNR10(LL)                                 00000750
       CP2I,HANR2I=LKEQ(WNRR(LL),TNR20(LL),AFLO,DRTUBE,HART)              00000760
       TNR20(LL)=QA2(LL)/WNRR(LL)/CP2I+TNR10(LL)                          00000770
       TRW20(LL)=QA2(LL)/HANR2I+TNR20(LL)                                 00000780
       CP3I,HANR3I=LKEQ(WNRR(LL),TNR30(LL),AFLO,DRTUBE,HART)              00000790
       TNR30(LL)=QA3(LL)/WNRR(LL)/CP3I+TNR20(LL)                          00000800
       TRW30(LL)=QA3(LL)/HANR3I+TNR30(LL)                                 00000810
       CPMEAN(LL)=(CP1I+CP2I+CP3I)/3.                                     00000820
       QCR1=HFA(LL)*AR*(TRW10(LL)-TA)                                     00000830
```

```
      QCR2=HFA(LL)*AR*(TRW20(LL)-TA)
      QCR3=HFA(LL)*AR*(TRW30(LL)-TA)
      TRW14=(TRW10(LL)+460.)**4
      TRW24=(TRW20(LL)+460.)**4
      TRW34=(TRW30(LL)+460.)**4
      QRG1=ASRA*(TRW14-TG)
      QRG2=ASRA*(TRW24-TG)
      QRG3=ASRA*(TRW34-TG)
      QRS1=ASRA*(TRW14-TS)
      QRS2=ASRA*(TRW24-TS)
      QRS3=ASRA*(TRW34-TS)
      QR1=(QRS1+QRG1)/2.
      QR2=(QRS2+QRG2)/2.
      QR3=(QRS3+QRG3)/2.
      NQA1(LL)=QI1(LL)*ALPHA-QR1-QCR1
      NQA2(LL)=QI2(LL)*ALPHA-QR2-QCR2
   20 NQA3(LL)=QI3(LL)*ALPHA-QR3-QCR3
      ERRFLG=0.0
      DO 30 MM=1,24
      ERROR1=ABS((NQA1(MM)-QA1(MM))/QA1(MM))
      ERROR2=ABS((NQA2(MM)-QA2(MM))/QA2(MM))
      ERROR3=ABS((NQA3(MM)-QA3(MM))/QA3(MM))
      IF (ERROR1.GT..001) ERRFLG=1.0
      IF (ERROR2.GT..001) ERRFLG=1.0
      IF (ERROR3.GT..001) ERRFLG=1.0
      QA1(MM)=NQA1(MM)
      QA2(MM)=NQA2(MM)
      QA3(MM)=NQA3(MM)
   30 QAI(MM)=QA1(MM)+QA2(MM)+QA3(MM)
      IF (ERRFLG.GT.0.0) GO TO 15
      WRITE(6,40)
  40 FORMAT(54H1PANEL    TNR10    TNR20    TNR30    TRW10    TRW20    TRW30/)
      WRITE(6,41)(MM,TNR10(MM),TNR20(MM),TNR30(MM),TRW10(MM),         ...
     TRW20(MM),TRW30(MM),MM=1,24)
   41 FORMAT(I3,5X,6F8.2)
     WRITE(6,42)
   42 FORMAT(31H1PANEL    QA1        QA2          QA3/)
      WRITE(6,43)(MM,QA1(MM),QA2(MM),QA3(MM),MM=1,24)
   43 FORMAT(I3,5X,3F9.2)
ENDPROCEDURE
       PORI=POROT+SLROT*RHODC0/SINSFT
      PIRI=PUCT+(LNACTO-LRI)*RHORP0/SINSFT-KFHRP+HRP0
```

41

```
         LNACTO=MNACTO/RHOCTO/CACT
         RHORPO=RHONA((TNCTO+TNRIO)/2.)
         RHOCTO=RHONA(TNCTO)

 PROCEDURE KFHC,IR,VPI     =HYDINT(KFH,WNRR,PLOGA,TNR10,TNR20,INR30 ,...
             PIRI,PORI,RH,SINSFT,LBSGPM,TNRIO,CV)
         DO 50 NN=1,24
         KFHC(NN)=WNRR(NN)**2*KFH(NN)
         IR(NN)=PLOGA*WNRR(NN)
         RHO1I=RHONA(TNR10(NN))
         RHO2I=RHONA(TNR20(NN))
         RHO3I=RHONA(TNR30(NN))
         SHI=RH*(RHO1I+RHO2I+RHO3I)/3./SINSFT
         DPCVI=PIRI-PORI-KFHC(NN)-SHI
         RHONRI=RHONA(TNRIO)
         SGNRI=RHONRI/62.4
         QI=WNRR(NN)*LBSGPM/SGNRI
         ISRSG=SQRT(SGNRI)
         CVCI=QI*ISRSG/SQRT(DPCVI)
      50 VPI(NN)=1.00086+.272681*ALOG(CVCI/CV(NN))
         WRITE(6,1001)
    1001 FORMAT(36H1PANEL    WNRR     KFHC     IR      VPI/)
         WRITE(6,1010)(NN,WNRR(NN),KFHC(NN),IR(NN),VPI(NN),NN=1,24)
    1010 FORMAT(I3,5X,4F8.2)
 ENDPROCEDURE

 PROCEDURE WNO=WNOINT(ZERO,WNRR)
          WNO=ZERO
          DO 1020 JI=1,24
     1020 WNO=WNO+WNRR(JI)
 ENDPROCEDURE

          KFHRP=KFHRPR*WNO**2
          RHOHTO=RHONA(TNHTO)
          LNAHTO=MNAHTO/RHOHTO/CAHT
          LROTO=MNROTO/RHODCO/CAROT
          RHODCO=RHONA(TNROO)
          SHDCI=(LROTO+EBROT-LNAHTO)*RHODCO/SINSFT
          KFHDC=KFHDCR*WNO**2
          DPDVI=SHDCI-KFHDC
          SGDV=RHODCO/62.4
```

41

```
           QIDC=WNO*LBSGPM/SGDV                                           00001680
           SRSGDV=SQRT(SGDV)                                              00001690
           CVCDV=QIDC*SRSGDV/SQRT(DPDVI)                                  00001700
           VPDVI=1.00086+.272681*ALOG(CVCDV/CVDV)                         00001710
           WCTIR=2./3.*WNO                                                00001720
                                                                          00001730
*2.1.3.3.1          SODIUM FILM COEFFICIENTS                              00001740
                                                                          00001750
CONST                    AFLU=.2535     ,DRTUBE=.0542  ,HART=327.45       00001760
                                                                          00001770
*2.2.1.1.1          RECEIVER PANEL FLOW                                   00001840
                                                                          00001850
CONST       ZERO=0.0        ,LBSGPM=7.1928 ,RH=55.48       ,SINSFT=144.  ,...00001860
           ONE=1.0,          AREEF=.9                                     00001870
                                                                          00001880
*          LBSGPM=CONVERSION LBM/SEC TO GAL/MIN                           00001890
*          RH=RECEIVER PANEL HEIGHT (FT)                                  00001900
*          SINSFT=CONVERSION FACTOR SQ IN TO SQ FT                        00001910
*          PIR=PRESSURE AT RECEIVER INLET (PSIA)                          00001920
                                                                          00001930
 TABLE      KFH(1)=9.68E-04,KFH(2)=9.50E-04,KFH(3)=9.13E-04             ,...00001940
            KFH(4)=8.96E-04,KFH(5)=8.71E-04,KFH(6)=8.39E-04             ,...00001950
            KFH(7)=8.02E-04,KFH(8)=8.11E-04,KFH(9)=8.03E-04             ,...00001960
            KFH(10)=7.92E-04,KFH(11)=7.85E-04,KFH(12)=7.81E-04          ,...00001970
            KFH(13)=7.85E-04,KFH(14)=7.92E-04,KFH(15)=8.03E-04          ,...00001980
            KFH(16)=8.11E-04,KFH(17)=8.20E-04,KFH(18)=8.39E-04          ,...00001990
            KFH(19)=8.71E-04,KFH(20)=8.96E-04,KFH(21)=9.13E-04          ,...00002000
            KFH(22)=9.50E-04,KFH(23)=9.68E-04,KFH(24)=9.68E-04              00002010
                                                                          00002020
TABLE      CV(1-2)=2*76.,CV(3-5)=3*133.,CV(6)=224.,CV(7-9)=3*415.      ,... 00002030
           CV(10-14)=5*640.,CV(15-17)=3*415.,CV(18)=224.               ,... 00002040
           CV(19-21)=3*133.,CV(22-24)=3*76.                               00002050
TABLE      WNR0(1-24)=24*1.0                                              00002060
                                                                          00002070
*2.2.1.1.2          RECEIVER OUTLET TANK                                  00002120
                                                                          00002130
INCON      MNROT0=40158.4                                                 00002140
                                                                          00002150
           WDNR=WNO                                                       00002160
                                                                          00002170
                                                                          00002180
CONST           CAROT=176.71                                              00002190
```

```
*2.2.1.1.3          COLD TANK

INCON   MNACTO=8.4E06

CONST   WCTI=1.0,         CACT=7854.

*2.2.1.1.4          RECEIVER PUMP

CONST         STQ=.0266,      RTQ=.0216
CONST   TA1=.58889,       TA2=.63333,     TA3=-.22222
CONST   HA1=1.22694,      HA2=.05925,     HA3=-.28619
CONST   KRP=.1956,        TPT=1000.
INCON   NRP0=1.0

      POCT=POROT



*2.2.1.1.5          RISER PRESSURE

CONST   LRI=663.0,        LRRP=1100.,   G0=32.2,        RRPCA=359.4     ,...
        LRPSP=100.0,      RPSPCA=875.7, KFHRPR=3.159E-06                ,...
        HRP0=315.29,      POROT=15.7

        IWN=WNO*LRRP/G0/RRPCA+WNO*LRPSP/G0/RPSPCA
        IWNRPS=WNO*LRPSP/G0/RPSPCA
        LOGAR=IWN/WNO

*2.2.1.1.6          DOWNCOMER FLOW

      POHT=POROT

        IDC=WDNR*LRDCP/G0/RDCCA+WDNR*LRDVDP/G0/DVDPCA

CONST   LRDCP=1100.,   LRDVDP=100.0,  RDCCA=260.9,   DVDPCA=260.9 ,...
        KFHDCR=7.005E-06,CVDV=1445.,          EURUT=718.5

INCON   WDNO=1.0
*2.2.1.1.7              HOT TANK

INCON   MNAHTO=8.4E06
```

```
                                                                       00002620
CONST    WHTO=1.0,           CAHI=7854.0                               00002630
         WHTOR=WCTIR                                                   00002640
                                                                       00002650
*2.3.1.1              RECEIVER TUBE NODE TEMPERATURES                  00002660
                                                                       00002670
                                                                       00002680
FUNCTION RPOWER=(0.,433.09),(5.,433.09),(15.,422.06),(25.,406.32),...  00002690
          (35.,384.27),(45.,352.77),(55.,314.97),(65.,267.33),     ...  00002691
           (75.,223.63),(85.,182.68),(95.,144.89),(105.,113.39), ...    00002692
           (115.,81.9),(125.,59.84),(135.,42.52),(145.,28.35), ...      00002693
           (155.,18.9),(165.,11.02),(175.,6.3),(185.,0.)                00002694
                                                                       00002695
                                                                       00002700
                                                                       00002710
CONST     ALPHA=0.95    ,ASRA=5.42E-11 ,TG=7.31E10     ,TS=7.31E10  ,...00002720
          TA=60.        ,AR=120.17     ,MCPTW=78.87    ,PF1=.1964   ,...00002730
          PLOGA=.1584               ,MWBTUS=948.06     ,RPI=433.09      00002740
                                                                       00002750
TABLE    HFA(1-24)=24*5.56E-04                                         00002760
                                                                       00002770
TABLE    NPP(1)=.0176,NPP(2)=.0187,NPP(3)=.02,NPP(4)=.0245          ,...00002780
         NPP(5)=.0313,NPP(6)=.0398,NPP(7)=.0493,NPP(8)=.0551         ,...00002790
         NPP(9)=.0614,NPP(10)=.0661,NPP(11)=.0705,NPP(12)=.0738      ,...00002800
         NPP(13)=.0705,NPP(14)=.0661,NPP(15)=.0614,NPP(16)=.0551     ,...00002810
         NPP(17)=.0493,NPP(18)=.0398,NPP(19)=.0313,NPP(20)=.0245     ,...00002820
         NPP(21)=.02,NPP(22)=.0187,NPP(23)=.0176,NPP(24)=.0176          00002830
CONST     PF2=.6072                                                    00002840
                                                                       00002850
CONST     PF3=.1964                                                    00002860
                                                                       00002870
TABLE    TNR10G(1-24)=24*658.0                                         00003040
TABLE    TNR20G(1-24)=24*992.                                          00003050
TABLE    TNR30G(1-24)=24*1100.                                         00003060
                                                                       00003070
*2.3.1.2              RECEIVER SODIUM NODE TEMPERATURES                00003080
                                                                       00003090
CONST     NVOL=4.434     ,     NVOLIH=277.5                            00003100
                                                                       00003110
                                                                       00003140
*2.3.2.1             RECEIVER OUTLET TANK TEMPERATURES                 00003150
                                                                       00003160
```

```
INCON      TNRO0=1101.9                                              00003170
                                                                     00003180
*2.3.2.2              RISER PIPING                                   00003190
                                                                     00003200
CONST   TAURN=8.42                                                   00003210
                                                                     00003220
TABLE   TNRP0(1-9)=9*550.0                                           00003230
                                                                     00003240
INCON   TNRI0=550.                                                   00003250
                                                                     00003260
*2.3.2.4                  COLD TANK TO RECEIVER PUMP                 00003310
                                                                     00003320
CONST   TAURPS=15.5                                                  00003330
                                                                     00003340
INCON   TNCT0=549.0                                                  00003350
                                                                     00003360
*2.3.2.5                  COLD TANK                                  00003370
                                                                     00003380
CONST   WCTI=1.0,         TNCTI=549.0                                00003390
                                                                     00003400
*2.3.2.6                  DOWNCOMER PIPING                           00003410
                                                                     00003420
CONST   TAUDC=11.21                                                  00003430
                                                                     00003440
TABLE   TNDC0(1-4)=4*1101.9                                          00003450
                                                                     00003460
*2.3.2.8                  PRESSURE REDUCING DEVICE TO HOT TANK       00003470
                                                                     00003480
CONST   TAUDHT=3.94                                                  00003490
                                                                     00003500
INCON   TNHTI0=1104.5                                                00003510
                                                                     00003520
*2.3.2.9                  HOT TANK                                   00003530
                                                                     00003540
INCON   TNHT0= 1104.5                                                00003550
                                                                     00003560
CONST   WHT0=1.0                                                     00003570
                                                                     00003580
CONST  STR=1101.85    ,TAUTC=0.6     ,TAUVLV=0.3                     00003590
                                                                     00003600
                                                                     00003610
                                                                     00003620
```

```
TABLE KC(1)=.0142,KC(2)=.0132,KC(3)=.015,KC(4)=.013,KC(5)=.01       ,...
      KC(6)=.01,KC(7)=.011,KC(8)=.0102,KC(9)=.011,KC(10)=.013       ,...
      KC(11)=.014,KC(12)=.0151,KC(13)=.014,KC(14)=.013              ,...
      KC(15)=.011,KC(16)=.0102,KC(17)=.011,KC(18)=.01               ,...
      KC(19)=.01,KC(20)=.013,KC(21)=.015,KC(22)=.0132               ,...
      KC(23-24)=2*.0142

TABLE TAU(1)=6.07,TAU(2)=5.802,TAU(3)=5.49,TAU(4)=4.84,TAU(5)=4.27  ,...
      TAU(6)=3.86,TAU(7)=3.62,TAU(8)=3.53,TAU(9)=3.47,TAU(10)=3.43  ,...
      TAU(11)=3.4,TAU(12)=3.39,TAU(13)=3.4,TAU(14)=3.43             ,...
      TAU(15)=3.47,TAU(16)=3.53,TAU(17)=3.62,TAU(18)=3.86           ,...
      TAU(19)=4.27,TAU(20)=4.84,TAU(21)=5.49,TAU(22)=5.8             ,...
      TAU(23-24)=2*6.07

TABLE TAUD(1)=.912,TAUD(2)=.873,TAUD(3)=.826,TAUD(4)=.728           ,...
      TAUD(5)=.645,TAUD(6)=.585,TAUD(7)=.55,TAUD(8)=.538            ,...
      TAUD(9)=.53,TAUD(10)=.524,TAUD(11)=.521,TAUD(12)=.52          ,...
      TAUD(13)=.521,TAUD(14)=.524,TAUD(15)=.530,TAUD(16)=.538       ,...
      TAUD(17)=.55,TAUD(18)=.585,TAUD(19)=.621,TAUD(20)=.728        ,...
      TAUD(21)=.826,TAUD(22)=.873,TAUD(23-24)=2*.912

*2.4.2             PRESSURE REDUCING DEVICE CONTROLLER

CONST      TAUDV=3.0,    TAUDVI=69.93, KCDV=0.045, TAUDVD=11.1     ,...
           SLROT=4.50


*3.0               DYNAMIC SEGMENT

DYNAMIC SEGMENT


*3.1               INPUT AND BOUNDARY CONDITIONS

*3.1.3.3.1         SODIUM FILM COEFFICIENTS

PROCEDURE CP1,HANR1,RHO1,CP2,HANR2,RHO2,CP3,HANR3,RHO3,WNRA=HANR(WNR,...
            TNR1,TNR2,TNR3,AFLO,DRTUBE,HART,WNRR)
          DO 500 II=1,24
          WNRA(II)=ABS(WNR(II))*WNRR(II)
          X1,Y1=LKEQ(WNRA(II),TNR1(II),AFLO,DRTUBE,HART)
          CP1(II)=X1
```

```
          HANR1(II)=Y1                                                  00004130
          Z1=RHONA(TNR1(II))                                            00004140
          RHO1(II)=Z1                                                   00004150
          X2,Y2=LKEQ(WNRA(II),TNR2(II),AFLO,DRTUBE,HART)                00004160
          CP2(II)=X2                                                    00004170
          HANR2(II)=Y2                                                  00004180
          Z2=RHONA(TNR2(II))                                            00004190
          RHO2(II)=Z2                                                   00004200
          X3,Y3=LKEQ(WNRA(II),TNR3(II),AFLO,DRTUBE,HART)                00004210
          CP3(II)=X3                                                    00004220
          HANR3(II)=Y3                                                  00004230
          Z3=RHONA(TNR3(II))                                            00004240
      500 RHO3(II)=Z3                                                   00004250
ENDPROCEDURE                                                            00004260
          CPIH=CPNA(TNRI)                                               00004270
          RP=AFGEN(RPOWER,TIME)                                         00004280
                                                                        00004290
*3.1.3.3.2.1      RECEIVER OUTLET TANK                                  00004300
                                                                        00004310
          CPROT=CPNA(TNRO)                                              00004320
          RHOROT=RHONA(TNRO)                                            00004330
          MCPROT=MNAROT*CPROT                                           00004340
                                                                        00004350
*3.1.2.5               COLD TANK                                        00004360
                                                                        00004370
          MCPCT=MNACT*CPCT                                              00004380
          CPCT=CPNA(TNCT)                                               00004390
          RHOCT=RHONA(TNCT)                                             00004400
                                                                        00004410
                                                                        00004420
*3.1.2.7                     PRESSURE REDUCING DEVICE                   00004430
                                                                        00004440
           RHONDV=RHONA(TNDVI)                                          00004450
           CPNDV=CPNA(TNDVI)                                            00004460
                                                                        00004470
*3.1.2.9               HOT TANK                                         00004480
                                                                        00004490
          MCPHT=MNAHT*CPHT                                              00004500
          CPHT=CPNA(TNHT)                                               00004510
          RHOHT=RHONA(TNHT)                                             00004520
                                                                        00004530
                                                                        00004540
```

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```
*3.2              HYDRAULICS                                         00004550
                                                                     00004560
*3.2.1            RECEIVER SYSTEM                                    00004570
                                                                     00004580
*3.2.1.1          RECEIVER SIDE SODIUM COMPONENTS                    00004590
                                                                     00004600
*3.2.1.1.1        RECEIVER PANEL FLOW                                00004610
                                                                     00004620
          WNR=INTGRL(WNRO,DWNR,24)                                   00004630
          SNARII=RHONA(TNRI)                                         00004640
          SNARI=SNARII/62.4                                          00004650
                                                                     00004660
PROCEDURE DWNR=DW(PIR,POR,FH,DPCV,SH,IR)                             00004670
          DO 2000 JJ=1,24                                            00004680
    2000 DWNR(JJ)=(PIR-POR-FH(JJ)-DPCV(JJ)-SH(JJ))/IR(JJ)            00004690
ENDPROCEDURE                                                         00004700
                                                                     00004709
PROCEDURE SH,TSH=STATIC(EBROT,LRI,RHO1,RHO2,RHO3,SINSFT,WNR,ZERO)    00004710
          TSH=ZERO                                                   00004711
          DO 1201 LL=1,24                                            00004712
          SH(LL)=(EBROT-LRI)*(RHO1(LL)+RHO2(LL)+RHO3(LL))/3./SINSFT  00004713
    1201 TSH=TSH+SH(LL)                                              00004714
ENDPROCEDURE                                                         00004715
                                                                     00004716
                                                                     00004730
PROCEDURE FH,DPCV,TFHR,TFHCV=HEAD(ZERO,KFHC,WNR,WNRR,LBSGPM,SNARI,VP,CV)00004740
          TFHR=ZERO                                                  00004750
          TFHCV=ZERO                                                 00004760
          DO 2050 LL=1,24                                            00004770
          FH(LL)=KFHC(LL)*WNR(LL)*ABS(WNR(LL))                       00004780
          Q=WNR(LL)*WNRR(LL)*LBSGPM/SNARI                            00004790
          CVC=.025465*EXP(3.667293*VP(LL))*CV(LL)                    00004800
          DPCV(LL)=SNARI*Q*ABS(Q)/CVC**2                             00004810
          TFHR=TFHR+FH(LL)                                           00004820
    2050 TFHCV=TFHCV+DPCV(LL)                                        00004830
ENDPROCEDURE                                                         00004840
                                                                     00004850
          WNA=ABS(WN)                                                00004860
PROCEDURE WN=TEST(ZERO,WNI)                                          00004870
          IF (WNI.LT.ZERO)CALL DEBUG(1,0,0)                          00004871
          WN=LIMIT(ZERO,2.0,WNI)                                     00004872
ENDPROCEDURE                                                         00004873
```

```
          WNI=INTGRL(WDNO,DWN)                                             00004880
          DWN=(POCT-PIR+(LNACT-LRI)*(RHOCT+SNARII)/2./SINSFT-WN*WNA*    ...00004890
          KFHRP+HRP*HRPO)/LOGAR/WNO                                        00004900
                                                                           00004920
                                                                           00004930
*3.2.1.1.2       RECEIVER OUTLET TANK                                      00004940
                                                                           00004950
         DMNROT=WNIRT-WDN*WDNR                                             00004960
PROCEDURE WNIRT=FLOROT(WNRR,WNR,ZERO)                                      00004961
          WNIRT=ZERO                                                       00004962
          DO 2100 KL=1,24                                                  00004963
    2100  WNIRT=WNIRT+WNRR(KL)*WNR(KL)                                     00004964
ENDPROCEDURE                                                               00004965
         MNAROT=INTGRL(MNROTO,DMNROT)                                      00004970
         LROT=MNAROT/RHOROT/CAROT                                          00004980
         POR=POROT+LROT*RHOROT/SINSFT                                      00004990
                                                                           00005000
                                                                           00005010
*3.2.1.1.3         COLD TANK                                               00005020
         DMNACT=WCTI*WCTIR-WN*WNO                                          00005030
         MNACT=INTGRL(MNACTO,DMNACT)                                       00005040
         LNACT=MNACT/RHOCT/CACT                                            00005050
                                                                           00005060
*3.2.1.1.4         RECEIVER PUMP                                           00005070
                                                                           00005080
         RPIP=POCT+LNACT*RHOCT/SINSFT                                      00005090
         NRPX=NRP                                                          00005100
         SSRP=INSW(NRPX,0.0,1.0)                                           00005110
         TILL=INSW(NRP,STQ,RTQ)                                            00005120
         TIMRP=TA1*NRP**2+TA2*WN*NRP+TA3*WN*WNA                            00005130
         TIMRPX=(1.0-RTQ)*TIMRP+TILL                                       00005140
         DNRP=KRP*(TMRP-TIMRPX)*SSRP                                       00005150
         NRP=INTGRL(NRPO,DNRP)                                             00005160
         HRP=LIMIT(0.,1.2,HA1*NRP**2+HA2*WN*NRP+HA3*WN*WNA)                00005170
         RPOP=RPIP+HRP*HRPO                                                00005180
*3.2.1.1.5         RISER PRESSURE                                          00005190
                                                                           00005200
         PIRFLO=((24.*POR+TSH+TFHR+TFHCV)/PLOGA+(POCT+(LNACT-LRI)*      ...00005210
         (RHOCT+SNARII)/2./SINSFT-WN*WNA*KFHRP+HRP*HRPO)/LOGAR)/...        00005220
         (24./PLOGA+1./LOGAR)                                              00005230
         PIRSO=(TSH+TFHR+TFHCV)/24.+POR                                    00005235
         PIR=INSW(WN-.0001,PIRSO,PIRFLO)                                   00005236
```

```
                                                                          00005240
*3.2.1.1.6          DOWNCOMER FLOW                                        00005250
                                                                          00005260
        DWDN=(POROT-POHT-FHDC-DPDV+SHDC)/IDC                              00005270
        WDNA=ABS(WDN)                                                     00005280
        WDN=INTGRL(WDN0,DWDN)                                             00005290
        FHDC=KFHDC*WDN*WDNA                                               00005300
        DPDV=QDC*ABS(QDC)/CVCDV**2*SNDV                                   00005310
        SNDV=RHONDV/62.4                                                  00005320
        QDC=WDN*WDNR*LBSGPM/SNDV                                          00005330
        CVCDV=.025465*EXP(3.667293*VPDV)*CVDV                             00005340
        SHDC=(LROT+EBROT-LNAHT)*(RHOROT+RHONDV)/2./SINSFT                 00005350
                                                                          00005360
*3.2.1.1.7          HOT TANK                                              00005370
        DMNAHT=WDN*WDNR-WHTO*WHTOR                                        00005380
        MNAHT=INTGRL(MNAHT0,DMNAHT)                                       00005390
        LNAHT=MNAHT/RHOHT/CAHT                                            00005400
                                                                          00005410
*3.2.1.2            STEAM GENERATOR SODIUM COMPONENTS                     00005420
                                                                          00005430
                                                                          00005440
*3.2.2              BALANCE OF PLANT                                      00005450
                                                                          00005460
*3.2.2.1            WATER SYSTEM COMPONENTS                               00005470
                                                                          00005480
                                                                          00005490
                                                                          00005500
*3.3                HEAT TRANSFER                                         00005510
                                                                          00005520
*3.3.1              RECEIVER                                              00005530
                                                                          00005540
*3.3.1.1            RECEIVER TUBE NODE TEMPERATURES                       00005550
                                                                          00005560
        TRW1=INTGRL(TRW10,DTRW1,24)                                       00005570
        TRW2=INTGRL(TRW20,DTRW2,24)                                       00005580
        TRW3=INTGRL(TRW30,DTRW3,24)                                       00005590
                                                                          00005600
                                                                          00005610
PROCEDURE   QI1,QA1,DTRW1,PP =DTRT1(NPP,TRW1,TNR1,ALPHA,ASRA,TG,TS,    ...00005620
            TA,AR,HFA,MCPTW,PF1,HANR1,MWBTUS,RP)                          00005630
        DO 100 I=1,24                                                     00005640
        PP(I)=NPP(I)*RP                                                   00005650
```

```
      QI1(I)=PF1*PP(I)*MWBTUS
      QCR1=HFA(I)*AR*(TRW1(I)-TA)
      TRW14=(TRW1(I)+460.)**4
      QRG1=ASRA*(TRW14-TG)
      QRS1=ASRA*(TRW14-TS)
      QR1=(QRS1+QRG1)/2.
      QA1(I)= QI1(I)*ALPHA-QR1-QCR1
   100 DTRW1(I)=(QA1(I)-HANR1(I)*(TRW1(I)-TNR1(I)))/MCPTW
ENDPROCEDURE

PROCEDURE   QI2,QA2,DTRW2 = DTRT2(TRW2,TNR2,        ALPHA,ASRA,TG,TS,  ...
         TA,AR,HFA,MCPTW,PF2,PP,HANR2,MWBTUS)
      DO 101 J=1,24
      QI2(J)=PF2*PP(J)*MWBTUS
      QCR2=HFA(J)*AR*(TRW2(J)-TA)
      TRW24=(TRW2(J)+460.)**4
      QRG2=ASRA*(TRW24-TG)
      QRS2=ASRA*(TRW24-TS)
      QR2=(QRS2+QRG2)/2.
      QA2(J)= QI2(J)*ALPHA-QR2-QCR2
   101 DTRW2(J)=(QA2(J)-HANR2(J)*(TRW2(J)-TNR2(J)))/MCPTW
ENDPROCEDURE

PROCEDURE   QI3,QA3,DTRW3 = DTRT3(TRW3,TNR3,ALPHA,ASRA,TG,TS,TA,AR,  ...
         HFA,MCPTW,PF3,PP,HANR3,MWBTUS)
      DO 102 K=1,24
      QI3(K)=PF3*PP(K)*MWBTUS
      QCR3=HFA(K)*AR*(TRW3(K)-TA)
      TRW34=(TRW3(K)+460.)**4
      QRG3=ASRA*(TRW34-TG)
      QRS3=ASRA*(TRW34-TS)
      QR3=(QRS3+QRG3)/2.
      QA3(K)=QI3(K)*ALPHA-QR3-QCR3
   102 DTRW3(K)=(QA3(K)-HANR3(K)*(TRW3(K)-TNR3(K)))/MCPTW
ENDPROCEDURE
PROCEDURE QI,QA=QIASUM(QI1,QI2,QI3,QA1,QA2,QA3,MWBTUS)
      QI=0.0
      QA=0.0
      DO 200 N=1,24
      QI=QI+(QI1(N)+QI2(N)+QI3(N))/MWBTUS
   200 QA=QA+(QA1(N)+QA2(N)+QA3(N))/MWBTUS
ENDPROCEDURE
```

```
*3.3.1.2          RECEIVER SODIUM NODE TEMPERATURE

          TNR1=INTGRL(TNR10,DTNR1,24)
          TNR2=INTGRL(TNR20,DTNR2,24)
          TNR3=INTGRL(TNR30,DTNR3,24)

PROCEDURE DTNRI=BKFLOW(ZERO,WNR,WNRR,TNR1,TNRI,WN,WN0,TNRPO, ...
                    NVOLIH,SNARII,CPIH)
          MTNSER=ZERO
          DO 1200 KK=1,24
     1200 MTNSER=MTNSER+WNR(KK)*WNRR(KK)*INSW(WNR(KK),TNR1(KK),TNRI)
          DTNRI=(WN*WN0*TNRPO-MTNSER)/(NVOLIH*SNARII*CPIH)
ENDPROCEDURE


PROCEDURE DTNR1,DTNR2,DTNR3=DTN(HANR1,HANR2,HANR3,TRW1,TRW2,TRW3,     ...
            TNR1,TNR2,TNR3,WNR,CP1,CP2,CP3,TNRI,NVOL,RHO1,RHO2,RHO3,  ...
            TNRO,WNRA)
          DO 1000 L=1,24
          TNR1I=INSW(WNR(L),TNR2(L),TNRI)
          DTNR1(L)=(HANR1(L)*(TRW1(L)-TNR1(L))+WNRA(L)*CP1(L)*(TNR1I-...
          TNR1(L)))/(NVOL*RHO1(L)*CP1(L))
          TNR2I=INSW(WNR(L),TNR3(L),TNR1(L))
          DTNR2(L)=(HANR2(L)*(TRW2(L)-TNR2(L))+WNRA(L)*CP2(L)*(TNR2I-...
          TNR2(L)))/(NVOL*RHO2(L)*CP2(L))
          TNR3I=INSW(WNR(L),TNRO,TNR2(L))
     1000 DTNR3(L)=(HANR3(L)*(TRW3(L)-TNR3(L))+WNRA(L)*CP3(L)*(TNR3I-...
          TNR3(L)))/(NVOL*RHO3(L)*CP3(L))
ENDPROCEDURE

PROCEDURE MTINSM=MDT(WNR,WNRR,TNR3,TNRO)
          MTINSM=0.0
          DO 1500 IJ=1,24
     1500 MTINSM=MTINSM+INSW(WNR(IJ),TNRO*WNR(IJ)*WNRR(IJ),TNR3(IJ)* ...
          WNR(IJ)*WNRR(IJ))
ENDPROCEDURE



*3.3.2            INTERCONECTING LINES, TANKS AND PUMPS
```

```
*3.3.2.1          RECEIVER OUTLET TANK

          DTNRO=(MTINSM-WDN*TNRO*WDNR-DMNROT*TNRO)/MNAROT
          TNRO=INTGRL(TNRO0,DTNRO)

*3.3.2.2            RISER PIPING

        KLNR=WNA/TAURN

        TNRP=INTGRL(TNRP0 ,DTNRP,9)
        TNRPO=INTGRL(TNRI0,DTNRII)
        TNRI=INTGRL(TNRI0,DTNRI)

PROCEDURE DTNRP,DTNRII=RISER(TNRP,KLNR,TNRPUO,TNRI)
        DTNRP(1)=KLNR*(TNRPUO-TNRP(1))
        DO 300 IK=2,9
    300 DTNRP(IK)=KLNR*(TNRP(IK-1)-TNRP(IK))
        DTNRII    =KLNR*(TNRP(9)-TNRPO)
ENDPROCEDURE

*3.3.2.3            RECEIVER PUMP

        TNRPUO=INSW(WN-.01,TNRPUI,TNRPUI-HRP*HRPO*SINSFT/778./...
        RHOCT/CPCT*(1.-1./(ETARP+.01)))
        ETARP=.75*WN

*3.3.2.4            COLD TANK TO RECEIVER PUMP

        KLRPS=WNA/TAURPS
        TNRPUI=INTGRL(TNCT0,KLRPS*(TNCT-TNRPUI))

*3.3.2.5            COLD TANK

        TNCT=INTGRL(TNCT0,(WCTI*TNCTI*WCTIR-WN*WNO*TNCT-DMNACT*TNCT)/...
        MCPCT)

*3.3.2.6            DOWNCOMER PIPING

        KLDC=WDNA/TAUDC

        TNDC=INTGRL(TNDC0,DTNDC,4)
```

```
          TNDVI=INTGRL(TNRDO,DTNDVI)

PROCEDURE DTNDC,DTNDVI=DWNCOM(KLDC,TNRO,TNDC)
          DTNDC(1)=KLDC*(TNRO-TNDC(1))
          DO 400 KI=2,4
      400 DTNDC(KI)=KLDC*(TNDC(KI-1)-TNDC(KI))
          DTNDVI=KLDC*(TNDC(4)-TNDVI)
ENDPROCEDURE

*3.3.2.7            PRESSURE REDUCING DEVICE

          TNDVO=TNDVI+DPDV*SINSFT/RHONDV/778.16/CPNDV

*3.3.2.8            PRESSURE REDUCING DEVICE TO HOT TANK

          KLDVHT=WDNA/TAUDHT

          TNHTI=INTGRL(TNHTIO,KLDVHT*(TNDVO-TNHTI))

*3.3.2.9            HOT TANK

          DTNHT=(WDN*WDNR*TNHTI-WHTO*WHTOR*TNHT-DMNAHT*TNHT)/MCPHT
          TNHT=INTGRL(TNHTO,DTNHT)



*3.3.3              EVAPORATOR



*3.3.4              SUPERHEATER



*3.3.5              REHEATER



*3.3.6              HIGH PRESSURE TURBINE


```

```
*3.3.7            LOW PRESSURE  TURBINE



*3.3.8            FEED WATER HEATERS



*3.3.9            CONDENSER



*3.4              PLANT PROTECTION AND CONTROL SYSTEM

*3.4.1            RECEIVER PANEL CONTROLLERS

PROCEDURE ETI=INTCON(ES,VPOX,ZERO,ONE,TAU,KC,STR,DTNR3)
        DO 2500 JK=1,24
        ET=ES(JK)-STR
        EIR=NAND(ET,(VPOX(JK)-ONE)*NAND(-ET,(ZERO-VPOX(JK))))*ET
   2500 ETI(JK)=EIR*KC(JK)/TAU(JK)
ENDPROCEDURE


         IRX=INTGRL(VPI,ETI,24)

PROCEDURE  VPX,VPOX=RCONT(IRX,ZERO,ONE,TAUD,KC,ES,STR,VP,TAUVLV,VPI,...
        DTNR3,NRP)
        DO 3000 M=1,24
        IRA=LIMIT(ZERO,ONE,IRX(M))
       ET=ES(M)-STR
        DR=TAUD(M)*DTNR3(M)
        VPOX(M)=INSW(NRP,ONE,IRA+KC(M)*(DR+ET))
   3000 VPX(M)=(LIMIT(ZERO,ONE,VPOX(M))-VP(M))/TAUVLV
ENDPROCEDURE

PROCEDURE TNR3X=DLAY(TNR3,ES,TAUTC)
         DO 4000 KJ=1,24
    4000 TNR3X(KJ)=(TNR3(KJ)-ES(KJ))/TAUTC
ENDPROCEDURE

        ES=INTGRL(TNR30,TNR3X,24)
```

```
                                                                                 00007590
          VP=INTGRL(VPI,VPX,24)                                                  00007600
                                                                                 00007610
*3.4.2                        PRESSURE REDUCING DEVICE CONTROLLER                00007620
                                                                                 00007630
          ELROT=LROT-SLROT                                                       00007640
          EROTL=DEADSP(-0.25,0.25,ELROT)                                         00007650
          LVLSW=INSW(ABS(EROTL)-.001,ZERO,ONE)                                   00007660
          DVE=EROTL                                                              00007670
          DVEIX=NAND(DVE,(VPDVOX-ONE)*NAND(-DVE,(ZERO-VPDVOX)))*DVE              00007680
          DVEI=DVEIX*KCDV/TAUDVI                                                 00007690
          IRDVX=INTGRL(VPDVI,DVEI)                                               00007700
          IRDV=LIMIT(ZERO,ONE,IRDVX)                                             00007710
          DLROT=(WN*WNO-WDN*WDNR)/RHOROT/CAROT                                   00007720
          DRDVC=TAUDVD*DLROT*LVLSW                                               00007730
          VPDVOX=INSW(TPT-TIME,ZERO,IRDV+KCDV*(DVE+DRDVC))                       00007740
          VPDVX=(LIMIT(ZERO,ONE,VPDVOX)-VPDV)/TAUDV                              00007750
          VPDV=INTGRL(VPDVI,VPDVX)                                               00007760
                                                                                 00007761
*3.4.3                   RECEIVER PUMP                                           00007762
                                                                                 00007763
          TMRP=INSW(TPT-TIME,ZERO,ONE)                                           00007764
                                                                                 00007765
                                                                                 00007790
                                                                                 00007800
*4.0                       CONTROL STATEMENTS                                    00007810
                                                                                 00007820
TIMER DELT=0.03,     FINTIM=.10,     PRDEL=1.0,      OUTDEL=1.0                  00007830
METHOD TRAPZ                                                                     00007840
FINISH LROT=ZERO,LROT=10.0,TNRO=1700.                                            00007845
                                                                                 00007850
                                                                                 00007860
*5.0                       OUTPUT STATEMENTS                                     00007870
                                                                                 00007880
*5.1                       DEBUG INSTRUCTIONS                                    00007890
                                                                                 00007900
          Y=DEBUG(1,0.0)                                                         00007910
                                                                                 00007920
                                                                                 00007930
*5.2                       PRINT OUT INSTRUCTIONS                                00007940
                                                                                 00007950
PRINT     TNCT,TNRPUI,TNRPUO,TNRI,QI,QA,WN,TNRO,PP(1),VP(1),WNR(1)          ,...00007960
```

```
        TNR3(1),PP(6),VP(6),WNR(6),TNR3(6),PP(12),VP(12),WNR(12)    ,...00007970
        TNR3(12),TNDVI,TNDVO,TNHTI,TNHT,VPDV,WDN,LROT,EROTL,NRP,HRP ,...00007980
        PIR,POR,LNACT,LNAMT,TRW2(1),TRW2(6),TRW2(12)                    00007990
                                                                        00008000
                                                                        00008010
*5.3               PLOT INSTRUCTIONS                                    00008020
                                                                        00008030
PAGE XYPLOT                                                             00008040
                                                                        00008050
LABEL RUN 04-07 CLOUD COVER TRANSIENT, 7-13-78, 200 SECONDS             00008060
                                                                        00008070
OUTPUT  TIME      ,TNCT     ,TNRPUI   ,TNRPUO   ,TNRI                   00008080
                                                                        00008090
LABEL   TNCT - TEMPERATURE OF SODIUM IN COLD TANK (F)                   00008100
LABEL   TNRPUI - TEMPERATURE OF SODIUM, RECEIVER PUMP INLET (F)         00008110
LABEL   TNRPUO - TEMPERATURE OF SODIUM, RECEIVER PUMP OUTLET (F)        00008120
LABEL   TNRI - TEMPERATURE OF SODIUM, RECEIVER INLET (F)                00008130
                                                                        00008140
OUTPUT  TIME      ,QI       ,QA       ,WN       ,TNRO                   00008150
                                                                        00008160
LABEL   QI - TOTAL INCIDENT SOLAR POWER (MWT)                           00008170
LABEL   QA - TOTAL ABSORPED SOLAR POWER (MWT)                           00008180
LABEL   WN - TOTAL RECEIVER FLOW (LB/SEC)                               00008190
LABEL   TNRO - TEMPERATURE OF SODIUM RECEIVER OUTLET TANK (F)           00008200
                                                                        00008210
OUTPUT  TIME      ,PP(1)    ,VP(1)    ,WNR(1)  ,TNR3(1)                 00008220
                                                                        00008230
LABEL   PP(1) - SOUTH PANEL INCIDENT POWER (MWT)                        00008240
LABEL   VP(1) - SOUTH PANEL VALVE POSITION (FRACTION OPEN)              00008250
LABEL   WNR(1) - SOUTH PANEL FLOW (NORMALIZED TO 36.17 LBM/SEC)         00008260
LABEL   TNR3(1) -TEMPERATURE OF SODIUM, SOUTH PANEL OUTLET (F)          00008270
                                                                        00008280
OUTPUT  TIME      ,PP(6)    ,VP(6)    ,WNR(6)   ,TNR3(6)                00008290
                                                                        00008300
LABEL   PP(6) - WEST PANEL INCEDENT POWER (MWT)                         00008310
LABEL   VP(6) - WEST PANEL VALVE POSITION (FRACTION OPEN)               00008320
LABEL   WNR(6) - WEST PANEL FLOW (NORMALIZED 88.15 LBM/SEC)             00008330
LABEL   TNR3(6) -TEMPERATURE OF SODIUM, WEST PANEL OUTLET (F)           00008340
                                                                        00008350
OUTPUT  TIME      ,PP(12)   ,VP(12)   ,WNR(12)  ,TNR3(12)               00008360
                                                                        00008370
LABEL   PP(12) - NORTH PANEL INCIDENT POWER (MWT)                       00008380
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LABEL    VP(12) - NORTH PANEL VALVE POSITION (FRACTION OPEN)                 00008390
LABEL    WNR(12) - NORTH PANEL FLOW (NORMALIZED TO 167.69 LBM/SEC)           00008400
LABEL    TNR3(12) - TEMPERATURE OF SODIUM, NORTH PANEL OUTLET (F)            00008410
                                                                             00008420
OUTPUT   TIME       ,TRW2(1)  ,TRW2(6)  ,TRW2(12)                            00008430
                                                                             00008440
LABEL    TRW2(1) - MEAN WALL TEMPERATURE, MIDPLANE SOUTH PANEL (F)           00008450
LABEL    TRW2(6) - MEAN WALL TEMPERATURE, MIDPLANE WEST PANEL (F)            00008460
LABEL    TRW2(12) - MEAN WALL TEMPERATURE, MIDPLANE NORTH PANEL (F)          00008470
                                                                             00008480
                                                                             00008490
OUTPUT   TIME       ,TNDVI     ,TNDVO     ,TNHTI     ,TNHT                   00008500
                                                                             00008510
LABEL    TNDVI - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE INLET, F00008520
LABEL    TNDVO - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE OUTLET F00008530
LABEL    TNHTI - TEMPERATURE OF SODIUM, HOT TANK INLET (F)                   00008540
LABEL    TNHT - TEMPERATURE OF SODIUM, HOT TANK (F)                          00008550
                                                                             00008560
OUTPUT   TIME       ,VPDV      ,WDN       ,LROT      ,EROTL                  00008570
                                                                             00008580
LABEL    VPDV - PRESSURE REDUCING DEVICE VALVE POSITION (FRACTION OPEN)      00008590
LABEL    WDN - DOWNCOMER FLOW (NORMALIZED TO 2220.1 LBM/SEC)                 00008600
LABEL    LROT - RECEIVER OUTLET TANK SODIUM LEVEL (FT)                       00008610
LABEL    EROTL - RECEIVER OUTLET TANK SODIUM LEVEL ERROR                     00008620
                                                                             00008630
OUTPUT   TIME       ,NRP       ,HRP       ,PIR       ,POR                    00008640
                                                                             00008650
LABEL    NRP - RECEIVER PUMP SPEED (NORMALIZED TO 700 RPM)                   00008660
LABEL    HRP - RECEIVER PUMP HEAD (NORMALIZED TO 824 FT)                     00008670
LABEL    PIR - PRESSURE AT RECEIVER INLET (PSIA)                             00008680
LABEL    POR - PRESSURE AT RECEIVER OUTLET (PSIA)                            00008690
                                                                             00008700
OUTPUT   TIME       ,LNACT     ,LNAHT                                        00008710
                                                                             00008720
LABEL    LNACT - LEVEL OF SODIUM IN COLD TANK (FT)                           00008730
LABEL    LNAHT - LEVEL OF SODIUM IN COLD TANK (FT)                           00008740
                                                                             00008750
                                                                             00008760
*                         VARIABLE AND FUNCTION INDEX                        00008769
*                                                                            00008770
*        A=HEAT TRANSFER AREA/NODE (SQ-FT)                                   00008771
                                                                             00008780
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*       ABS=ABSOLUTE VALUE FUNCTION                                        00008790
*       AFGEN=CSMP ARBITRARY FUNCTION GENERATOR                            00008800
*       AFLO=SODIUM FLOW AREA/PANEL (SQ FT)                                00008810
*       AFLOW=SODIUM FLOW AREA (SQ-FT)                                     00008820
*       ALPHA=RECEIVER SURFACE ABSORPTIVITY(EMISSIVITY)                    00008830
*       AR=PROJECTED RECEIVER NODAL SURFACE AREA (SQ FT)                   00008840
*       AREEF=INITIAL RECEIVER EFFICIENCY GUESS                            00008850
*       ASRA=RECEIVER SURFACE ALPHA*SIGMA*AREA (BTU/SEC-R**4)              00008860
                                                                           00008870
*       BKFLOW=RECEIVER INLET HEADER TEMPERATURE SIMULATION ROUTINE        00008880
                                                                           00008890
*       CACT=COLD TANK CROSS-SECTIONAL AREA (SQ-FT)                        00008900
*       CAHT=HOT TANK CROSS-SECTIONAL AREA (SQ-FT)                         00008910
*       CAROT=CROSS-SECTIONAL AREA OF THE RECEIVER OUTLET TANK (SQ-FT)     00008920
*       CP=SODIUM HEAT CAPACITY (BTU/LBM-F)(FUNCTION OUTPUT)               00008930
*       CPCT=SODIUM HEAT CAPACITY, COLD TANK (BTU/LBM-F)                   00008940
*       CPHT=HOT TANK SODIUM HEAT CAPACITY (BTU/LBM-F)                     00008950
*       CPIH=RECEIVER INLET HEADER HEAT CAPACITY (BTU/LBM-F)               00008960
*       CPMEAN(I)=PANEL I, SODIUM MEAN HEAT CAPACITY (BTU/LBM-F)           00008970
*       CPNA=SODIUM HEAT CAPACITY ROUTINE NAME                             00008980
*       CPNDV=DRAG VALVE SODIUM HEAT CAPACITY (BTU/LBM-F)                  00008990
*       CPROT=HEAT CAPACITY RECEIVER OUTLET TANK (BTU/LBM-F)               00009000
*       CPSOD=SODIUM HEAT CAPACITY (BTU/LBM-F)                             00009010
*       CP1I=INITIAL SODIUM HEAT CAPACITY, LOWER NODES (BTU/LBM-F)         00009020
*       CP2I=INITIAL SODIUM HEAT CAPACITY, MIDDLE NODES (BTU/LBM-F)        00009030
*       CP3I=INITIAL SODIUM HEAT CAPACITY, UPPER NODES (BTU/LBM-F)         00009040
*       CP1(I)=LOWER NODE, PANEL I SODIUM HEAT CAPACITY (BTU/LBM-F)        00009050
*       CP2(I)=MIDDLE NODE, PANEL I SODIUM HEAT CAPACITY (BTU/LBM-F)       00009060
*       CP3(I)=UPPER NODE, PANEL I SODIUM HEAT CAPACITY (BTU/LBM-F)        00009070
*       CVC=CONTROL VALVE FLOW COEFFICIENT (GPM/PSI)                       00009080
*       CVCDV=INITIAL DRAG VALVE FLOW COEFFICIENT (GPM/PSI)                00009090
*       CVCI=INITIAL CONTROL VALVE FLOW COEFFICIENT (GPM/PSI)              00009100
*       CVDV=DRAG VALVE FULL OPEN FLOW COEFFICIENT (GPM/PSI)               00009110
*       CV(I)=PANEL I CONTROL VALVE FLOW COEFFICIENT (GPM/PSI)(OPEN)       00009120
                                                                           00009130
*       D=FLOW PASSAGE DIAMETER (FT)                                       00009140
*       DEADSP=CSMP DEADBAND FUNCTION                                      00009150
*       DEBUG=CSMP DEBUG FUNCTION                                          00009160
*       DELT=CSMP TIME STEP (SEC)                                          00009170
*       DLAY=THERMOCOUPLE DYNAMIC SIMULATION ROUTINE                       00009180
*       DLROT=RECEIVER OUTLET TANK LEVEL DERIVATIVE (FT/SEC)               00009190
*       DMNACT=COLD TANK SODIUM NET INFLOW (LBM/SEC)                       00009200
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*         DMNAHT=HOT TANK SODIUM NET INFLOW (LBM/SEC)                          00009210
*         DMNROT=RECEIVER OUTLET TANK SODIUM MASS DERIVATIVE (LBM/SEC)         00009220
*         DNRP=RECEIVER PUMP SPEED ACCELERATION (NORMALIZED)                   00009230
*         DPCVI=INITIAL CONTROL VALVE PRESSURE DROP (PSI)                      00009240
*         DPCV(I)=PANEL I CONTROL VALVE PRESSURE DROP (PSI)                    00009250
*         DPDVI=INITIAL DRAG VALVE PRESSURE DROP (PSI)                         00009270
*         DPDVOX=UNLIMITED RECEIVER OUTLET TANK CONTROLLER RESPONSE            00009280
*         DPDV=DRAG VALVE PRESSURE DROP (PSI)                                  00009290
*         DR=CONTROLLER DERIVATIVE RESPONSE                                    00009300
*         DRDVC=DERIVATIVE RESPONSE RECEIVER OUTLET TANK LEVEL CONTROLLER00009310
*         DRTUBE=RECEIVER TUBE INSIDE DIAMETER (FT)                            00009320
*         DTN=SODIUM TEMPERATURE DERIVATIVE FUNCTION                           00009330
*         DTNDC(I)=DOWNCOMER NODE I TEMPERATURE DERIVATIVE (F/SEC)             00009340
*         DTNDVI=DRAG VALVE INLET TEMPERATURE DERIVATIVE (F/SEC)               00009350
*         DTNHT=HOT TANK SODIUM TEMPERATURE DERIVATIVE (F/SEC)                 00009360
*         DTNRI=RECEIVER INLET TEMPERATURE DERIVATIVE (F/SEC)                  00009370
*         DTNRII=RISER OUTLET TEMPERATURE DERIVATIVE (F/SEC)                   00009380
*         DTNRO=RECEIVER OUTLET TANK TEMPERATURE DERIVATIVE (F/SEC)            00009390
*         DTNRP(I)=RISER NODE I TEMPERATURE DERIVATIVE (F/SEC)                 00009400
*         DTNR1(I)=RECEIVER PANEL I, NODE 1, SODIUM TEMPERATURE DERIV.         00009410
*         DTNR2(I)=RECEIVER PANEL I, NODE 2, SODIUM TEMP. DERIVATIVE           00009420
*         DTNR3(I)=RECEIVER PANEL I, NODE 3, SODIUM TEMP. DERIVATIVE           00009430
*         DTRT1=NODE 1 RECEIVER TUBE TEMPERATURE DERIVATIVE ROUTINE NAME       00009440
*         DTRT2=NODE 2 RECEIVER TUBE TEMPERATURE DERIVATIVE ROUTINE            00009450
*         DTRT3=NODE 3 RECEIVER TUBE TEMPERATURE DERIVATIVE ROUTINE            00009460
*         DTRW1(I)=PANEL I, NODE 1 WALL TEMPERATURE DERIVATIVE (F/SEC)         00009470
*         DTRW2(I)=PANEL I, NODE 2 WALL TEMPERATURE DERIVATIVE (F/SEC)         00009480
*         DTRW3(I)=PANEL I, NODE 3 WALL TEMPERATURE DERIVATIVE (F/SEC)         00009490
*         DVDPCA=DRAG VALVE DISCHARGE PIPE CROSS-SECTIONAL AREA (SQ-IN)        00009500
*         DVE=SEE EROTL                                                        00009510
*         DVEI=PROCESSED INTEGRAL CONTROL RESPONSE                             00009520
*         DVEIX=LEVEL CONTROLLER INTEGRAL ERROR (FT)                           00009530
*         DW=RECEIVER PANEL FLOW ACCELERATION ROUTINE NAME                     00009540
*         DWDN=NORMALIZED DOWNCOMER FLOW ACCELERATION (1/SEC-SEC)              00009550
*         DWN=RISER FLOW ACCELERATION (NORMALIZED) (1/SEC-SEC)                 00009560
*         DWNCOM=DOWNCOMER SODIUM TEMPERATURE DERIVATIVE ROUTINE               00009570
*         DWNR(I)=FLOW DERIVATIVE, PANEL I, NORMALIZED (1/SEC-SEC)             00009580
                                                                               00009590
*         EBROT=ELEVATION OF BASE OF RECEIVER OUTLET TANK (FT)                 00009600
*         EIR=PROCESSED PANEL ERROR (F)                                        00009610
*         ELROT=RECEIVER OUTLET TANK LEVEL ERROR  (FT)                         00009620
*         EROTL=ERROR SIGNAL TO RECEIVER OUTLET TANK LEVEL CONTROLLER          00009630
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*        ERRFLG=INITIAL CONDITION ERROR FLAG
*        ERROR1=LOWER NODES ABSORBED POWER ERROR
*        ERROR2=MIDDLE NODES ABSORBED POWER ERROR
*        ERROR3=UPPER NODES ABSORBED POWER ERROR
*        ES(I)=THERMOCOUPLE OUTPUT TEMPERATURE PANEL I (F)
*        ET=PANEL OUTLET SODIUM TEMPERATURE ERROR(F)
*        ETARP=RECEIVER PUMP EFFICIENCY
*        ETI(I)=PROCESSED INTEGRAL ERROR

*        FHDC=DOWNCOMER FRICTION HEAD (PSI)
*        FH(I)=PANEL I FRICTION DROP (TIME VARYING)(PSI)
*        FINTIM=RUN FINISH TIME (SEC)
*        FLOROT=RECEIVER OUTLET TANK NET INFLOW ROUTINE NAME

*        G0=ACCELERATION DUE TO GRAVITY (32.2 FT/SEC-SEC)

*        H=SODIUM FILM COEFFICIENT (BTU/SQFT-SEC-F)
*        HA=SODIUM FILM COEFF.-AREA PRODUCT (BTU/SEC-F)(FUNCTION OUTPUT)
*        HART=TOTAL TUBE INSIDE HEAT TRANSFER AREA/NODE (SQ FT)
*        HANR=SODIUM FILM COEFF.-AREA PRODUCT (BTU/SEC-F)
*        HANR1I=INITIAL FILM COEF.-AREA PRODUCT, LOWER NODES (BTU/SEC-F)
*        HANR2I=INITIAL FILM COEF.-AREA PRODUCT, MID. NODES (BTU/SEC-F)
*        HANR3I=INITIAL FILM COEF.-AREA PRODUCT, UPPER NODES (BTU/SEC-F)
*        HANR1(I)=LOWER AXIAL NODE FILM COEFF.-AREA PRODUCT (BTU/SEC-F)
*        HANR2(I)=MIDDLE AXIAL NODE FILM COEFF.-AREA PRODUCT (BTU/SEC-F)
*        HANR3(I)=UPPER AXIAL NODE FILM COEFF.-AREA PRODUCT (BTU/SEC-F)
*        HA1=RECEIVER PUMP DEVELOPED HEAD COEFFICIENT 1
*        HA2=RECEIVER PUMP DEVELOPED HEAD COEFFICIENT 2
*        HA3=RECEIVER PUMP DEVELOPED HEAD COEFFICIENT 3
*        HFA(I)=LOCAL RECEIVER-AIR FILM COEFFICIENT(BTU/SQFT-DEGF-SEC)
*        HRP=NORMALIZED RECEIVER PUMP HEAD
*        HRP0=INITIAL RECEIVER PUMP HEAD (PSI)
*        HYDINT=RECEIVER HYDRAULIC INITIAL CONDITION ROUTINE NAME

*        IDC=DOWNCOMER INERTIA (PSI-SEC)
*        INITC=INITIAL TEMPERATURE CALCULATION ROUTINE NAME
*        INSW=CSMP INPUT SWITCH FUNCTION NAME
*        INTCON=RECEIVER PANEL CONTROLLER INTEGRATOR ROUTINE
*        INTGRL=CSMP INTEGRATION ROUTINE CALL-UP
*        IRA=ACTUAL INTEGRAL CONTROLLER RESPONSE
*        IRDV=ACTUAL RECEIVER OUTLET TANK LEVEL CONTROLLER INTEGRAL RES.
*        IRDVX=RECEIVER OUTLET TANK LEVEL CONTROLLER INTEGRAL RESPONSE
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*        IRX(I)=PANEL I, INTEGRAL CONTROL RESPONSE                          00010060
*        ISRSG=SQUARE ROOT RECEIVER INLET SPECIFIC GRAVITY                  00010070
*        IR(I)=PANEL I FLOW INERTIA (PSI-SEC)                               00010080
*        IWN=RISER PIPING INERTIA (PSI-SEC)                                 00010090
*        IWNRPS=RECEIVER PUMP SUCTION PIPEING INERTIA (PSI-SEC)             00010100
                                                                            00010110
*        KCDV=DRAG VALVE CONTROLLER GAIN                                    00010120
*        KC(I)=PANEL I CONTROLLER GAIN                                      00010130
*        KFHDC=STEADY-STATE DOWNCOMER FRICTION HEAD (PSI)                   00010150
*        KFHDCR=DOWNCOMER FRICTION HEAD PER UNIT FLOW SQUARED               00010160
*        KFHRP=INITIAL RISER FRICTION DROP (PSI)                            00010170
*        KFHRPR=RISER FRICTION HEAD PER UNIT FLOW SQUARED (PSI/SQ-LBM/S)00010180
*        KFHC(I)=PANEL I STEADY-STATE FRICTION DROP (PSI)                   00010190
*        KFH(I)=PANEL I STEADY-STATE FRICTION DROP/UNIT FLOW SQUARED        00010200
*        KLDC=DOWNCOMER VARIABLE TRANSPORT TERM (1/SEC)                     00010210
*        KLDVHT=DRAG VALVE DISCHARGE PIPE TRANSPORT TERM (1/SEC)            00010220
*        KLNR=RISER PIPING NODE VARIABLE TRANSPORT TERM (1/SEC)             00010230
*        KLRPS=RECEIVER PUMP SUCTION VARIABLE TRANSPORT TERM (1/SEC)        00010240
*        KNA=SODIUM THERMAL CONDUCTIVITY (BTU/FT-SEC-F)                     00010250
*        KRP=RECEIVER PUMP NORMALIZED INERTIA (1/SEC)                       00010260
                                                                            00010270
*        LBSGPM=CONVERSION  LBM/SEC TO GAL/MIN                              00010280
*        LIMIT=CSMP LIMITER FUNCTION                                        00010290
*        LKEQ=SODIUM FILM COEFFICIENT ROUTINE NAME                          00010300
*        LNACT=COLD TANK SODIUM LEVEL (FT)                                  00010310
*        LNACTO=INITIAL COLD TANK SODIUM LEVEL (FT)                         00010320
*        LNAHT=HOT TANK SODIUM LEVEL (FT)                                   00010330
*        LNAHTO=INITIAL HOT TANK SODIUM LEVEL (FT)                          00010340
*        LOGAR=RISER INERTIA/RISER REFERENCE FLOW (PSI-SEC-SEC/LBM)         00010350
*        LRDCP=DOWNCOMER PIPE LENGTH (FT)                                   00010360
*        LRDVDP=DRAG VALVE DISCHARGE PIPE LENGTH (FT)                       00010370
*        LRI=RECEIVER INLET ELEVATION (FT)                                  00010380
*        LROT=RECEIVER OUTLET TANK  LEVEL (FT)                              00010390
*        LROTO= INITIAL RECEIVER OUTLET TANK SODIUM LEVEL (FT)              00010400
*        LRPSP=RECEIVER PUMP SUCTION PIPE LENGTH (FT)                       00010410
*        LRRP=RISER PIPING LENGTH (FT)                                      00010420
                                                                            00010440
*        MCPCT=MASS CAPACITY, COLD TANK (BTU/F)                             00010450
*        MCPHT=HOT TANK SODIUM MASS-CAPACITY (BTU/F)                        00010460
*        MCPROT=MASS-CAPACITY PRODUCT RECEIVER OUTLET TANK (BTU/F)          00010470
*        MCPTW=MASS-HEAT CAPACITY PRODUCT/TUBE NODE (BTU/DEG F)             00010480
*        MDOT=SODIUM MASS FLOWRATE (LBM/SEC)                                00010490
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*          MDT=MASS-TEMPERATURE PRODUCT-SUMMATION RECEIVER OUTLET TANK     00010500
*          MNACT=COLD TANK SODIUM MASS (LBM)                               00010510
*          MNACTO=INITIAL COLD TANK SODIUM MASS (LBM)                      00010520
*          MNAHT=HOT TANK SODIUM MASS (LBM)                                00010530
*          MNAHTO=INITIAL HOT TANK SODIUM MASS (LBM)                       00010540
*          MNAROT=RECEIVER OUTLET TANK SODIUM MASS (LBM)                   00010550
*          MNROTO=INITIAL MASS OF SODIUM IN THE RECEIVER OUTLET TANK (LBM)00010560
*          MTINSM=MASS-TEMPERATURE PRODUCT-SUMMATION RECEIVER OUTLET TANK  00010570
*          MTNSER=MASS-TEMPERATURE PRODUCT SUMMATION RECEIVER INLET PLENUM00010580
*          MU=SODIUM ABSOLUTE VISCOSITY (LBM/FT-SEC)                       00010590
*          MULOG=BASE 10 LOG OF VISCOSITY                                  00010600
*          MWBTUS=CONVERSION FACTOR  MWT TO BTU/SEC                        00010610
                                                                           00010620
*          NPP(I)=PANEL I NORMALIZED INCIDENT POWER                        00010630
*          NQA1(I)=LOWER NODE, PANEL I, ABSORBED POWER (BTU/SEC) UPDATE    00010640
*          NQA2(I)=MIDDLE NODE, PANEL I, ABSORBED POWER (BTU/SEC) UPDATE   00010650
*          NQA3(I)=UPPER NODE, PANEL I, ABSORBED POWER (BTU/SEC) UPDATE    00010660
*          NRP=NORMALIZED RECEIVER PUMP SPEED                              00010670
*          NRPX=INTERMEDIATE RECEIVER PUMP SPEED, NORMALIZED               00010680
*          NRPO=INITIAL NORMALIZED RECEIVER PUMP SPEED                     00010690
*          NUN=NUSSELT NUMBER                                              00010700
*          NVOL=SODIUM VOLUME/RECEIVER NODE (CUFT)                         00010710
*          NVOLIH=SODIUM VOLUME, RECEIVER INLET HEADER (CUFT)              00010720
                                                                           00010730
*          ONE=ONE                                                         00010740
*          OUTDEL=OUTPUT INTERVAL (PLOT)                                   00010750
                                                                           00010760
*          PF1=FRACTION OF PANEL POWER INCIDENT ON AXIAL TUBE NODE 1       00010770
*          PF2=FRACTION OF PANEL POWER INCIDENT ON AXIAL TUBE NODE 2       00010780
*          PF3=FRACTION OF PANEL POWER INCIDENT ON AXIAL TUBE NODE 3       00010790
*          PIR=RECEIVER TOTAL INLET PRESSURE (PSIA)                        00010800
*          PIRFLO=RECEIVER INLET TOTAL PRESSURE-RISER FLOW (PSIA)          00010810
*          PIRI=STEADY-STATE RECEIVER INLET TOTAL PRESSURE (PSIA)          00010820
*          PIRSO=RECEIVER INLET PRESSURE-RISER SHUT-OFF (PSIA)             00010830
*          PLOGA=PANEL LENGTH/GRAVITY ACCELERATION-FLOW AREA               00010840
*          POCT=ULLAGE PRESSURE OF THE COLD TANK (PSIA)                    00010850
*          POHT=HOT TANK ULLAGE PRESSURE (PSIA)                            00010860
*          POR=TOTAL RECEIVER OUTLET PRESSURE (PSIA)                       00010870
*          PORI=STEADY-STATE RECEIVER OUTLET TOTAL PRESSURE (PSIA)         00010880
*          POROT=RECEIVER OUTLET TANK ULLAGE PRESSURE (PSIA)               00010890
*          PP(I)=PANEL I INCIDENT POWER, (MWT)                             00010900
*          PR=PRANDTL NUMBER                                               00010910
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*        PRDEL=OUTPUT INTERVAL (PRINT)                                  00010920
                                                                        00010930
*        Q=PANEL FLOW OF SODIUM (GPM H2O)                               00010940
*        QA=TOTAL RECEIVER TUBING ABSORBED POWER (MWT)                  00010950
*        QAI(I)=PANEL I, TOTAL ABSORBED POWER (BTU/SEC)                 00010960
*        QA1(I)=LOWER NODE, PANEL I, ABSORBED POWER (BTU/SEC)           00010970
*        QA2(I)=MIDDLE NODE, PANEL I, ABSORBED POWER (BTU/SEC)          00010980
*        QA3(I)=UPPER NODE, PANEL I, ABSORBED POWER (BTU/SEC)           00010990
*        QCR1=NODE 1 CONVECTIVE HEAT LOSS (BTU/SEC)                     00011000
*        QCR2=NODE 2 CONVECTIVE HEAT LOSS (BTU/SEC)                     00011010
*        QCR3=NODE 3 CONVECTIVE HEAT LOSS (BTU/SEC)                     00011020
*        QDC=DOWNCOMER FLOW (GPM)                                       00011030
*        QI=TOTAL RECEIVER INCIDENT POWER (MWT)                         00011040
*        QIASUM=TOTAL RECEIVER POWER ROUTINE                            00011050
*        QIDC=INITIAL DOWNCOMER FLOW (GPM)                              00011060
*        QI1(I)=LOWER AXIAL NODE, PANEL I, INCIDENT POWER (BTU/SEC)     00011070
*        QI2(I)=MIDDLE AXIAL NODE, PANEL I, INCIDENT POWER (BTU/SEC)    00011080
*        QI3(I)=UPPER AXIAL NODE, PANEL I, INCIDENT POWER (BTU/SEC)     00011090
*        QRG1=NODE 1 RADIATIVE LOSS TO GROUND (BTU/SEC)                 00011100
*        QRG2=NODE 2 RADIATIVE LOSS TO GROUND (BTU/SEC)                 00011110
*        QRG3=NODE 3 RADIATIVE LOSS TO GROUND (BTU/SEC)                 00011120
*        QRS1=NODE 1 RADIATIVE LOSS TO SKY (BTU/SEC)                    00011130
*        QRS2=NODE 2 RADIATIVE LOSS TO SKY (BTU/SEC)                    00011140
*        QRS3=NODE 3 RADIATIVE LOSS TO SKY (BTU/SEC)                    00011150
*        QR1=NODE 1 TOTAL RADIATIVE LOSS (BTU/SEC)                      00011160
*        QR2= NODE 2 TOTAL RADIATIVE LOSS (BTU/SEC)                     00011170
*        QR3=NODE 3 TOTAL RADIATIVE LOSS (BTU/SEC)                      00011180
                                                                        00011190
*        RCONT=RECEIVER PANEL CONTROLLER ROUTINE                        00011200
*        RDCCA=DOWNCOMER CROSS-SECTIONAL AREA (SQ-IN)                   00011210
*        RED=REYNOLDS NUMBER                                            00011220
*        RH=RECEIVER PANEL HEIGHT (FT)                                  00011230
*        RHOCT=COLD TANK SODIUM DENSITY (LBM/CU-FT)                     00011240
*        RHOCT0=INITIAL COLD TANK SODIUM DENSITY (LBM/CU-FT)            00011250
*        RHODC0=INITIAL DOWNCOMER SODIUM DENSITY (LBM/CU-FT)            00011260
*        RHOHT=HOT TANK SODIUM DENSITY (LBM/CU-FT)                      00011270
*        RHOHT0=INITIAL HOT TANK SODIUM DENSITY (LBM/CU-FT)             00011280
*        RHON=SODIUM DENSITY (LBM/CU-FT)                                00011290
*        RHONA=SODIUM DENSITY ROUTINE NAME                              00011300
*        RHONDV=DRAG VALVE SODIUM DENSITY (LBM/CU-FT)                   00011310
*        RHONRI=RECEIVER INLET SODIUM DENSITY (LBM/CU-FT)               00011320
*        RHOROT=SODIUM DENSITY RECEIVER OUTLET TANK (LBM-CUFT)          00011330
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*       RHORP0=INITIAL RISER PIPE SODIUM DENSITY (LBM/CU-FT)                   00011340
*       RHO1I=INITIAL SODIUM LOWER NODE DENSITY (LBM/CU-FT)                    00011350
*       RHO2I=INITIAL SODIUM MIDDLE NODE DENSITY (LBM/CU-FT)                   00011360
*       RHO3I=INITIAL SODIUM UPPER NODE DENSITY (LBM/CU-FT)                    00011370
*       RHO1(I)=LOWER NODE, PANEL I SODIUM DENSITY (LBM/CU-FT)                 00011380
*       RHO2(I)=MIDDLE NODE, PANEL I SODIUM DENSITY (LBM/CU-FT)                00011390
*       RHO3(I)=UPPER NODE, PANEL I SODIUM DENSITY (LBM/CU-FT)                 00011400
*       RISER=RISER PIPE TEMPERATURE DERIVATIVE ROUTINE                        00011410
*       RP=TOTAL INCIDENT RECEIVER POWER (MWT)                                 00011420
*       RPI=INITIAL INCIDENT RECEIVER POWER (MWT)                              00011430
*       RPIP=RECEIVER PUMP INLET PRESSURE (PSIA)                               00011440
*       RPOP=RECEIVER PUMP OUTLET PRESSURE (PSIA)                              00011450
*       RPOWER=INCIDENT RECEIVER POWER FUNCTION NAME                           00011460
*       RPSPCA=RECEIVER PUMP SUCTION PIPE CROSS-SECTIONAL AREA (SQ-IN)         00011470
*       RRPCA=RISER PIPING CROSS-SECTIONAL AREA (SQ-IN)                        00011480
*       RTQ=RECEIVER PUMP AND MOTOR NORMALIZED RUNNING TORQUE                  00011490
                                                                               00011500
*       SGDV=DRAG VALVE SODIUM SPECIFIC GRAVITY                                00011510
*       SGNRI=RECEIVER INLET SPECIFIC GRAVITY                                  00011520
*       SHDC=DOWNCOMER STATIC HEAD (PSI)                                       00011530
*       SHDCI=INITIAL DOWNCOMER STATIC HEAD (PSI)                              00011540
*       SHI=INITIAL RECEIVER STATIC HEAD (PSI)                                 00011550
*       SH(I)=PANEL I STATIC HEAD (PSI)                                        00011560
*       SINSFT=CONVERSION FACTOR SQUARE INCHES TO SQUARE FOOT                  00011570
*       SLROT=RECEIVER OUTLET TANK SET LEVEL (FT)                              00011580
*       SNARI=RECEIVER INLET SODIUM SPECIFIC GRAVITY                           00011590
*       SNARII=RECEIVER INLET SODIUM DENSITY (LBM/CU-FT)                       00011600
*       SNDV=DRAG VALVE SODIUM SPECIFIC GRAVITY                                00011610
*       SRSGDV=SQUARE ROOT OF THE DRAG VALVE SODIUM SPECIFIC GRAVITY           00011620
*       SSRP=RECEIVER PUMP SPEED SWITCH                                        00011630
*       STATIC=RECEIVER PANEL STATIC HEAD ROUTINE NAME                         00011640
*       STQ=NORMALIZED STATIC TORQUE OF THE RECEIVER PUMP AND MOTOR            00011650
*       STR=RECEIVER OUTLET SET POINT (F)                                      00011660
                                                                               00011670
*       T=SODIUM TEMPERATURE (F)                                               00011680
*       TA=AMBIENT AIR TEMPERATURE (DEGREES F)                                 00011690
*       TAUDC=DOWNCOMER FLOW TIME CONSTANT (SEC)                               00011700
*       TAUDHT=DRAG VALVE DISCHARGE PIPE TIME CONSTANT (SEC)                   00011710
*       TAUDV=DRAG VALVE TIME CONSTANT (SEC)                                   00011715
*       TAUDVD=DRAG VALVE CONTROLLER DERIVITIVE TIME (SEC)                     00011720
*       TAUDVI=DRAG VALVE CONTROLLER INTEGRAL TIME (SEC)                       00011730
*       TAUD(I)=DERIVITIVE TIME, PANEL I CONTROLLER (SEC)                      00011740
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*          TAU(I)=INTEGRAL TIME, PANEL I CONTROLLER (SEC)(1/RESET)              00011750
*          TAURN=RISER PIPING NODE TIME CONSTANT (MASS/MASS-FLOW, SEC)          00011760
*          TAURPS=RECEIVER PUMP SUCTION PIPE TIME CONSTANT (SEC)                00011770
*          TAUTC= PANEL THERMOCOUPLE TIME CONSTANT (SEC)                        00011780
*          TAUVLV=PANEL VALVE ACTUATORS TIME CONSTANT (SEC)                     00011790
*          TA1=RECEIVER PUMP REQUIRED TORQUE COEFFICIENT 1                      00011800
*          TA2=RECEIVER PUMP REQUIRED TORQUE COEFFICIENT 2                      00011810
*          TA3=RECEIVER PUMP REQUIRED TORQUE COEFFICIENT 3                      00011820
*          TEST=CHECK VALVE SIMULATION FUNCTION                                 00011830
*          TFHCV=SUM OF PANEL CONTROL VALVE DROPS (PSI)                         00011840
*          TFHR=SUM OF PANEL FRICTION HEAD (PSI)                                00011850
*          TG=EFFECTIVE GROUND TEMPERATURE (R**4)                               00011860
*          TILL=RECEIVER PUMP INPUT TORQUE FRACTION                             00011870
*          TIME=TIME                                                            00011880
*          TIMRP=RECEIVER PUMP REQUIRED TORQUE (NORMALIZED)                     00011890
*          TIMRPX=RECEIVER PUMP REQUIRED NORMALIZED TORQUE                      00011900
*          TMRP=RECEIVER PUMP MOTOR NORMALIZED TORQUE                           00011910
*          TNA=SODIUM TEMPERATURE (F)                                           00011920
*          TNCT=COLD TANK SODIUM TEMPERATURE (F)                                00011930
*          TNCTI=COLD TANK SODIUM INLET TEMPERATURE (F)                         00011940
*          TNCTO=INITIAL COLD TANK SODIUM TEMPERATURE (F)                       00011950
*          TNDCO(I)=INITIAL DOWNCOMER NODE I TEMPERATURE (F)                    00011960
*          TNDC(I)=DOWNCOMER NODE I TEMPERATURE (F)                             00011970
*          TNDVI=DRAG VALVE SODIUM INLET TEMPERATURE (F)                        00011980
*          TNDVO=DRAG VALVE SODIUM OUTLET TEMPERATURE (F)                       00011990
*          TNHT=HOT TANK SODIUM TEMPERATURE (F)                                 00012000
*          TNHTI=HOT TANK SODIUM INLET TEMPERATURE (F)                          00012010
*          TNHTIO=INITIAL HOT TANK SODIUM INLET TEMPERATURE (F)                 00012020
*          TNHTO=INITIAL HOT TANK SODIUM TEMPERATURE (F)                        00012030
*          TNRI=RECEIVER INLET MANIFOLD TEMPERATURE (F)                         00012040
*          TNRIO=INITIAL RECEIVER INLET TEMPERATURE (F)                         00012050
*          TNRO=RECEIVER OUTLET TANK TEMPERATURE (F)                            00012060
*          TNROO=INITIAL RECEIVER OUTLET TANK TEMPERATURE (F)                   00012070
*          TNRPO=RISER PIPING OUTLET TEMPERATURE (F)                            00012080
*          TNRPUI=RECEIVER PUMP SODIUM INLET TEMPERATURE (F)                    00012090
*          TNRPUO=RECEIVER PUMP OUTLET TEMPERATURE (F)                          00012100
*          TNRPO(I)=RISER PIPING NODE INITIAL TEMPERATURE (F)                   00012110
*          TNRP(I)=RISER PIPING NODE I SODIUM TEMPERATURE (F)                   00012120
*          TNR1I=NODE 1 SODIUM INLET TEMPERATURE (F)                            00012130
*          TNR2I=NODE 2 SODIUM INLET TEMPERATURE (F)                            00012140
*          TNR3I=NODE 3 SODIUM INLET TEMPERATURE (F)                            00012150
*          TNR1(I)=RECEIVER PANEL I, NODE 1, SODIUM TEMPERATURE (F)             00012160
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*       TNR2(I)=RECEIVER PANEL I, NODE 2, SODIUM TEMPERATURE (F)          00012170
*       TNR3(I)=RECEIVER PANEL I, NODE 3, SODIUM TEMPERATURE (F)          00012180
*       TNR10G(I)=LOWER NODE, PANEL I, INITIAL SODIUM TEMP. GUESS (F)     00012190
*       TNR20G(I)=MIDDLE NODE, PANEL I, INITIAL SODIUM TEMP. GUESS (F)    00012200
*       TNR30G(I)=UPPER NODE, PANEL I, INITIAL SODIUM TEMP. GUESS (F)     00012210
*       TNR10(I)=PANEL I,AXIAL NODE 1 INITIAL SODIUM TEMPERATURE (F)      00012220
*       TNR20(I)=PANEL I,AXIAL NODE 2 INITIAL SODIUM TEMPERATURE (F)      00012230
*       TNR30(I)=PANEL I,AXIAL NODE 3 INITIAL SODIUM TEMPERATURE (F)      00012240
*       TPT=TIME OF THE RECEIVER PUMP TRIP (SEC)                          00012250
*       TR=SODIUM TEMPERATURE (R)                                         00012260
*       TRAPZ=INTEGRATION METHOD (TRAPAZOIDAL)                            00012270
*       TRW14=NODE 1 TUBE TEMPERATURE RAISED TO FOURTH POWER (R)          00012280
*       TRW24=NODE 2 TUBE TEMPERATURE RAISED TO FOURTH POWER (R)          00012290
*       TRW34=NODE 3 TUBE TEMPERATURE RAISED TO FOURTH POWER (R)          00012300
*       TRW1(I)=PANEL I, NODE 1 WALL TEMPERATURE (F)                      00012310
*       TRW2(I)=PANEL I, NODE 2 WALL TEMPERATURE (F)                      00012320
*       TRW3(I)=PANEL I, NODE 3 WALL TEMPERATURE (F)                      00012330
*       TRW10(I)=PANEL I, AXIAL NODE 1 INITIAL WALL TEMPERATURE (F)       00012340
*       TRW20(I)=PANEL I, AXIAL NODE 2 INITIAL WALL TEMPERATURE (F)       00012350
*       TRW30(I)=PANEL I, AXIAL NODE 3 INITIAL WALL TEMPERATURE (F)       00012360
*       TS=EFFECTIVE SKY TEMPERATURE (R**4)                               00012370
*       TSH=SUM OF PANEL STATIC HEADS (PSI)                               00012380
*       TSOD=SODIUM TEMPERATURE (F)                                       00012390
                                                                          00012400
*       VPDV=DRAG VALVE POSITION (FRACTION OPEN)                          00012410
*       VPDVI=INITIAL DRAG VALVE POSITION (PERCENT OPEN)                  00012420
*       VPDVX=DRAG VALVE INTERMEDIATE POSITION DEMAND (FRACTION OPEN)     00012430
*       VPI(I)=INITIAL VALVE POSITION, PANEL I (PERCENT OF FULL OPEN)     00012440
*       VPOX(I)=PANEL I CONTROLLER VALVE POSITION DEMAND (PERCENT OPEN)00012450
*       VPX(I)=CONTROLLER I VALVE POSITION SIGNAL (FRACTION OPEN)         00012460
*       VP(I)=PANEL I VALVE POSITION (FRACTION OPEN)                      00012470
                                                                          00012480
*       WCTI=NORMALIZED COLD TANK SODIUM INLET FLOW (LBM/SEC)             00012490
*       WCTIR=REFERENCE COLD TANK INLET SODIUM FLOW (LBM/SEC)             00012500
*       WDN=NORMALIZED DOWNCOMER FLOW                                     00012510
*       WDNA=ABSOLUTE VALUE OF NORMALIZED DOWNCOMER FLOW                  00012520
*       WDNR=DOWNCOMER REFERENCE FLOW (LBM/SEC)                           00012530
*       WDNO=INITIAL DOWNCOMER NORMALIZED FLOW                            00012540
*       WHTO=NORMALIZED HOT TANK SODIUM OUT LET FLOW                      00012550
*       WHTOR=HOT TANK OUTLET REFERENCE FLOW (LBM/SEC)                    00012560
*       WHTO=INITIAL HOT TANK NORMALIZED SODIUM INLET FLOW                00012570
*       WN=RISER NORMALIZED SODIUM FLOW                                   00012580
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*       WNA=ABSOLUTE VALUE OF RISER FLOW (LBM/SEC)                      00012590
*       WNI=NORMALIZED RISER SODIUM FLOW                                00012600
*       WNIRT=NET FLOW INTO RECEIVER OUTLET TANK (LBM/SEC)              00012610
*       WNRA(I)=ABSOLUTE VALUE OF PANEL I FLOW (LBM/SEC)                00012630
*       WNRR(I)=PANEL I REFERENCE SODIUM FLOW (LBM/SEC)                 00012640
*       WNRO(I)=PANEL I INITIAL NORMALIZED SODIUM FLOW                  00012670
*       WNR(I)=PANEL I NORMALIZED SODIUM FLOW                           00012675
*       WNO=INITIAL RISER FLOW (LB/SEC)                                 00012680
*       WNOINT=INITIAL RISER FLOW ROUTINE NAME                          00012690
                                                                        00012700
*      .X1,2 AND3=RECEIVER AXIALNODE HEAT CAPACITY (BTU/LBM-F)          00012710
                                                                        00012720
*       Y1,2 AND3=REC. AXIAL NODE FILM-COEFF.-AREA PRODUCT (BTU/F-SEC) 00012730
                                                                        00012740
*       ZERO=ZERO                                                       00012750
*       Z1,2 AND3=REC. AXIAL NODE SODIUM DENSITY (LBM/CUFT)             00012760
*                                                                       00012770
*6.0                 END CONTINUE STATEMENTS                            00012780
                                                                        00012790
 END                                                                    00012800
 STOP                                                                   00012810

OUTPUT VARIABLE SEQUENCE
WNRR   TRW10  TRW20  TRW30  TNR10  TNR20  TNR30  POCT   RHOCTO LNACTO
ZZ1030 RHORPO WNO    KFHRP  PIRI   RHODCO PORI   KFHC   IR     VPI
SGDV   QIDC   SRSGDV LROTO  RHOHTO LNAHTO SHDCI  KFHDC  DPDVI  CVCDV
VPDVI  IWNRPS IWN    LOGAR  POHT   WDNR   IDC    WCTIR  WHTOR  WN
CP1    RHO1   RHO2   RHO3   SH     TSH    SNARII SNARI  FH     TFHR
TFHCV  RHOROT LROT   POR    PIRSO  RHOCT  LNACT  WNA    HRP    PIRFLO
PIR    DPCV   DWNR   WNR    DWN    WNI    WNIRT  DMNROT MNAROT DMNACT
MNACT  TMRP   TIMRP  TILL   TIMRPX NRPX   SSRP   DNRP   NRP    WDNA
FHDC   RHONDV SNDV   QDC    CVCDV  DPDV   RHOHT  LNAHT  SHDC   DWDN
WDN    DMNAHT MNAHT  HANR1  RP     QI1    DTRW1  TRW1   PP     HANR2
QI2    DTRW2  TRW2   HANR3  QI3    DTRW3  TRW3   CP2    CP3    WNRA
DTNR1  TNR1   DTNR2  TNR2   DTNR3  TNR3   MTINSM DTNRO  TNRO   KLNR
CPCT   ETARP  TNRPUO DTNRP  TNRP   DTNRII TNRPO  CPIH   DTNRI  TNRI
KLRPS  ZZ1085 TNRPUI MCPCT  ZZ1087 TNCT   KLDC   DTNDC  TNDC   DTNDVI
TNDVI  KLDVHT CPNDV  TNDVO  ZZ1091 TNHTI  CPHT   MCPHT  DTNHT  TNHT
VPX    VPOX   ETI    IRX    TNR3X  ES     VP     ELROT  EROTL  DVE
IRDV   DLROT  LVLSW  DRDVC  VPDVOX DVEIX  DVEI   IRDVX  VPDVX  VPDV
CPROT  MCPROT RPIP   RPOP   QA1    QA2    QA3    QI     QA     Y
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$$$ TRANSLATION TABLE CONTENTS $$$       CURRENT        MAXIMUM

    MACRO AND STATEMENT OUTPUTS            190            1200
    STATEMENT INPUT WORK AREA              645            3800
    INTEGRATORS+MEMORY BLOCK OUTPUTS        28 +  0        300
    PARAMETERS+FUNCTION GENERATORS          83 +  1        400
    STORAGE VARIABLES+INTEGRATOR ARRAYS     39 + 12/2       50
    HISTORY AND MEMORY BLOCK NAMES          21              50
    MACRO DEFINITIONS AND NESTED MACROS      9             126
    MACRO STATEMENT STORAGE                 25             200
    LITERAL CONSTANT STORAGE                 0             100
    SORT SECTIONS                            2              20
    MAXIMUM STATEMENTS IN SECTION          249             987



$$$END OF TRANSLATOR OUTPUT$$$
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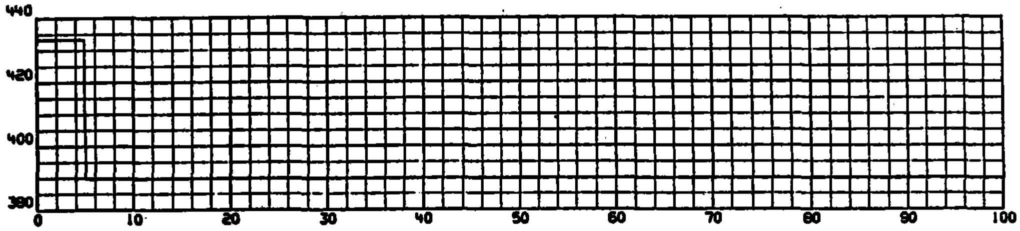
APPENDIX B

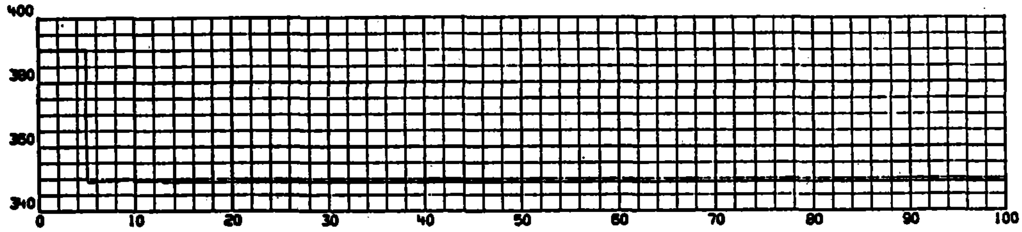
MODEL RESPONSE TO 10% STEP CHANGE IN INCIDENT FLUX

RUN 04-04 100 SEC, 10% STEP FLUX DECREASE AT 5 SEC., PID
QI - TOTAL INCIDENT SOLAR POWER (MWT)
QA - TOTAL ABSORPED SOLAR POWER (MWT)
WN - TOTAL RECEIVER FLOW (LB/SEC)
TNRO - TEMPERATURE OF SODIUM RECEIVER OUTLET TANK (F)

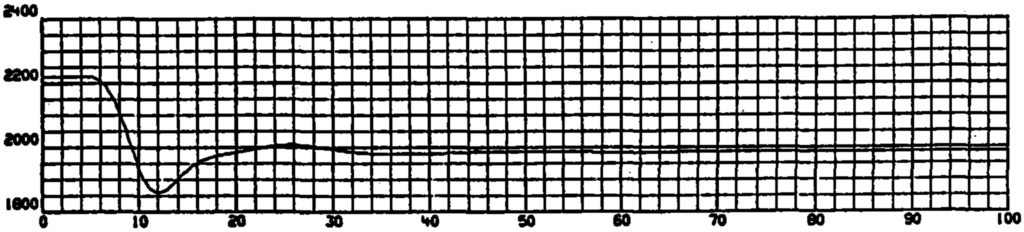
•071758301
050978 0002



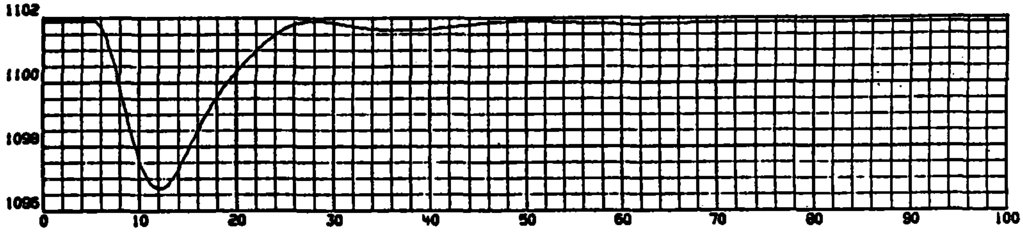
QI VS TIME



QA VS TIME



WN VS TIME

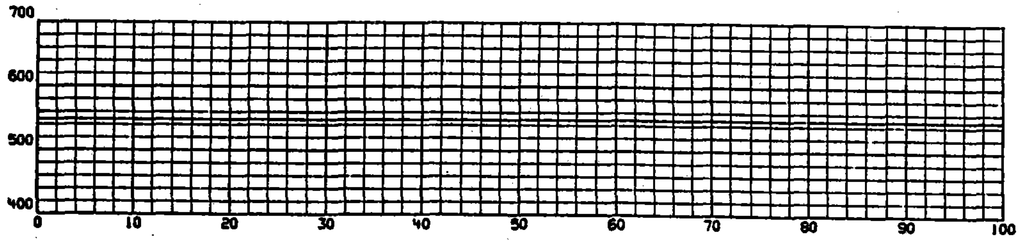


TNRO VS TIME

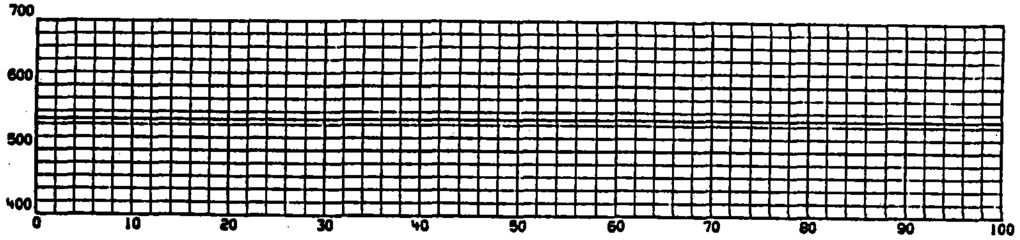
72

RUN 04-04 100 SEC. 100 STEP FLUX DECREASE AT 5 SEC., PID
TNCT - TEMPERATURE OF SODIUM IN COLD TANK (F)
TNRPUI - TEMPERATURE OF SODIUM, RECEIVER PUMP INLET (F)
TNRPUO - TEMPERATURE OF SODIUM, RECEIVER PUMP OUTLET (F)
TNRI - TEMPERATURE OF SODIUM, RECEIVER INLET (F)

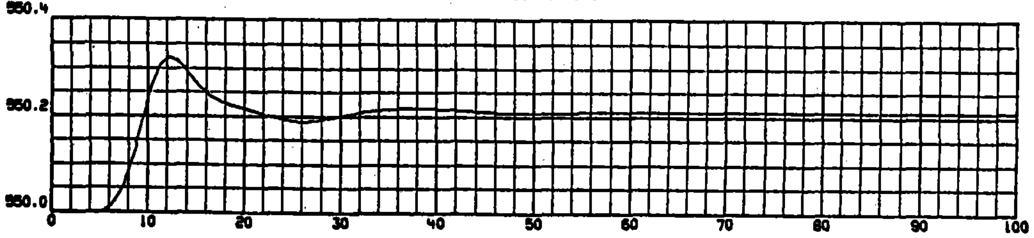
*071758301
050978 0001



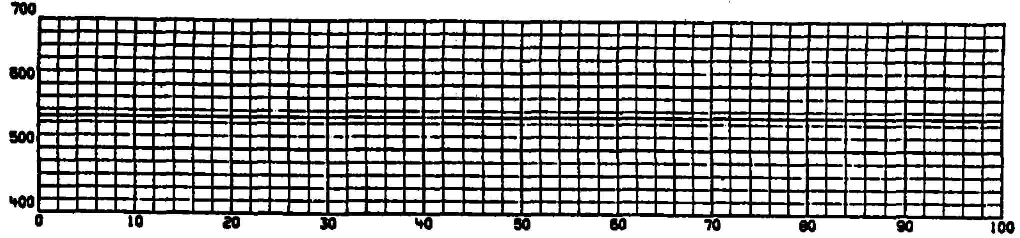
TNCT VS TIME



TNRPUI VS TIME



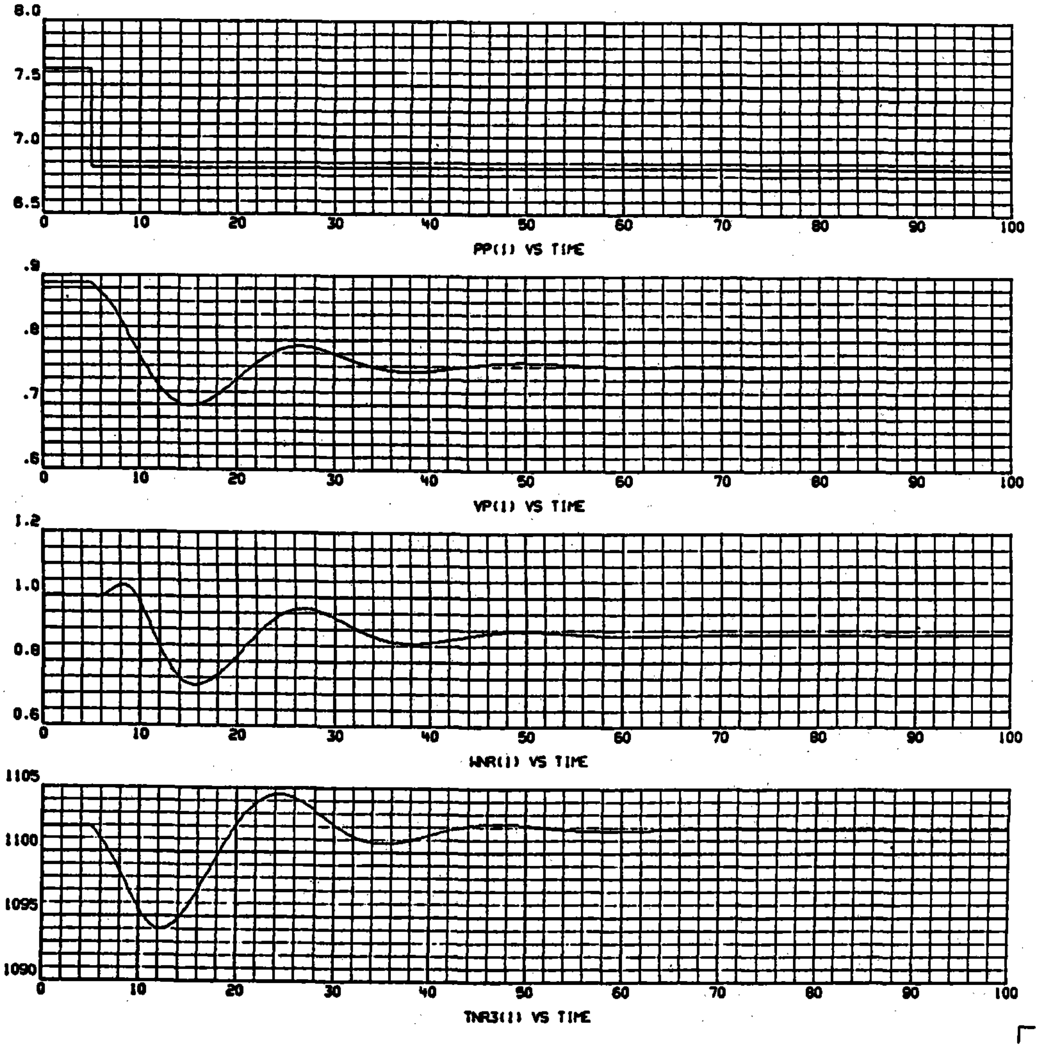
TNRPUO VS TIME



TNRI VS TIME

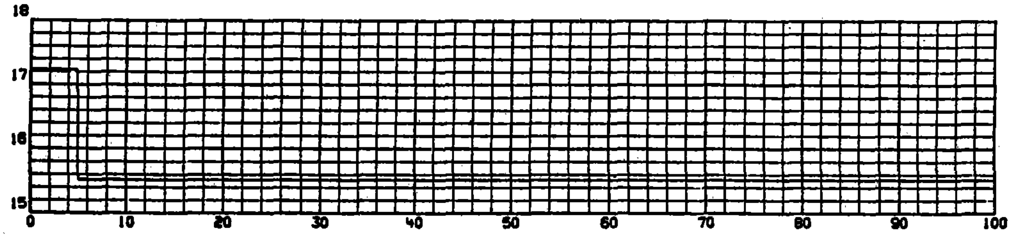
RUN 04-04 100 SEC, 10% STEP FLUX DECREASE AT 5 SEC., PID
PP(1) - SOUTH PANEL INCIDENT POWER (MWT)
VP(1) - SOUTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(1) - SOUTH PANEL FLOW (NORMALIZED TO 36.17 LBM/SEC)
TNR3(1) -TEMPERATURE OF SODIUM, SOUTH PANEL OUTLET (F)

*071758301
050978 0003

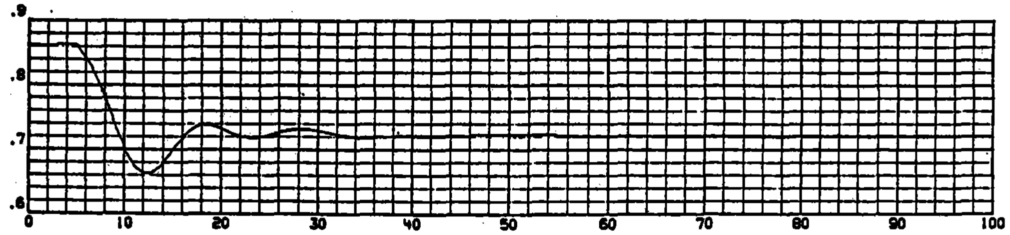


RUN 04-04 100 SEC. 10% STEP FLUX DECREASE AT 5 SEC., PID
PP(6) - WEST PANEL INCEDENT POWER (MWT)
VP(6) - WEST PANEL VALVE POSITION (FRACTION OPEN)
WNR(6) - WEST PANEL FLOW (NORMALIZED 88.15 LBM/SEC)
TNR3(6) -TEMPERATURE OF SODIUM, WEST PANEL OUTLET (F)

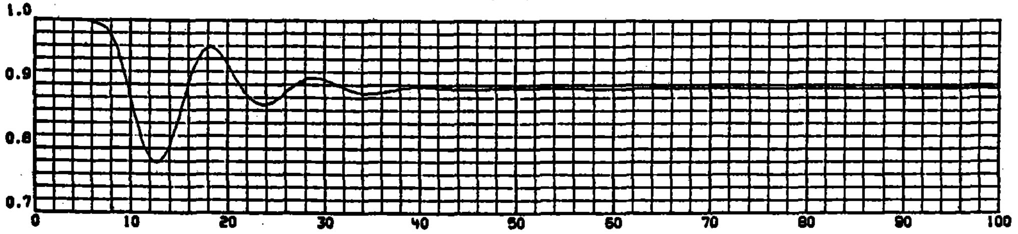
*071758301
050978 0004



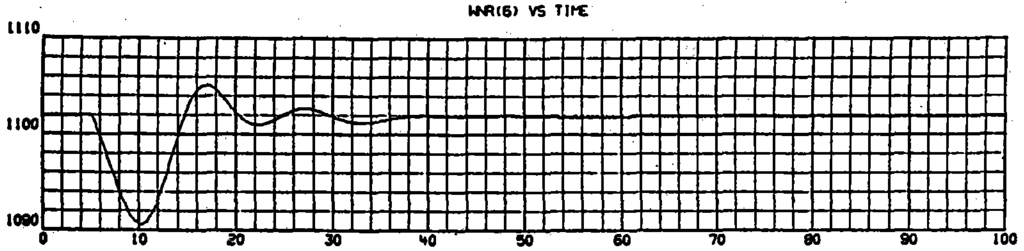
PP(6) VS TIME



VP(6) VS TIME



WNR(6) VS TIME



TNR3(6) VS TIME

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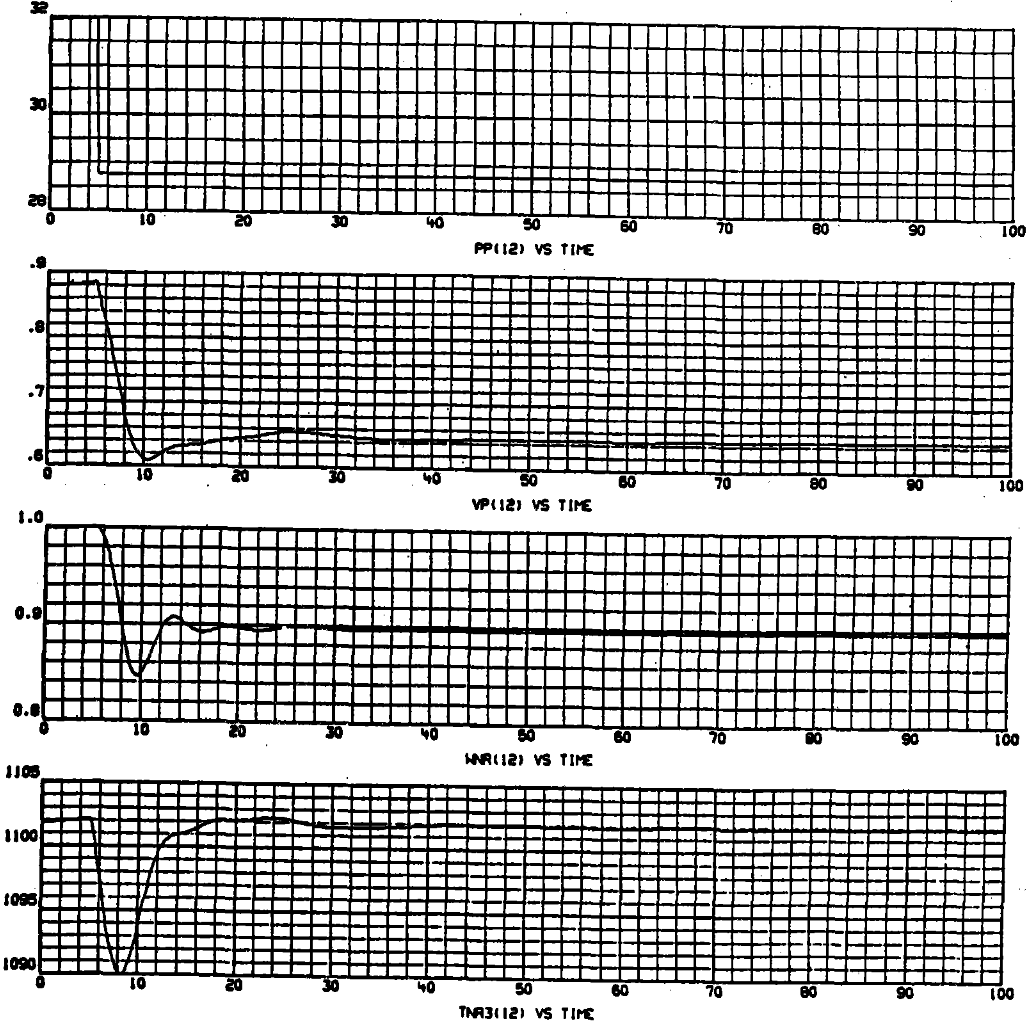
RUN 04-04 100 SEC, 10% STEP FLUX DECREASE AT 5 SEC., PID
PP(12) - NORTH PANEL INCIDENT POWER (MWT)
VP(12) - NORTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(12) - NORTH PANEL FLOW (NORMALIZED TO 167.69 LBM/SEC)
TNR3(12) - TEMPERATURE OF SODIUM, NORTH PANEL OUTLET (F)

*071758301
050978 0005



RUN 04-04 100 SEC, 10% STEP FLUX DECREASE AT 5 SEC., PID
TRW2(1) - MEAN WALL TEMPERATURE, MIDPLANE SOUTH PANEL (F)
TRW2(6) - MEAN WALL TEMPERATURE, MIDPLANE WEST PANEL (F)
TRW2(12) - MEAN WALL TEMPERATURE, MIDPLANE NORTH PANEL (F)

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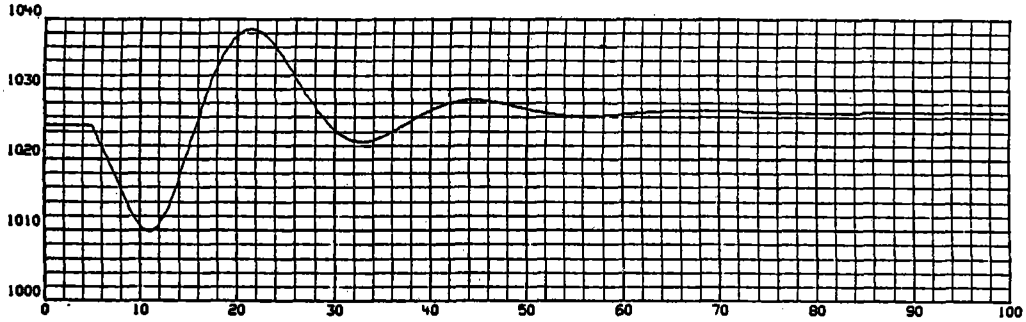
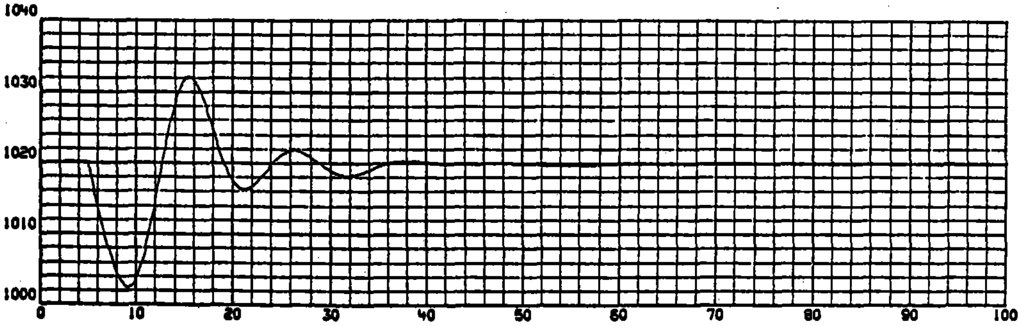
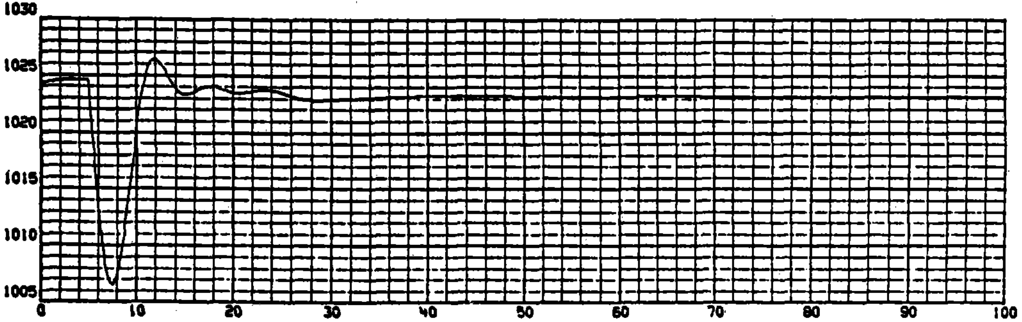
050978 0006



TRW2(1) VS TIME



TRW2(6) VS TIME

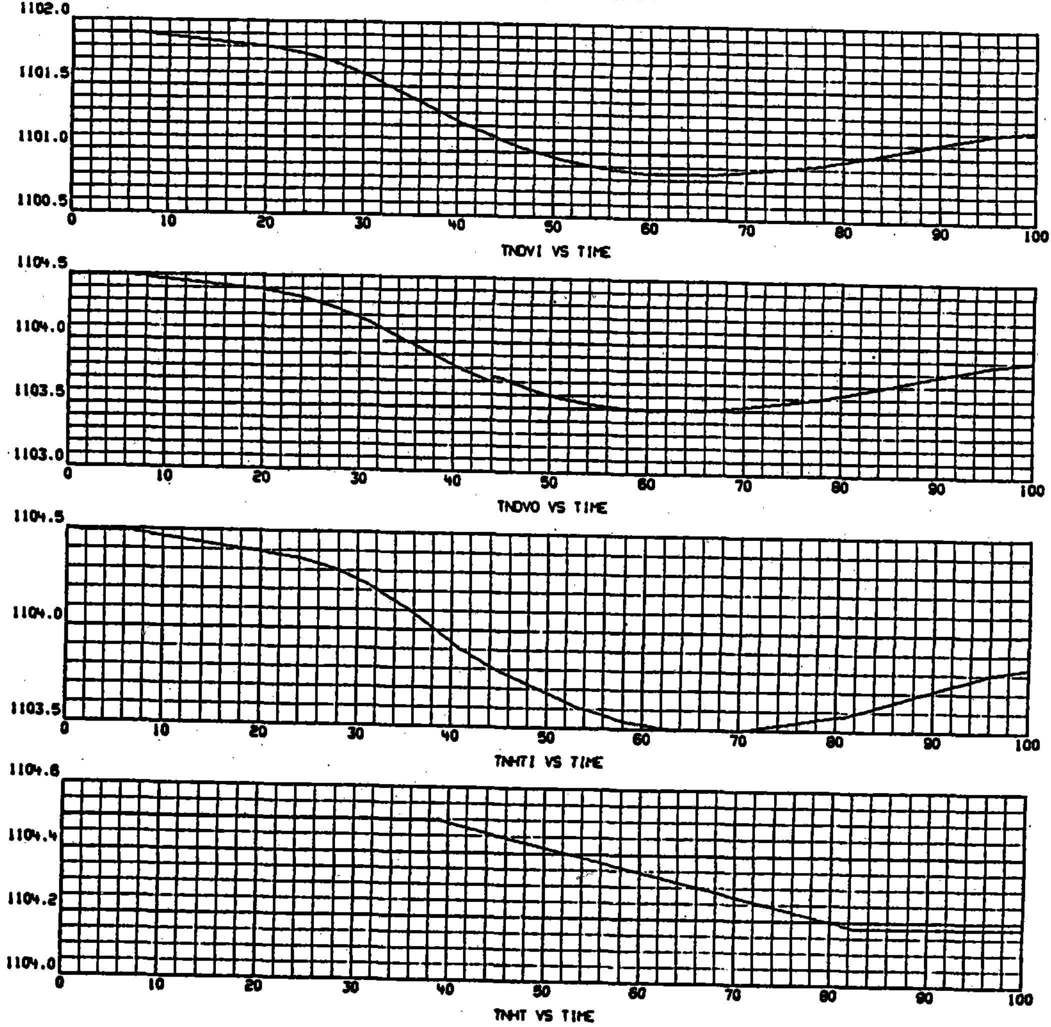


TRW2(12) VS TIME

77

RUN 04-04 100 SEC, 100 STEP FLUX DECREASE AT 5 SEC., PID
TNDVI - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE INLET,
TNDVO - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE OUTLET
TNHTI - TEMPERATURE OF SODIUM, HOT TANK INLET (F)
TNHT - TEMPERATURE OF SODIUM, HOT TANK (F)

•071758301
050978 0007



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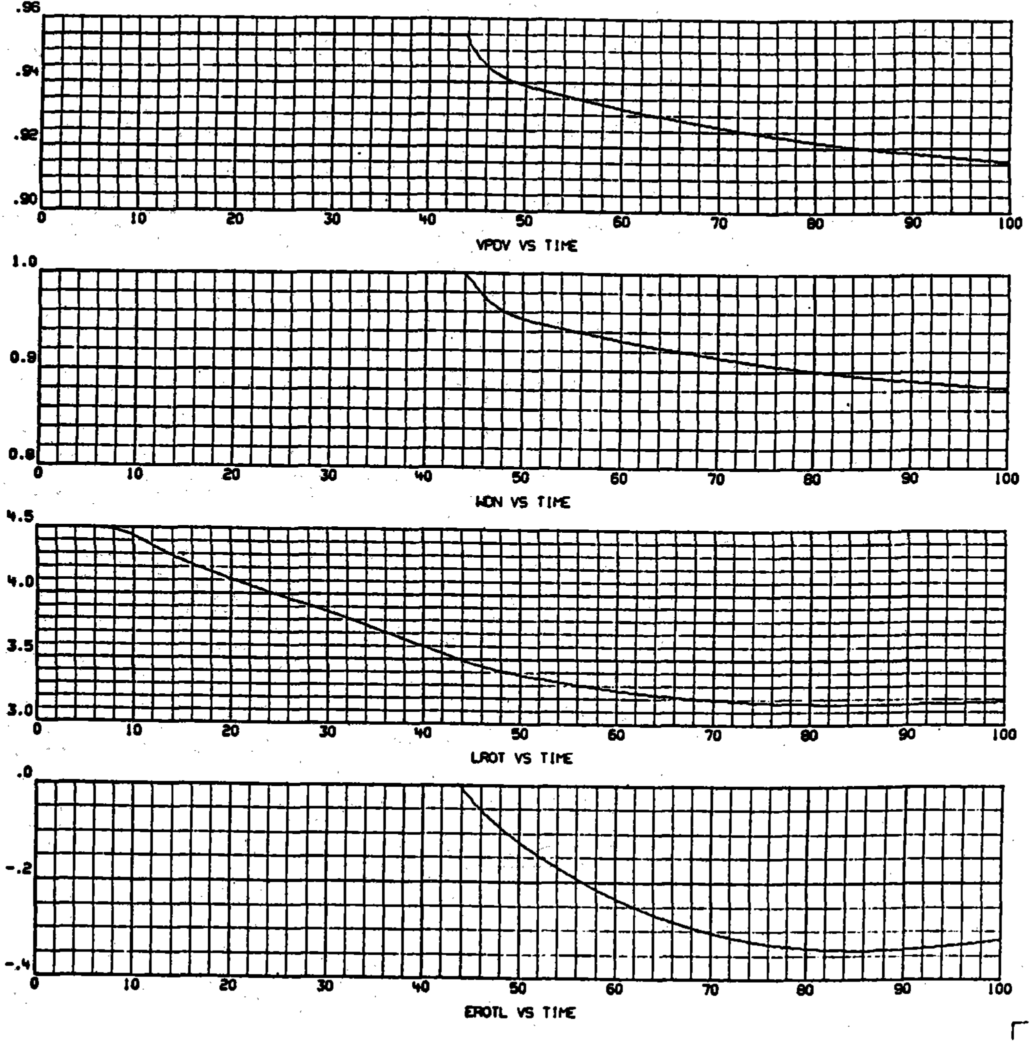
RUN 04-04 100 SEC. 100 STEP FLUX DECREASE AT 5 SEC., PID
VPDV - PRESSURE REDUCING DEVICE VALVE POSITION (FRACTION OPEN)
WDN - DOWNCOMER FLOW (NORMALIZED TO 2220.1 LBM/SEC)
LROT - RECEIVER OUTLET TANK SODIUM LEVEL (FT)
EROTL - RECEIVER OUTLET TANK SODIUM LEVEL ERROR

•071758301
050978 0008



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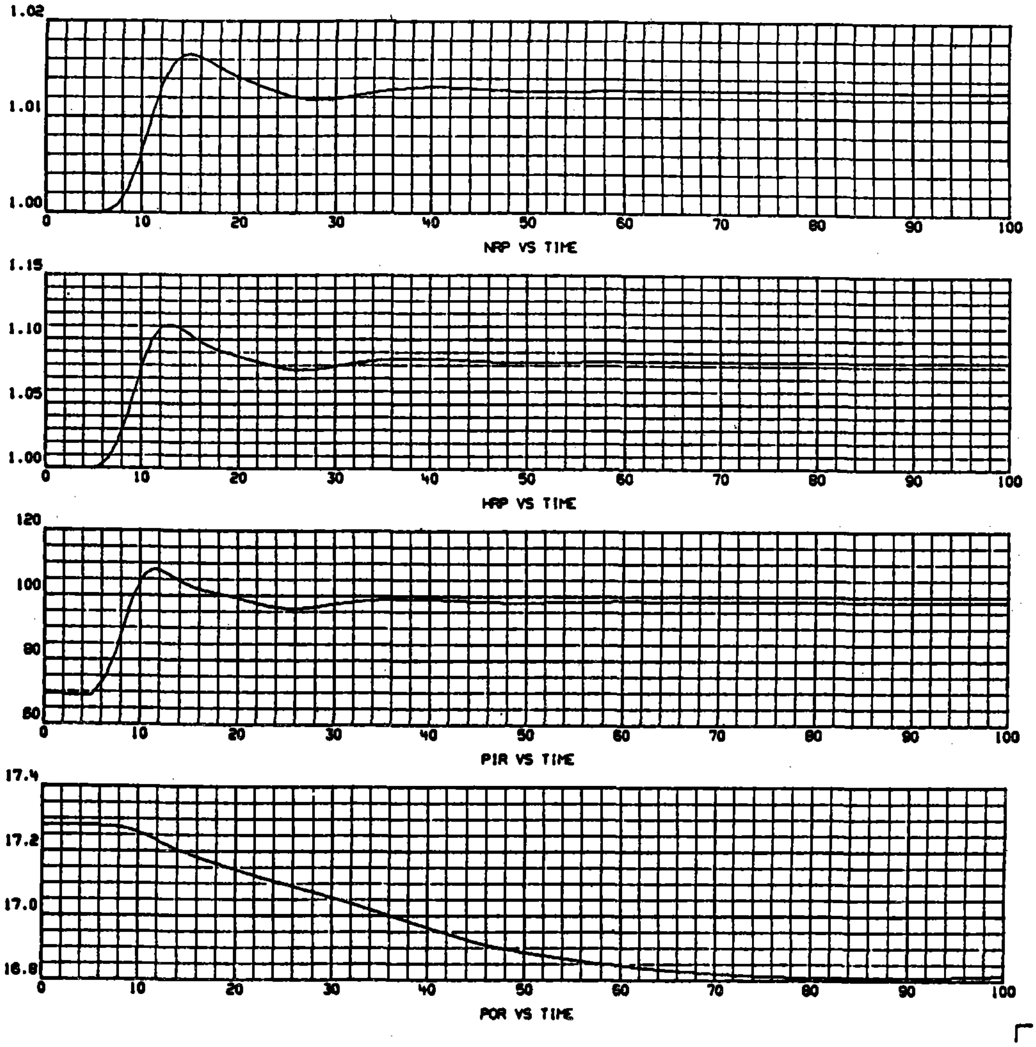
RUN 04-04 100 SEC, 10% STEP FLUX DECREASE AT 5 SEC., PID
NRP - RECEIVER PUMP SPEED (NORMALIZED TO 700 RPM)
HRP - RECEIVER PUMP HEAD (NORMALIZED TO 824 FT)
PIR - PRESSURE AT RECEIVER INLET (PSIA)
POR - PRESSURE AT RECEIVER OUTLET (PSIA)

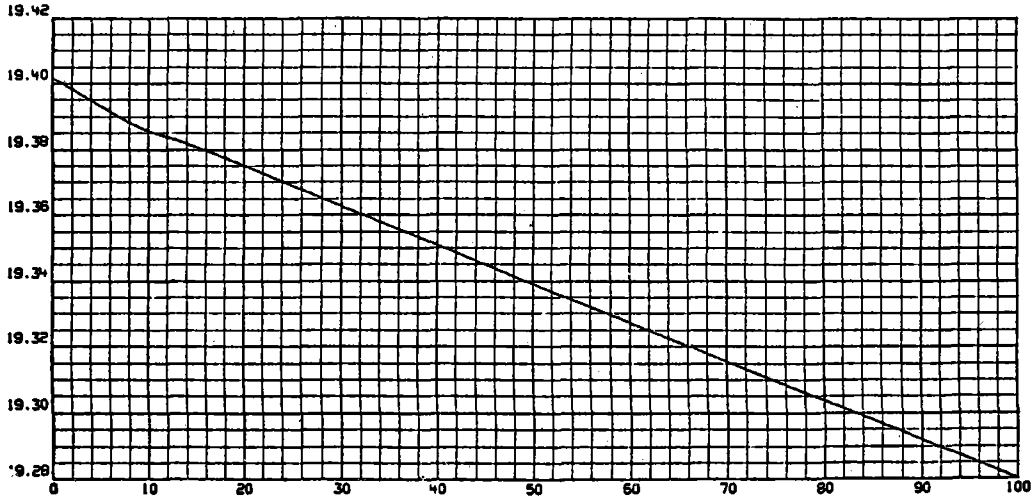
*071758301
050978 0009



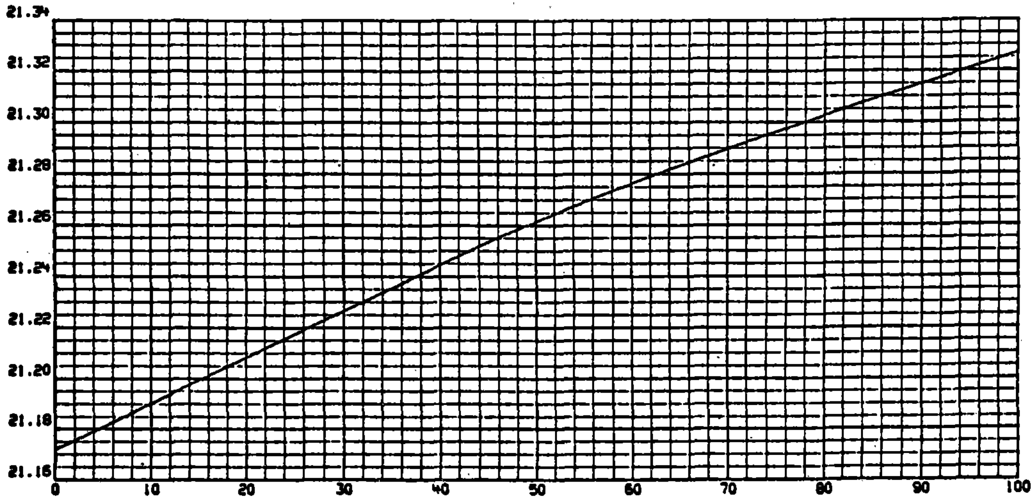
80

RUN 04-04 100 SEC, 100 STEP FLUX DECREASE AT 5 SEC., PID
LNACT - LEVEL OF SODIUM IN COLD TANK (FT)
LNAHT - LEVEL OF SODIUM IN COLD TANK (FT)

•071758301
050978 0010



LNACT VS TIME

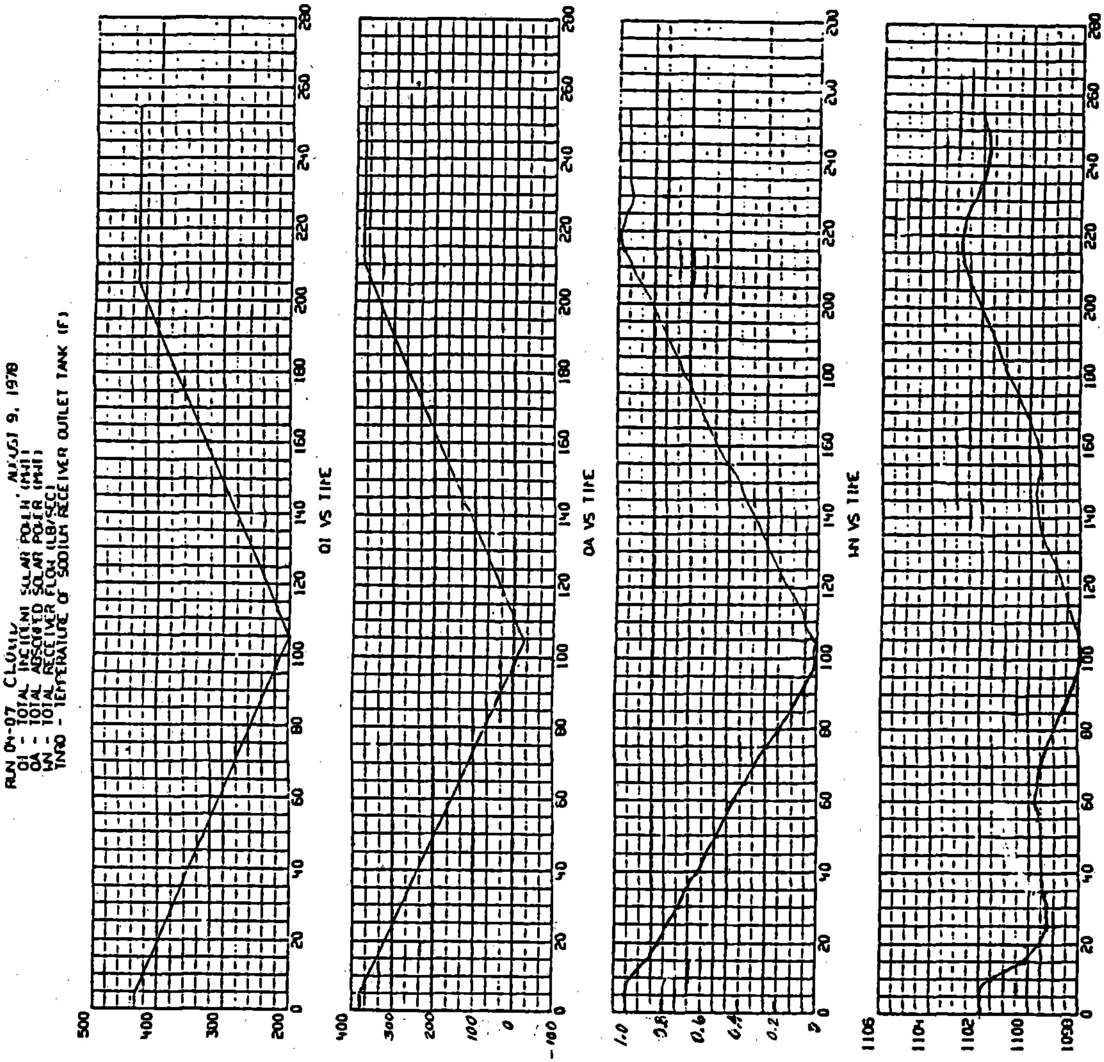


LNAHT VS TIME

APPENDIX C

MODEL RESPONSE TO CLOUD COVER TRANSIENT COVERING 1%/SEC OF THE TOTAL FIELD

82



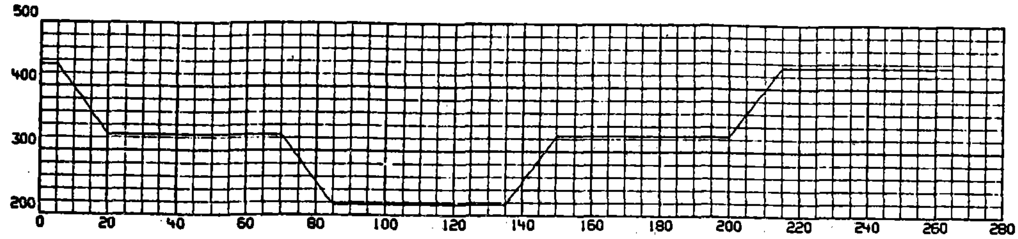
Rockwell International
Energy Systems Group

APPENDIX D

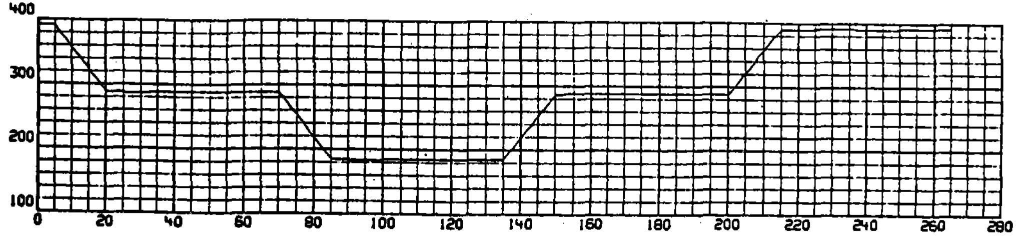
MODEL RESPONSE TO 25% STEP (STEEP RAMP) CHANGES IN INCIDENT FLUX

RUN 04-07 25 PERCENT STEP CHANGES, AUGUST 9, 1978
QI - TOTAL INCIDENT SOLAR POWER (MWT)
QA - TOTAL ABSORBED SOLAR POWER (MWT)
WN - TOTAL RECEIVER FLOW (LB/SEC)
TNRO - TEMPERATURE OF SODIUM RECEIVER OUTLET TANK (F)

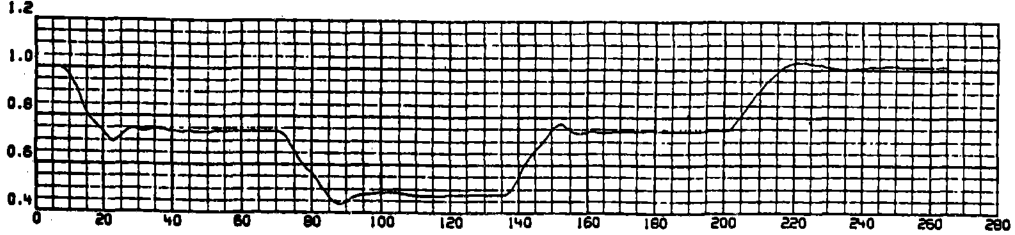
*071758301
081078 0002



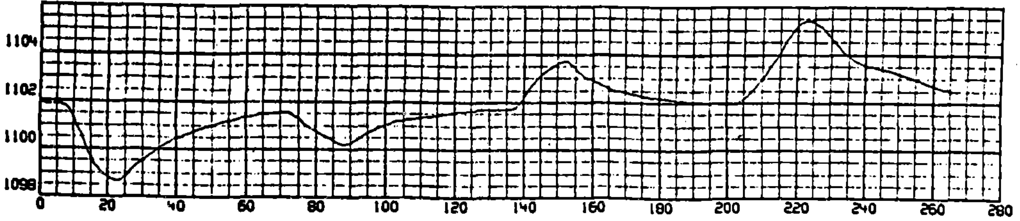
QI VS TIME



QA VS TIME



WN VS TIME

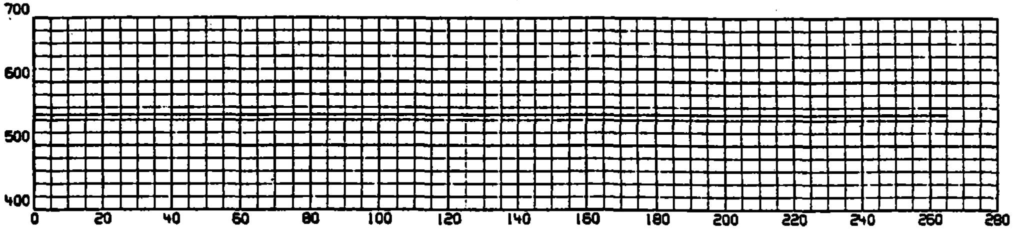


TNRO VS TIME

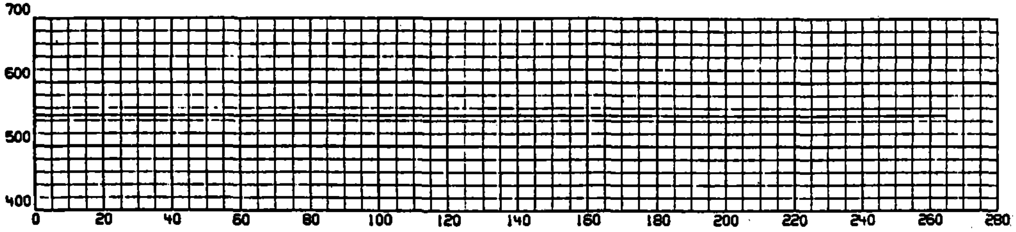
85

RUN 04-07 25 PERCENT STEP CHANGES, AUGUST 9, 1978
TNCT - TEMPERATURE OF SODIUM IN COLD TANK (F)
TNRPUI - TEMPERATURE OF SODIUM, RECEIVER PUMP INLET (F)
TNRPUO - TEMPERATURE OF SODIUM, RECEIVER PUMP OUTLET (F)
TNRI - TEMPERATURE OF SODIUM, RECEIVER INLET (F)

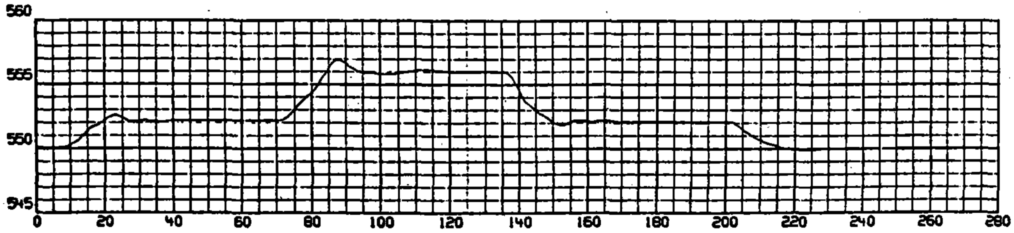
*071758301
081078 0001



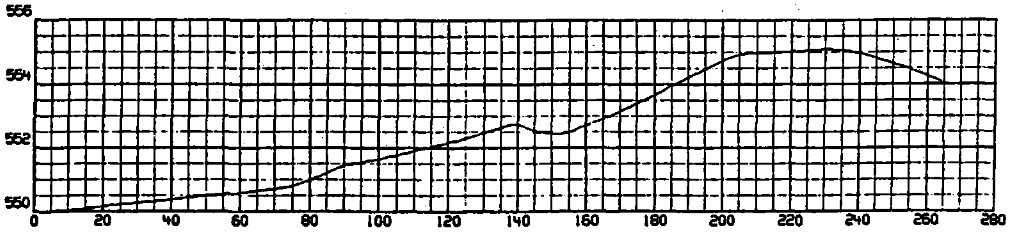
TNCT VS TIME



TNRPUI VS TIME



TNRPUO VS TIME

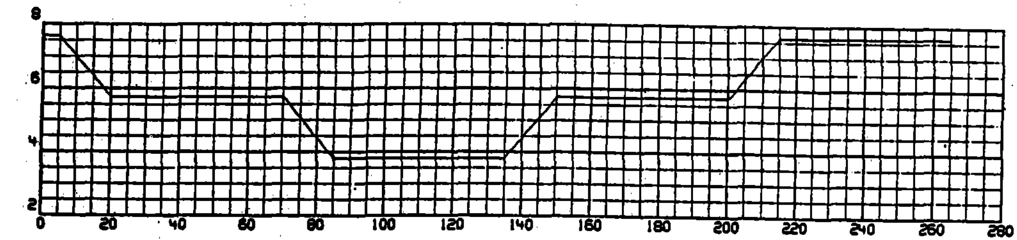


TNRI VS TIME

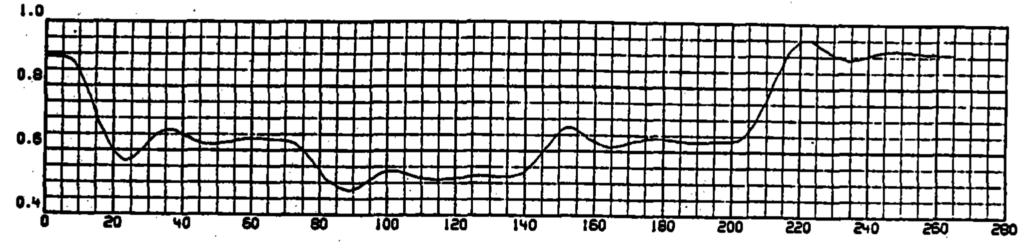
86

RUN 04-07 25 PERCENT STEP CHANGES, AUGUST 9, 1978
PP(I) - SOUTH PANEL INCIDENT POWER (MWT)
VP(I) - SOUTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(I) - SOUTH PANEL FLOW (NORMALIZED TO 36.17 LBM/SEC)
TNR3(I) -TEMPERATURE OF SODIUM, SOUTH PANEL OUTLET (F)

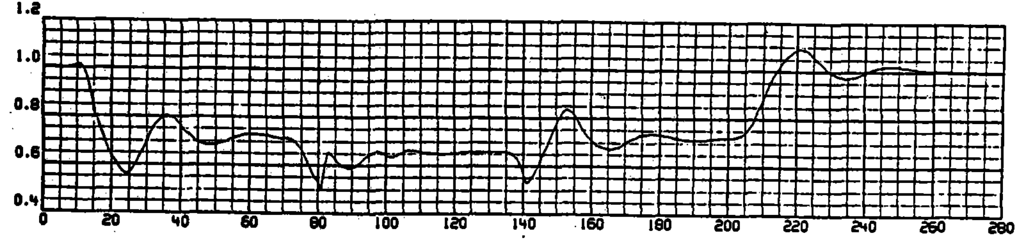
*071758301
081078 0003



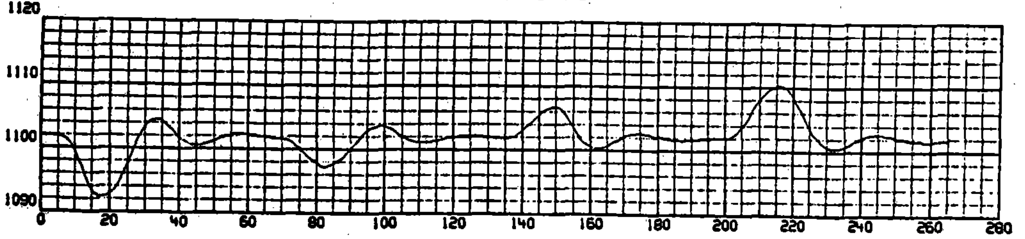
PP(I) VS TIME



VP(I) VS TIME



WNR(I) VS TIME

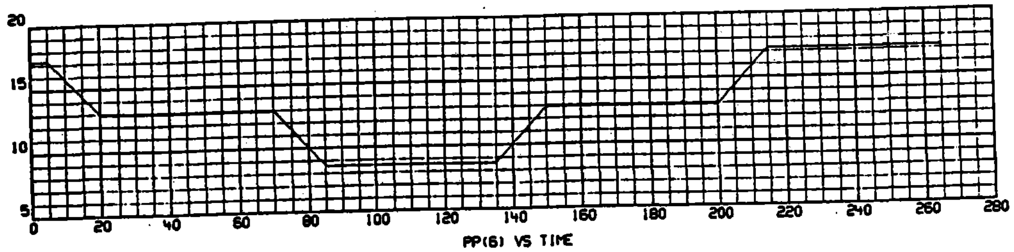


TNR3(I) VS TIME

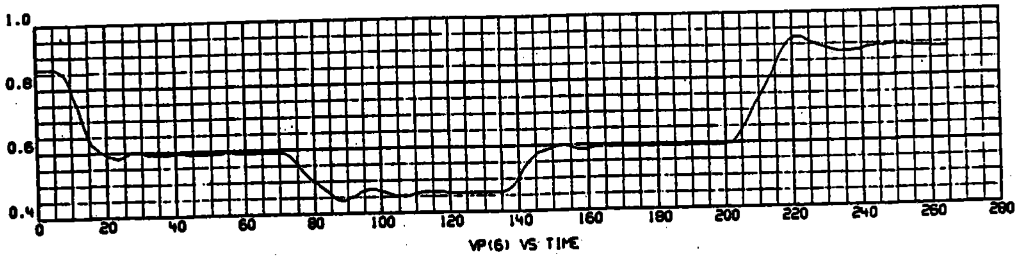
87

*071758301
081078 0004

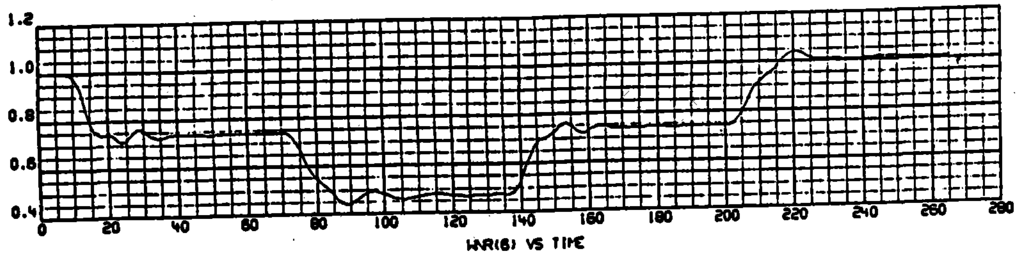
RUN 04-07 25 PERCENT STEP CHANGES, AUGUST 9, 1978
PP(6) - WEST PANEL INCEDENT POWER (MWT)
VP(6) - WEST PANEL VALVE POSITION (FRACTION OPEN)
WNR(6) - WEST PANEL FLOW (NORMALIZED 88.15 LBM/SEC)
TNR3(6) -TEMPERATURE OF SODIUM, WEST PANEL OUTLET (F)



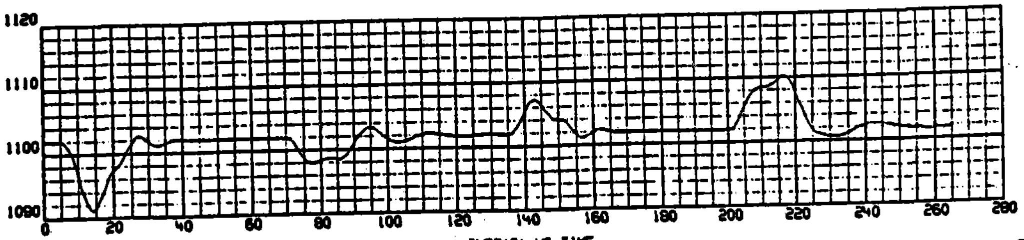
PP(6) VS TIME



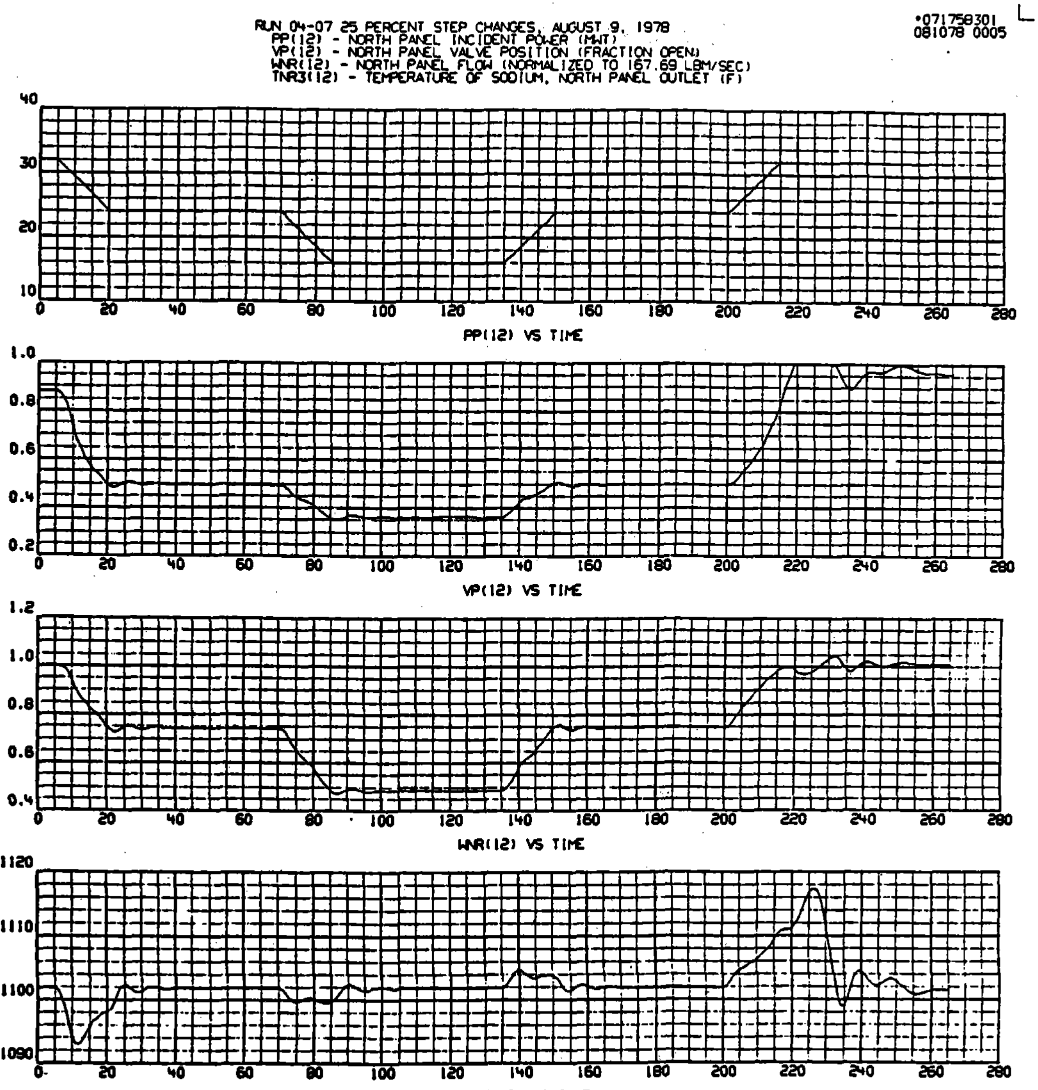
VP(6) VS TIME



WNR(6) VS TIME



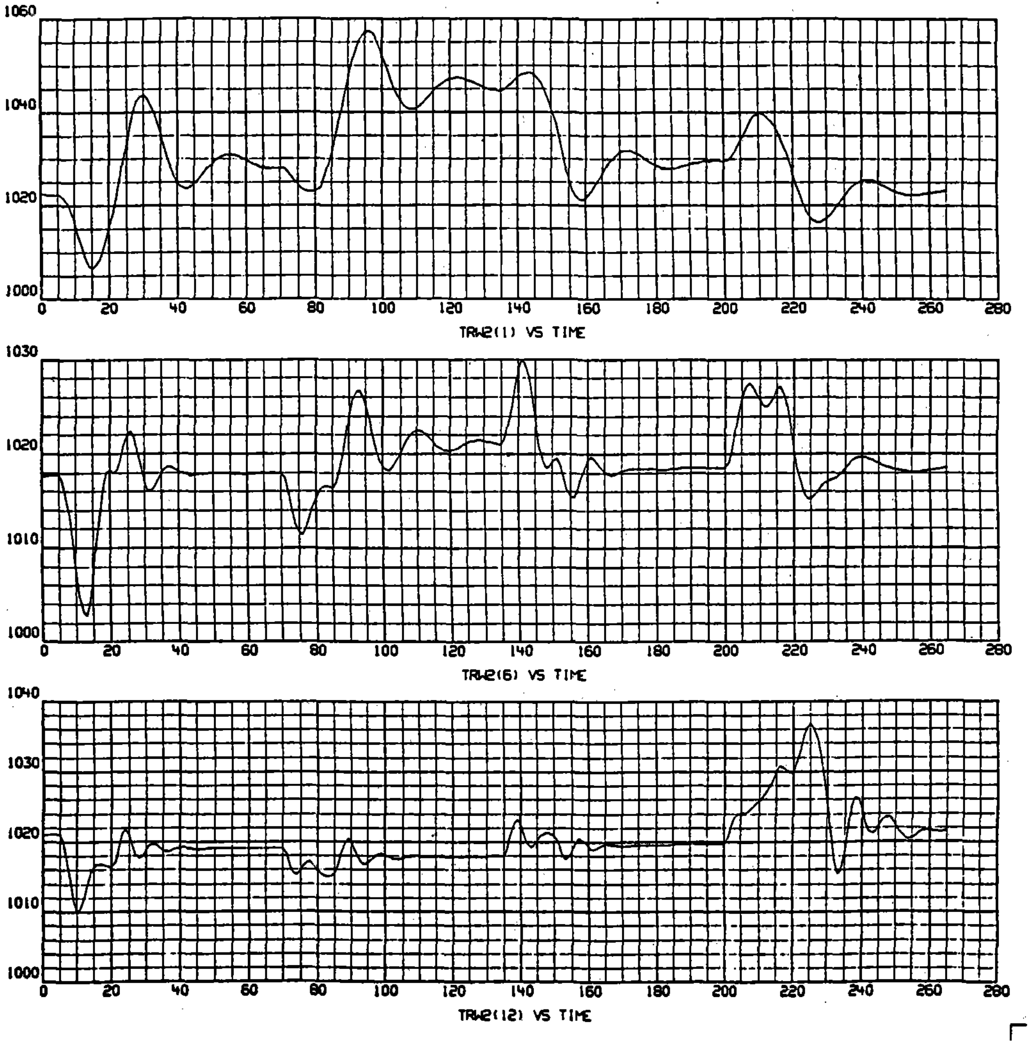
TNR3(6) VS TIME



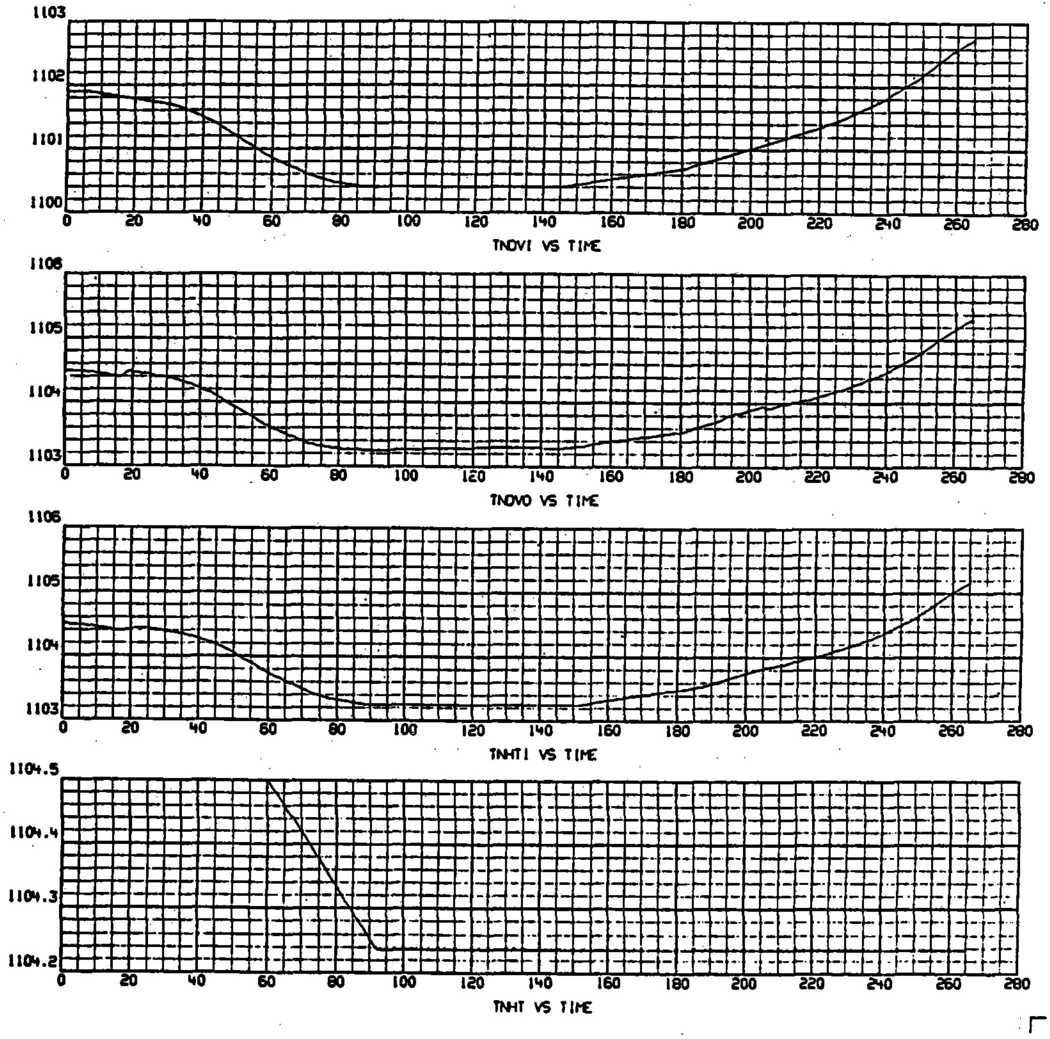
RUN 04-07 25 PERCENT STEP CHANGES, AUGUST 9, 1978
PP(12) - NORTH PANEL INCIDENT POWER (MWT)
VP(12) - NORTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(12) - NORTH PANEL FLOW (NORMALIZED TO 167.69 LBM/SEC)
TNR3(12) - TEMPERATURE OF SODIUM, NORTH PANEL OUTLET (F)

RUN 04-07 25 PERCENT STEP CHANGES, AUGUST 9, 1978
TRW2(1) - MEAN WALL TEMPERATURE, MIDPLANE SOUTH PANEL (F)
TRW2(6) - MEAN WALL TEMPERATURE, MIDPLANE WEST PANEL (F)
TRW2(12) - MEAN WALL TEMPERATURE, MIDPLANE NORTH PANEL (F)

*071758301
081078 0006



90



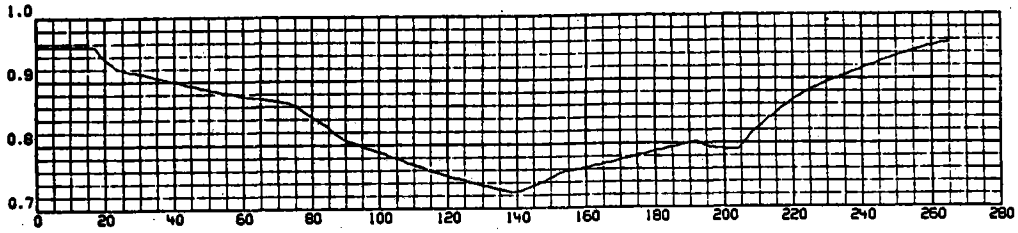
RUN 04-07 25 PERCENT STEP CHANGES, AUGUST 9, 1978
TNDVI - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE INLET,
TNDVO - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE OUTLET
TNHTI - TEMPERATURE OF SODIUM, HOT TANK INLET (F)
TNHT - TEMPERATURE OF SODIUM, HOT TANK (F)

*071758301
081078 0007

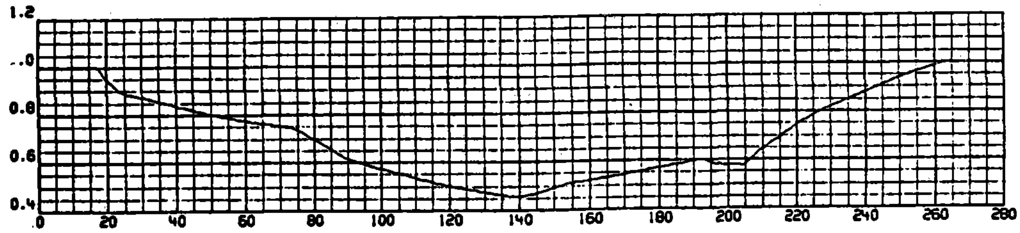
91

RUN 04-07 25 PERCENT STEP CHANGES, AUGUST 9, 1978
VPDV - PRESSURE REDUCING DEVICE VALVE POSITION (FRACTION OPEN)
WDN - DOWNCOMER FLOW (NORMALIZED TO 2220.1 LBM/SEC)
LROT - RECEIVER OUTLET TANK SODIUM LEVEL (FT)
EROTL - RECEIVER OUTLET TANK SODIUM LEVEL ERROR

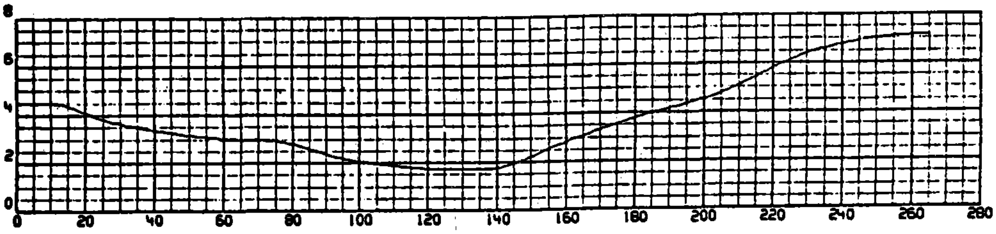
•071758301
081078 0008



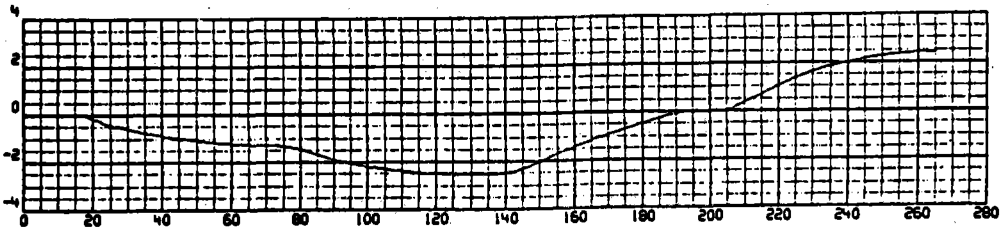
VPDV VS TIME



WDN VS TIME



LROT VS TIME



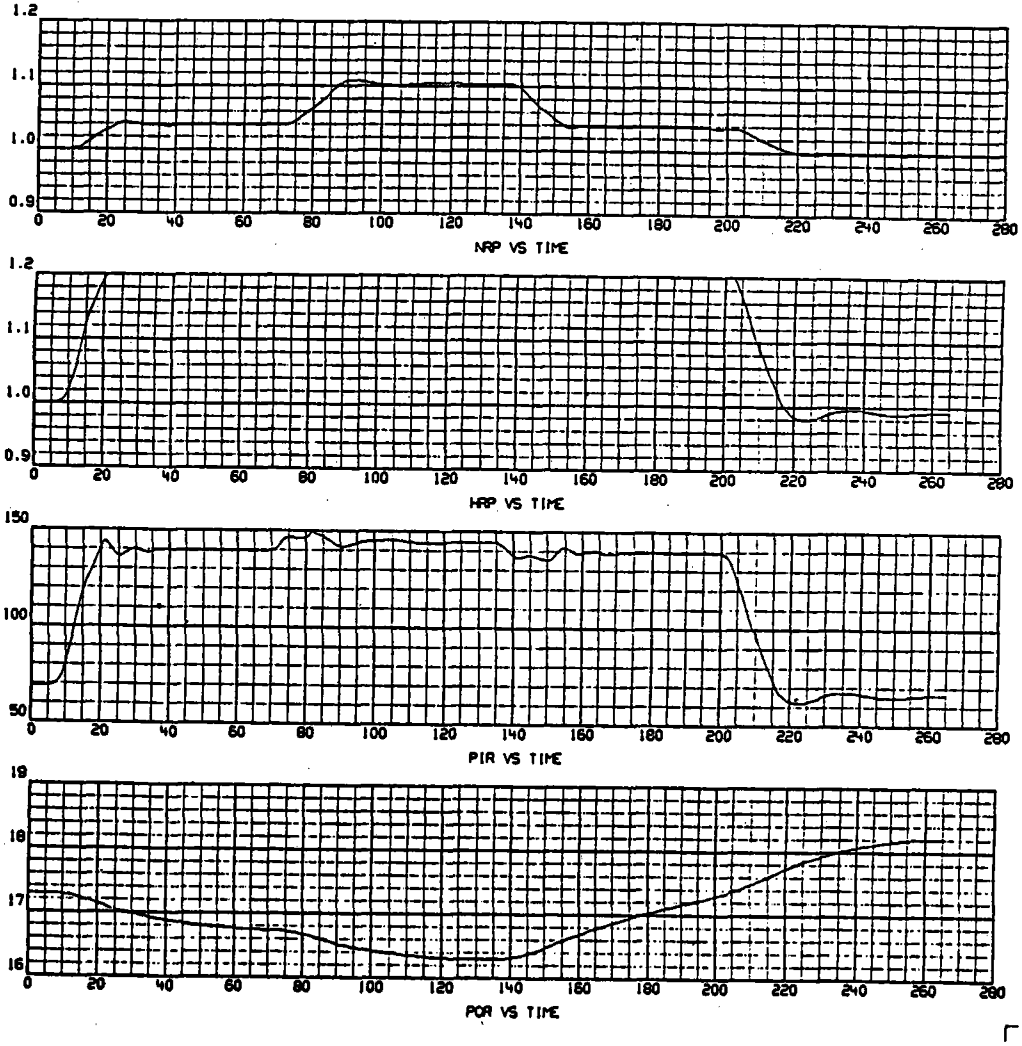
EROTL VS TIME

N272TI000006

92

RUN 04-07 25 PERCENT STEP CHANGES, AUGUST 9, 1978
NRP - RECEIVER PUMP SPEED (NORMALIZED TO 700 RPM)
HRP - RECEIVER PUMP HEAD (NORMALIZED TO 824 FT)
PIR - PRESSURE AT RECEIVER INLET (PSIA)
POR - PRESSURE AT RECEIVER OUTLET (PSIA)

•071758301
081078 0009



NRP VS TIME

HRP VS TIME

PIR VS TIME

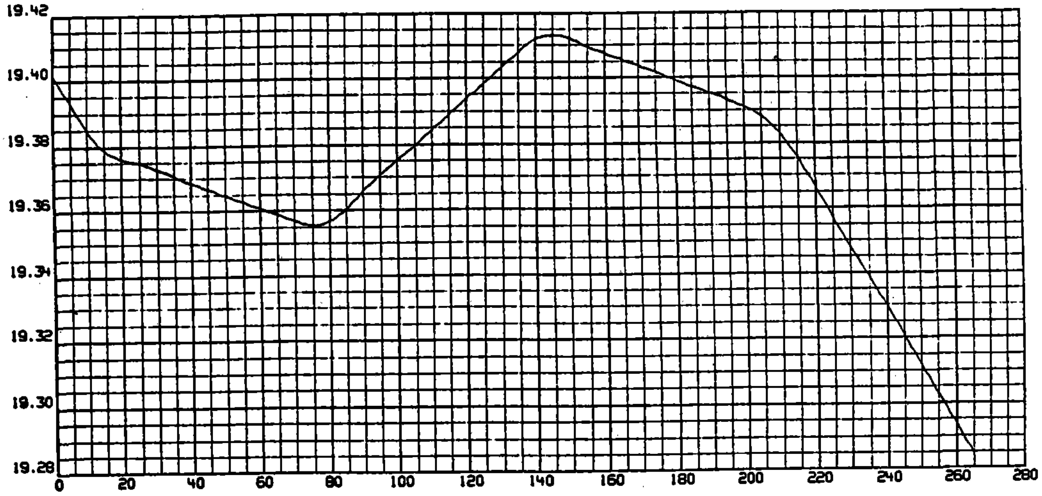
POR VS TIME

N272TI000006

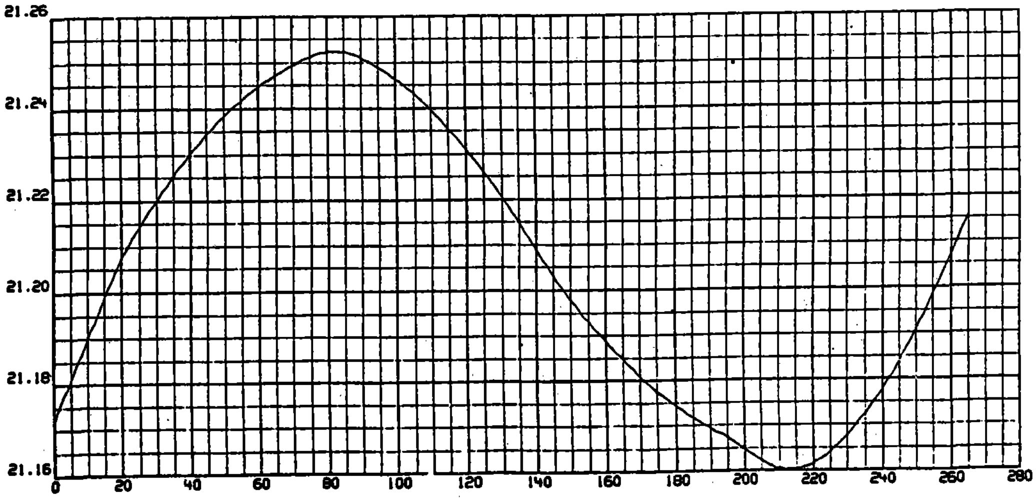
93

*071758301
081078 0010

RUN 04-07 25 PERCENT STEP CHANGES, AUGUST 9, 1978
LNACT - LEVEL OF SODIUM IN COLD TANK (FT)
LNAHT - LEVEL OF SODIUM IN COLD TANK (FT)



LNACT VS TIME



LNAHT VS TIME

APPENDIX E

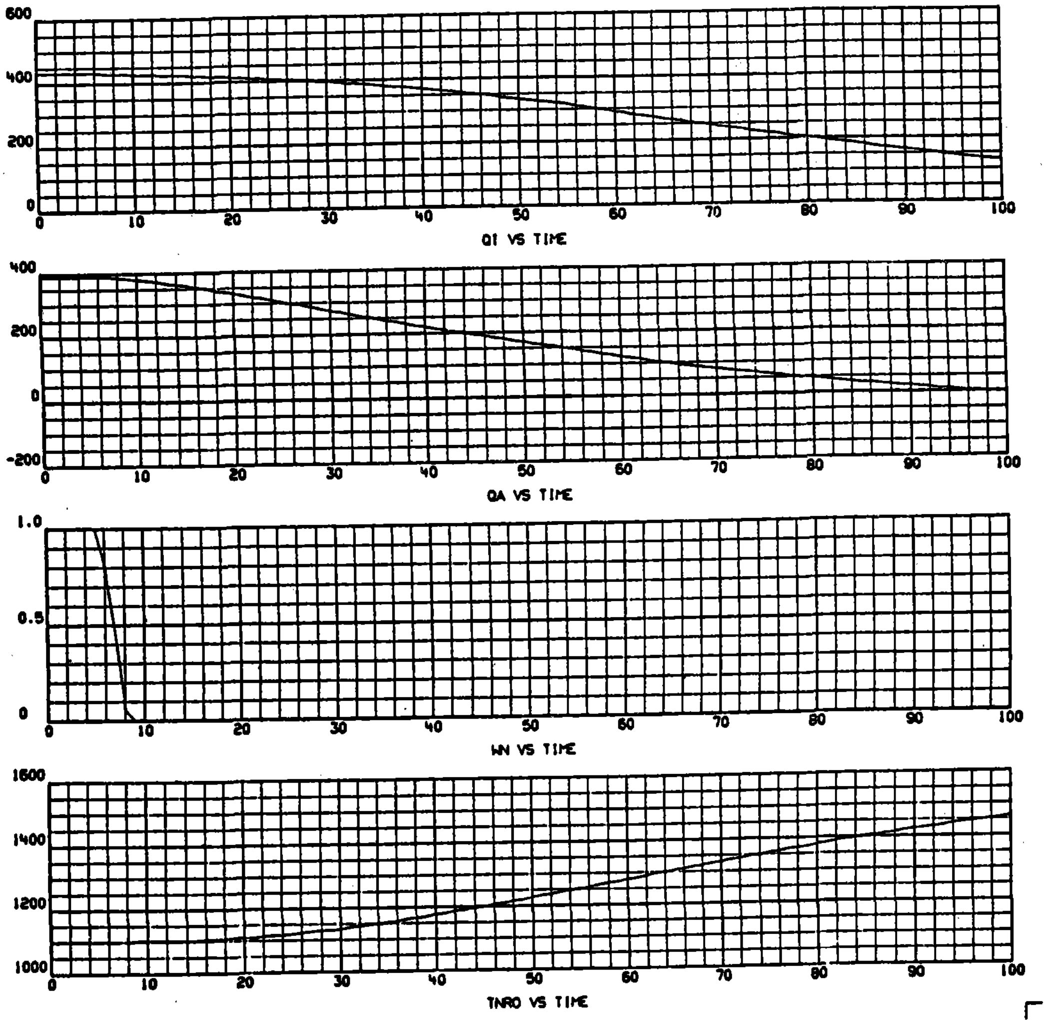
MODEL RESPONSE TO LOSS OF RECEIVER PUMP POWER (DRAG VALVE CLOSES WITH LOSS OF PUMP)

N272TI000006

95

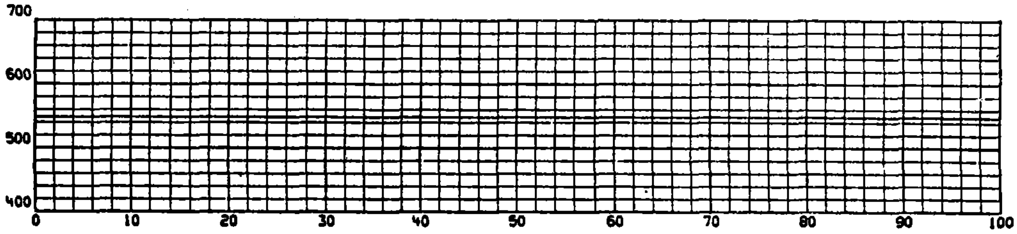
*071758301
071378 0002

RUN 04-038 PUMP TRIP, DEFOCUS, RUNDOWN INC. 7-13-78
QI - TOTAL INCIDENT SOLAR POWER (MWT)
QA - TOTAL ABSORPED SOLAR POWER (MWT)
WN - TOTAL RECEIVER FLOW (LB/SEC)
TNRO - TEMPERATURE OF SODIUM RECEIVER OUTLET TANK (F)

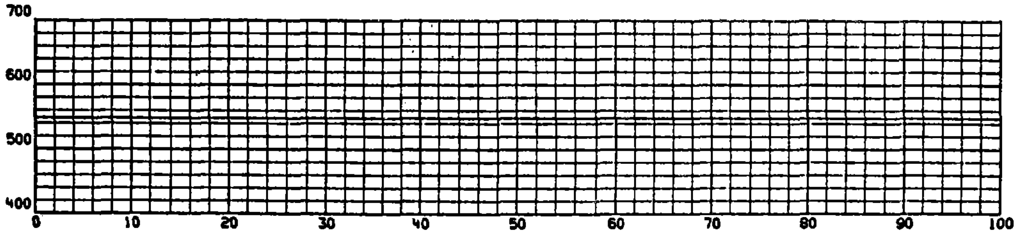


RUN 04-038 PUMP TRIP, DEFOCUS, RUNDOWN INC, 7-13-78
TNCT - TEMPERATURE OF SODIUM IN COLD TANK (F)
TNRPUI - TEMPERATURE OF SODIUM, RECEIVER PUMP INLET (F)
TNRPUO - TEMPERATURE OF SODIUM, RECEIVER PUMP OUTLET (F)
TNRI - TEMPERATURE OF SODIUM, RECEIVER INLET (F)

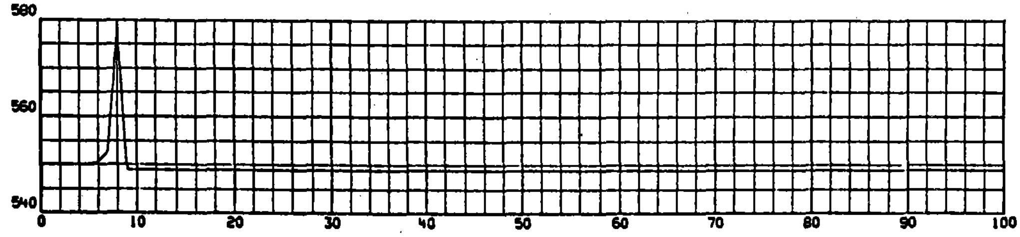
•071758301
071378 0001



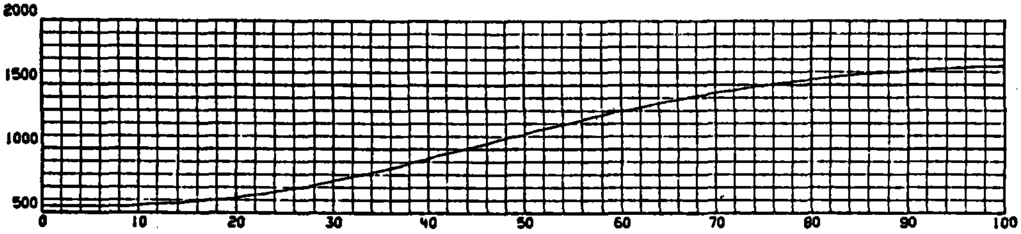
TNCT VS TIME



TNRPUI VS TIME



TNRPUO VS TIME

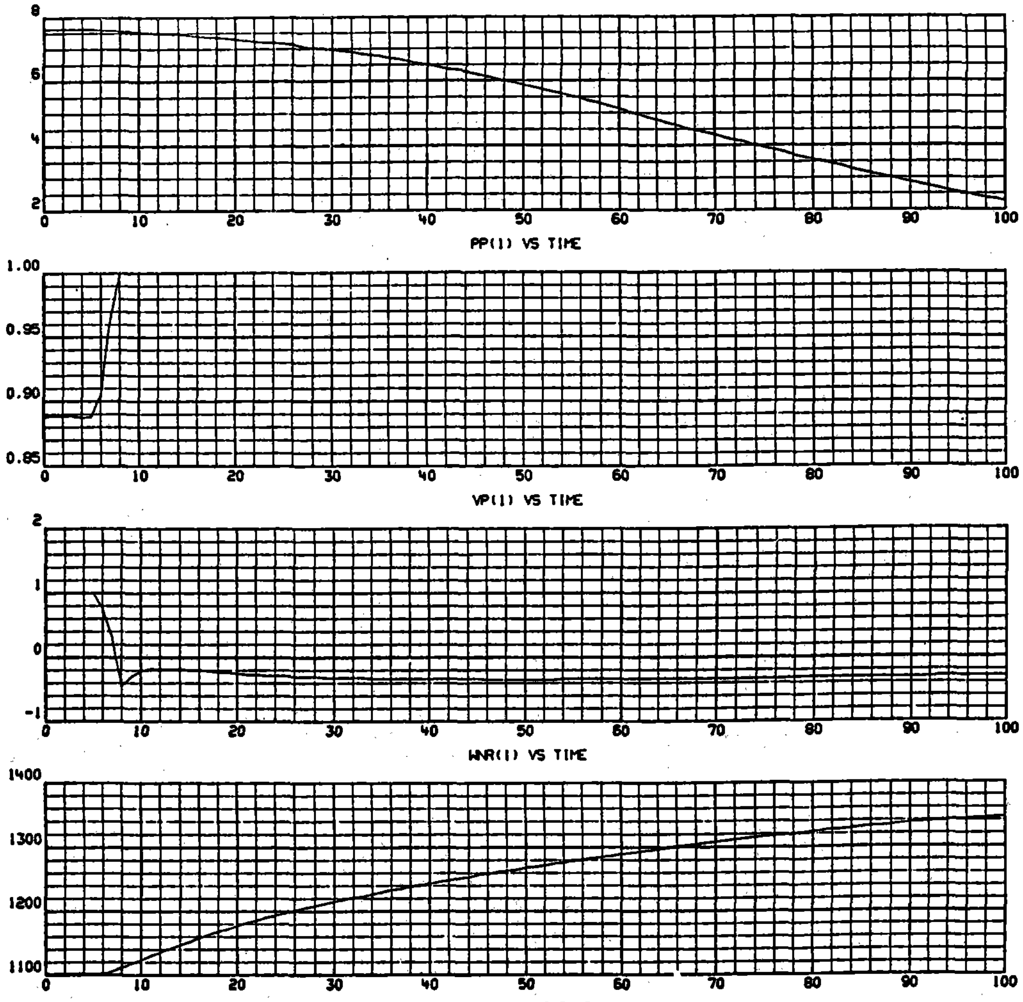


TNRI VS TIME

97

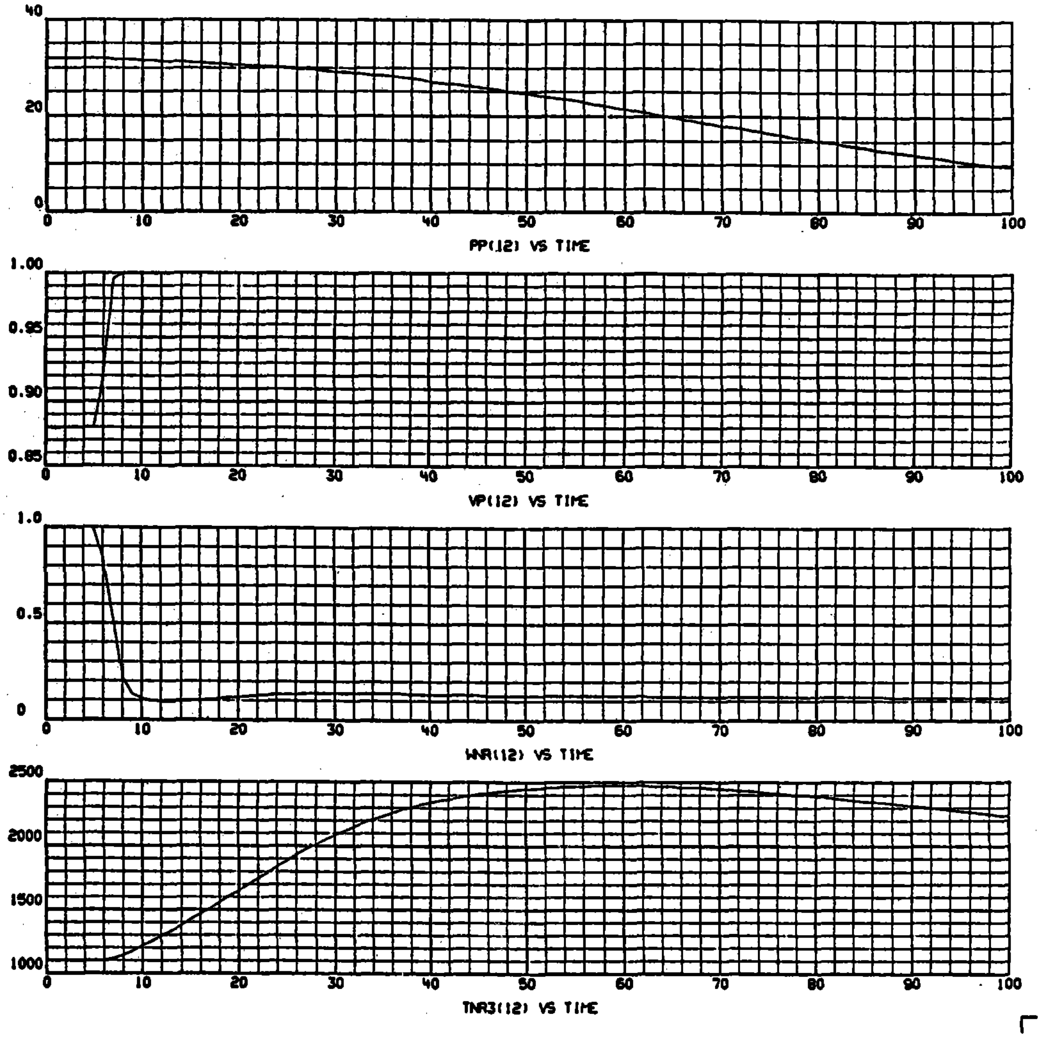
RUN 04-038 PUMP TRIP, DEFOCUS, RUNDOWN INC, 7-13-78
PP(1) - SOUTH PANEL INCIDENT POWER (MWT)
VP(1) - SOUTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(1) - SOUTH PANEL FLOW (NORMALIZED TO 36.17 LBM/SEC)
TNR3(1) -TEMPERATURE OF SODIUM, SOUTH PANEL OUTLET (F)

*071758301
071378 0003



RUN 04-038 PUMP TRIP, DEFOCUS, RUNDOWN INC, 7-13-78
PP(12) - NORTH PANEL INCIDENT POWER (MWT)
VP(12) - NORTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(12) - NORTH PANEL FLOW (NORMALIZED TO 167.69 LBM/SEC)
TNR3(12) - TEMPERATURE OF SODIUM, NORTH PANEL OUTLET (F)

*07175830)
071378 0005

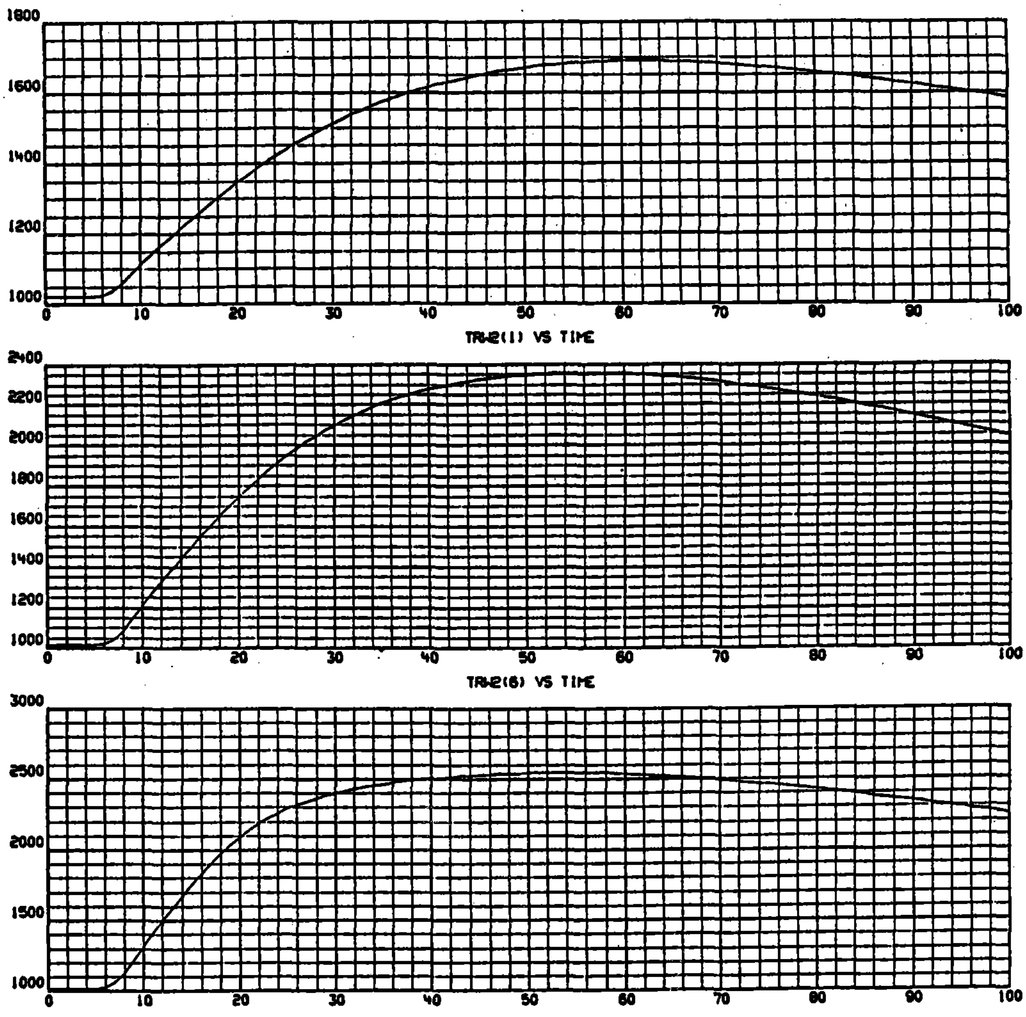


N272TI000006

99

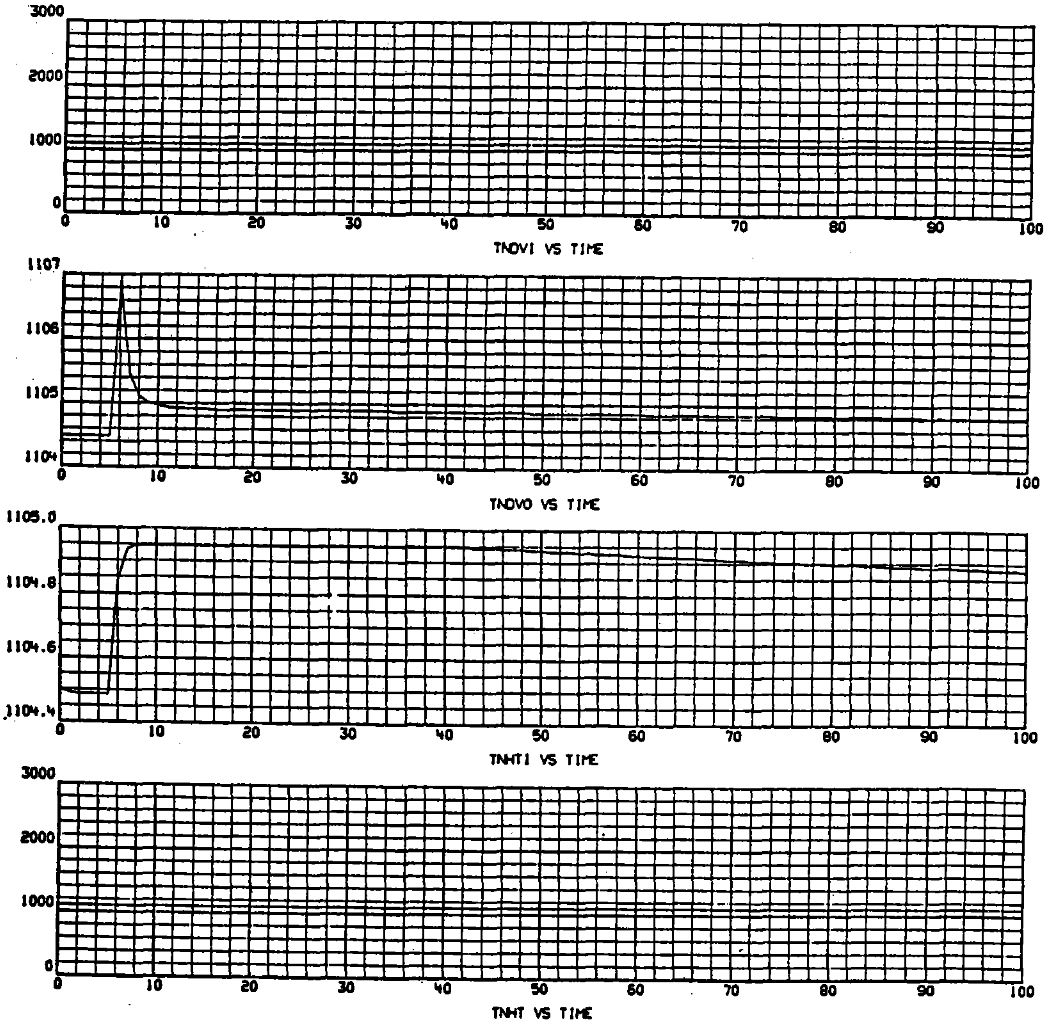
RUN 04-038 PUMP TRIP, DEFOCUS, RUNDOWN INC, 7-13-78
TRW2(1) - MEAN WALL TEMPERATURE, MIDPLANE SOUTH PANEL (F)
TRW2(6) - MEAN WALL TEMPERATURE, MIDPLANE WEST PANEL (F)
TRW2(12) - MEAN WALL TEMPERATURE, MIDPLANE NORTH PANEL (F)

•071758301
071378 0006



RUN 04-038 PUMP TRIP, DEFOCUS, RUNDOWN INC, 7-13-78
TNDVI - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE INLET,
TNDVO - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE OUTLET
TNHTI - TEMPERATURE OF SODIUM, HOT TANK INLET (F)
TNHT - TEMPERATURE OF SODIUM, HOT TANK (F)

*071758301
071378 0007



TNDVI VS TIME

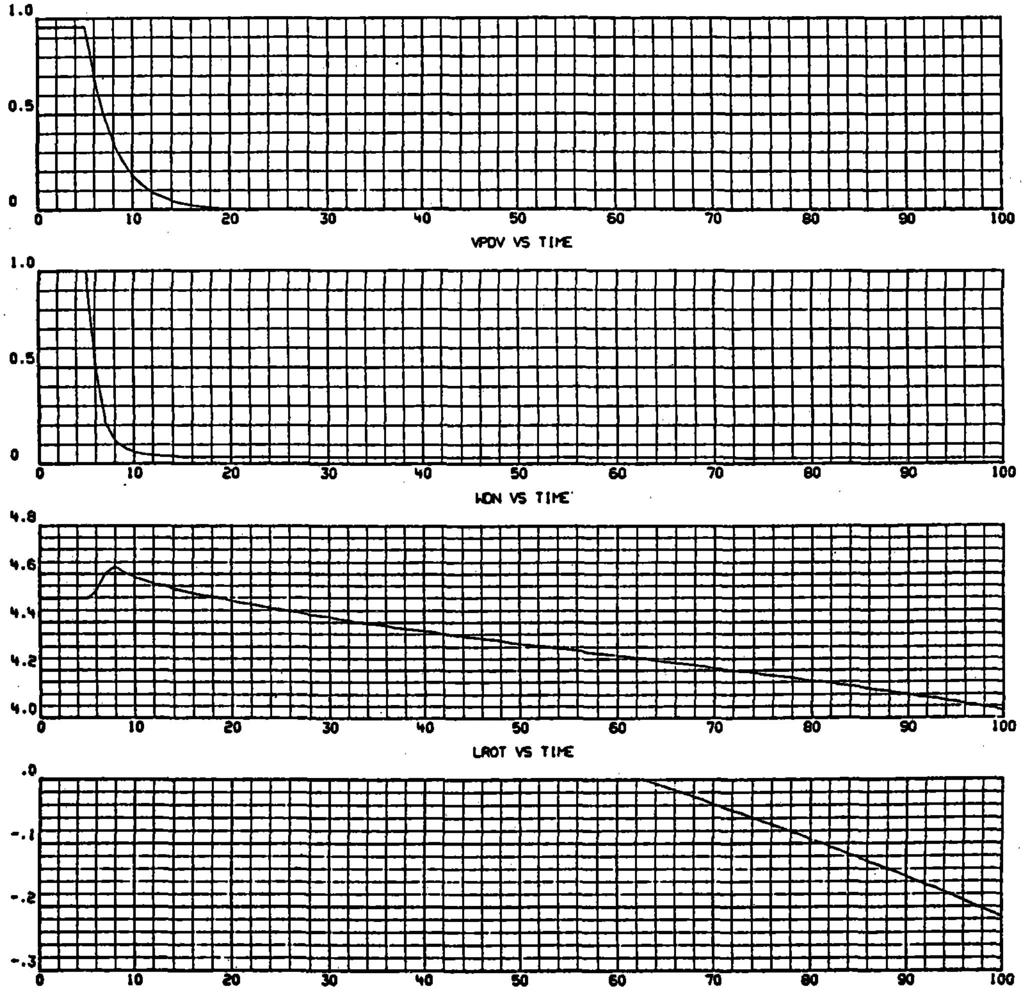
TNDVO VS TIME

TNHTI VS TIME

TNHT VS TIME

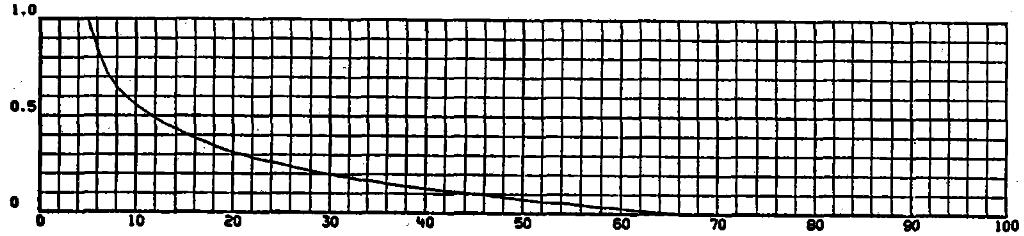
RUN 04-038 PUMP TRIP, DEFOCUS, RUNDOWN INC, 7-13-78
VPDV - PRESSURE REDUCING DEVICE VALVE POSITION (FRACTION OPEN)
WDN - DOWNCOMER FLOW (NORMALIZED TO 2220.1 LBM/SEC)
LROT - RECEIVER OUTLET TANK SODIUM LEVEL (FT)
EROTL - RECEIVER OUTLET TANK SODIUM LEVEL ERROR

*071758301
071378 0008

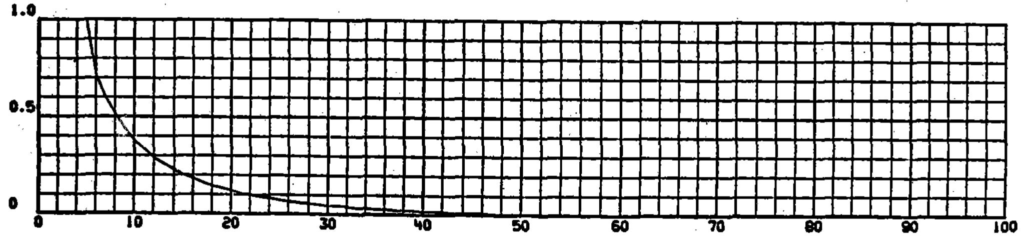


RUN 04-038 PUMP TRIP, DEFOCUS, RUNDOWN INC. 7-13-78
NRP - RECEIVER PUMP SPEED (NORMALIZED TO 700 RPM)
HRP - RECEIVER PUMP HEAD (NORMALIZED TO 824 FT)
PIR - PRESSURE AT RECEIVER INLET (PSIA)
POR - PRESSURE AT RECEIVER OUTLET (PSIA)

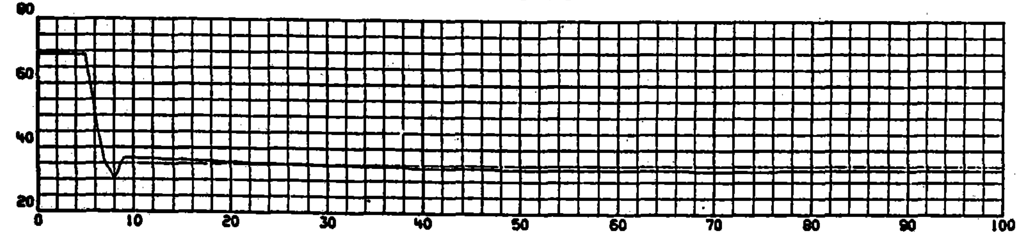
*071758301
071378 0009



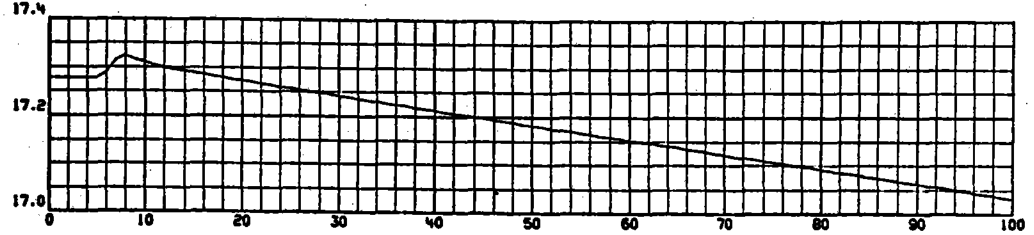
NRP VS TIME



HRP VS TIME



PIR VS TIME

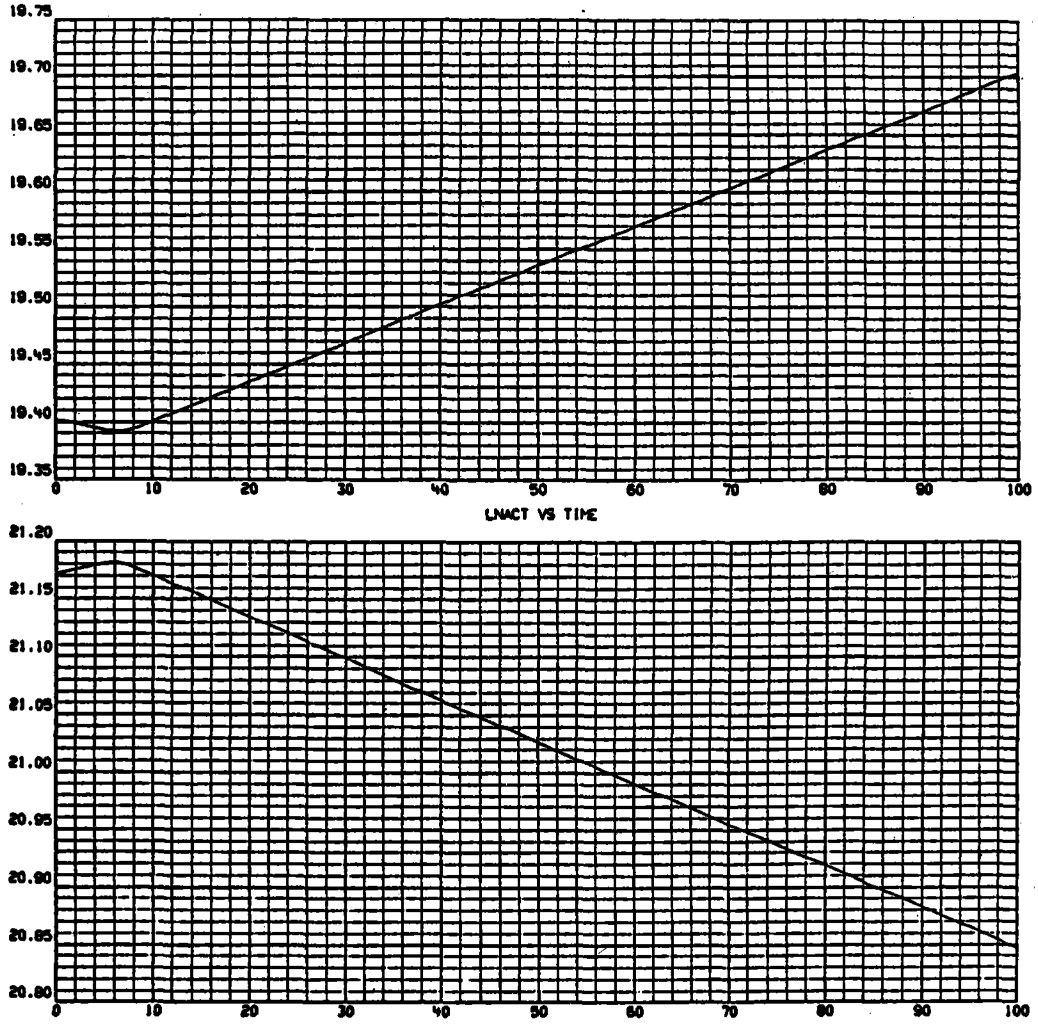


POR VS TIME

103

RUN 04-038 PUMP TRIP, DEFOCUS, RUNDOWN INC. 7-13-78
LNACT - LEVEL OF SODIUM IN COLD TANK (FT)
LNAHT - LEVEL OF SODIUM IN COLD TANK (FT)

*071758301
071378 0010

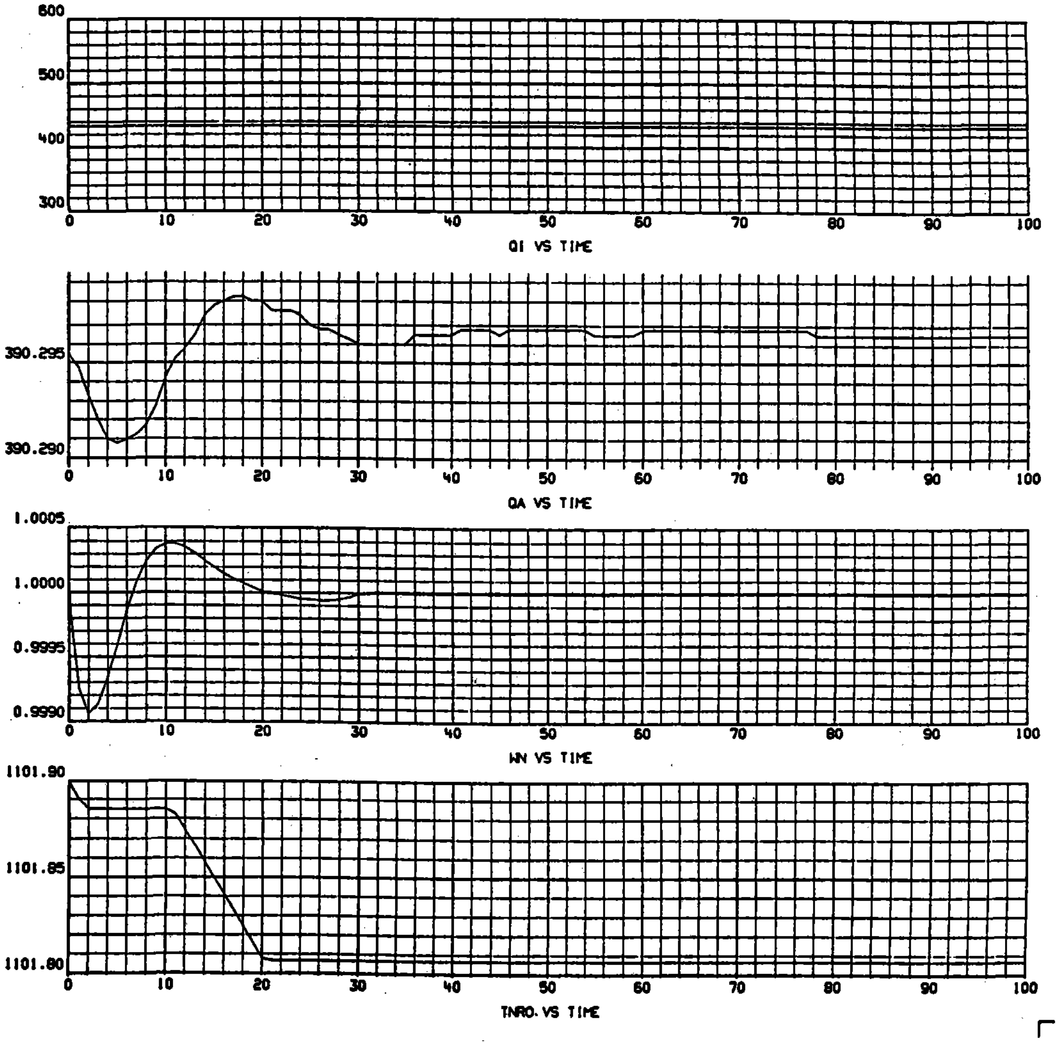


APPENDIX F

MODEL RESPONSE TO
ACCIDENTAL DRAG VALVE OPENING AND CLOSING

RUN 04-04 DRAG VALVE FAILS OPEN, NO DEFOCUS, 7-03-78
QI - TOTAL INCIDENT SOLAR POWER (MWT)
QA - TOTAL ABSORPED SOLAR POWER (MWT)
WN - TOTAL RECEIVER FLOW (LB/SEC)
TNRO - TEMPERATURE OF SODIUM RECEIVER OUTLET TANK (F)

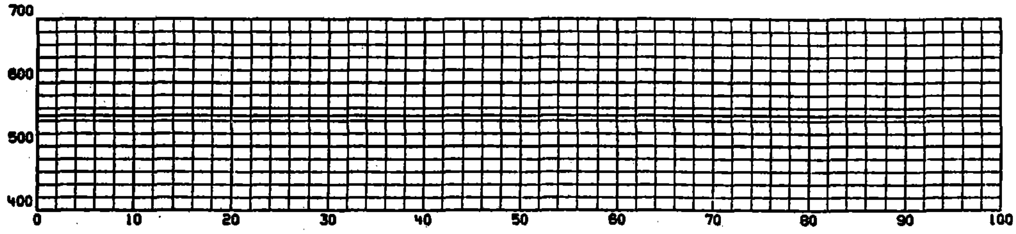
*071758301
070678 0002



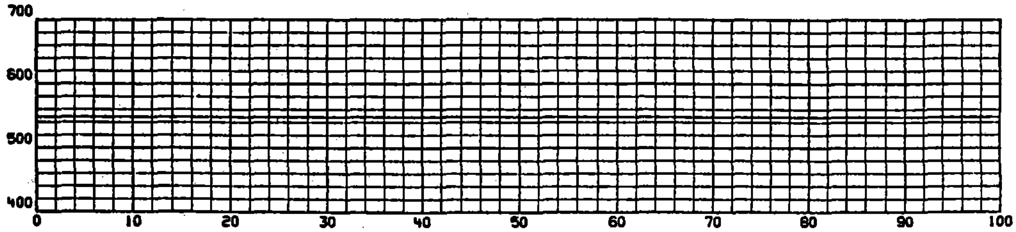
106

RUN 04-04 DRAG VALVE FAILS OPEN, NO DEFOCUS, 7-03-78
TNCT - TEMPERATURE OF SODIUM IN COLD TANK (F)
TNRPUI - TEMPERATURE OF SODIUM, RECEIVER PUMP INLET (F)
TNRPUO - TEMPERATURE OF SODIUM, RECEIVER PUMP OUTLET (F)
TNRI - TEMPERATURE OF SODIUM, RECEIVER INLET (F)

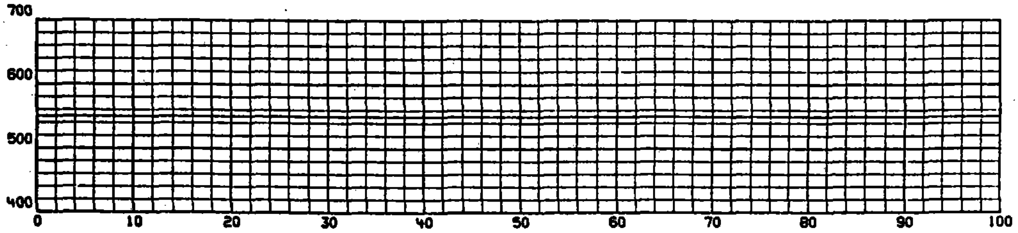
*071758301
070678 0001



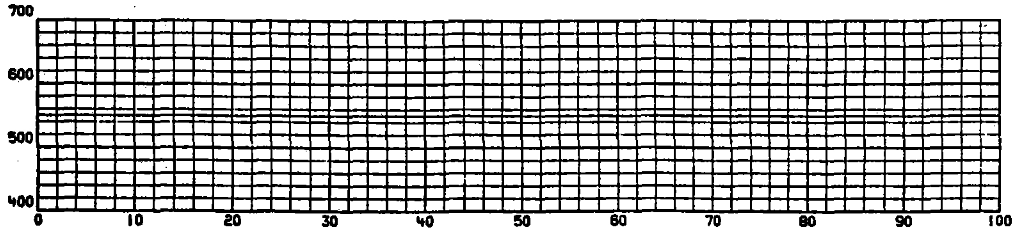
TNCT VS TIME



TNRPUI VS TIME



TNRPUO VS TIME

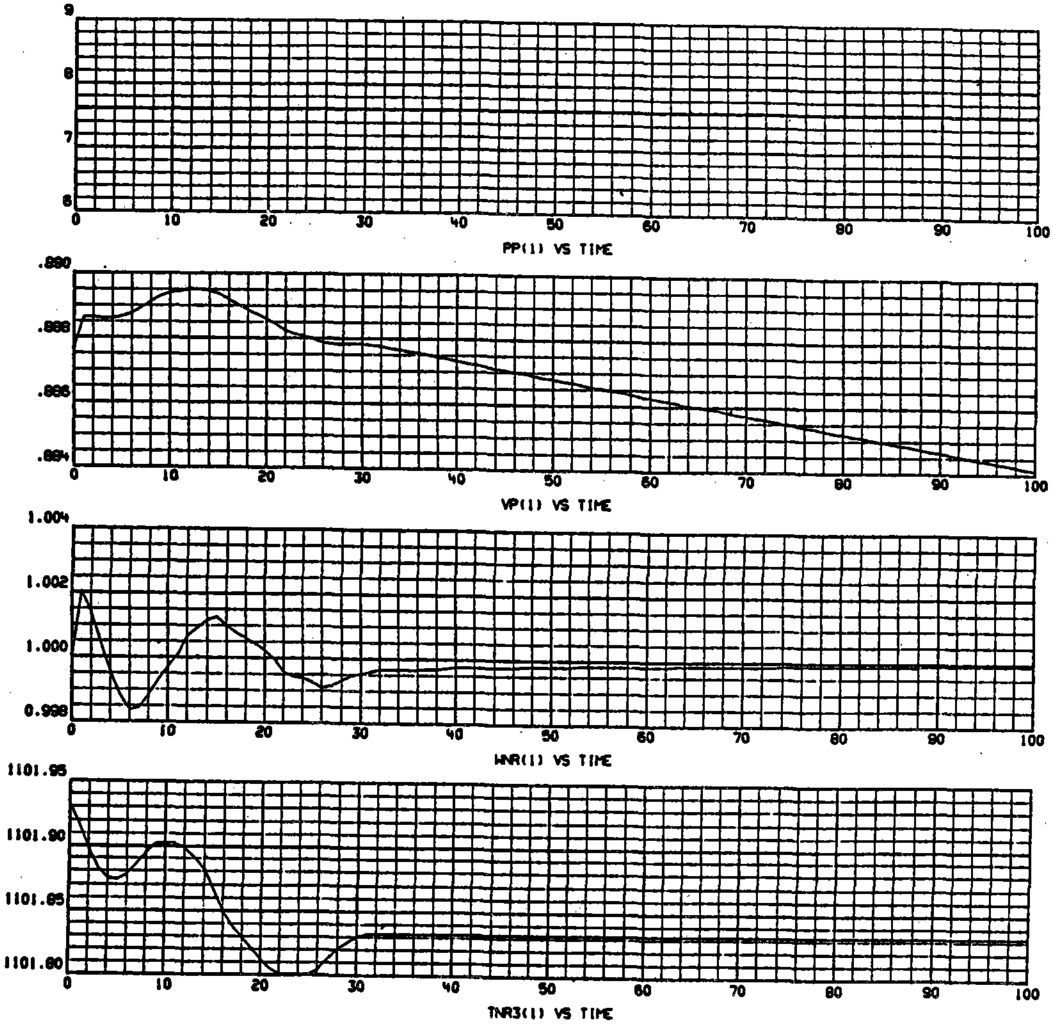


TNRI VS TIME

107

RUN 04-04 DRAG VALVE FAILS OPEN, NO DEFOCUS. 7-03-78
PP(1) - SOUTH PANEL INCIDENT POWER (MWT)
VP(1) - SOUTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(1) - SOUTH PANEL FLOW (NORMALIZED TO 36.17 LBM/SEC)
TNR3(1) -TEMPERATURE OF SODIUM, SOUTH PANEL OUTLET (F)

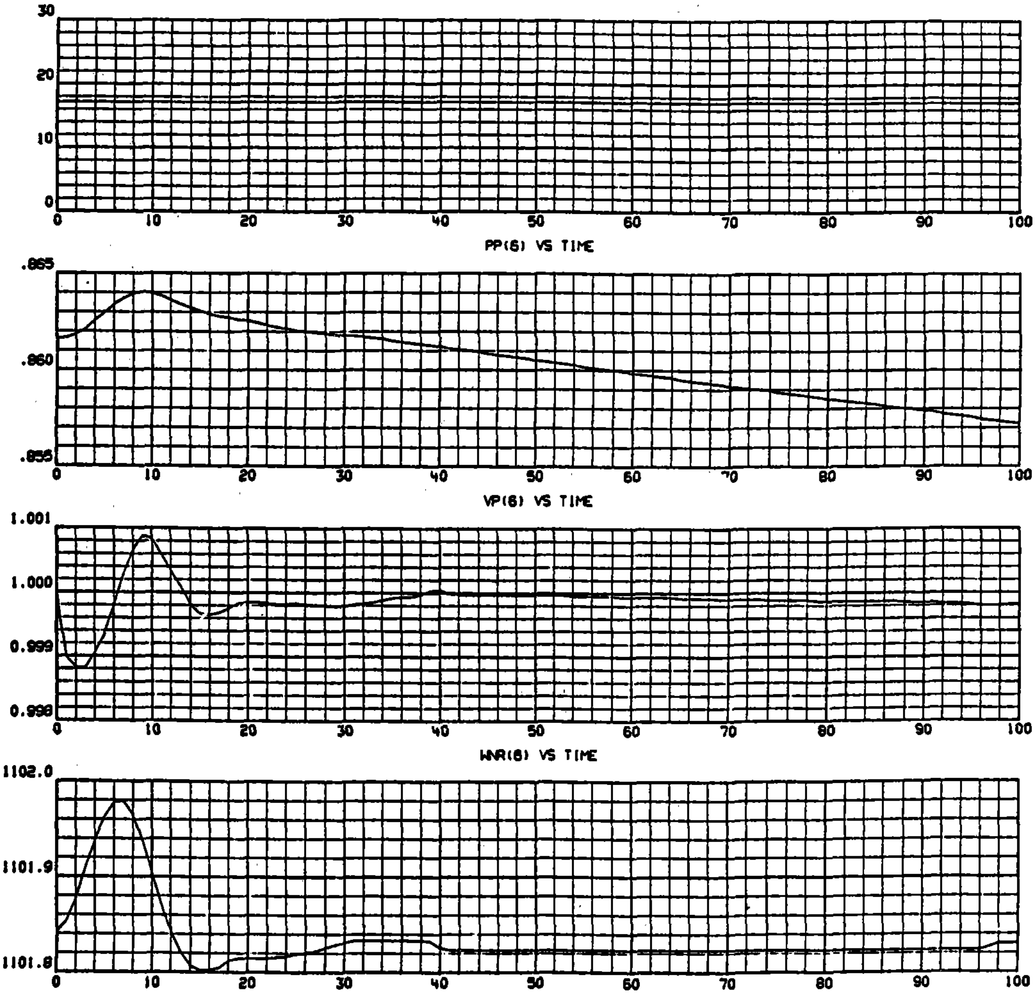
*071758301
070678 0003



108

RUN 04-04 DRAG VALVE FAILS OPEN, NO DEFOCUS, 7-03-78
PP(6) - WEST PANEL INCEDENT POWER (MWT)
VP(6) - WEST PANEL VALVE POSITION (FRACTION OPEN)
WNR(6) - WEST PANEL FLOW (NORMALIZED 88.15 LBM/SEC)
TNR3(6) -TEMPERATURE OF SODIUM, WEST PANEL OUTLET (F)

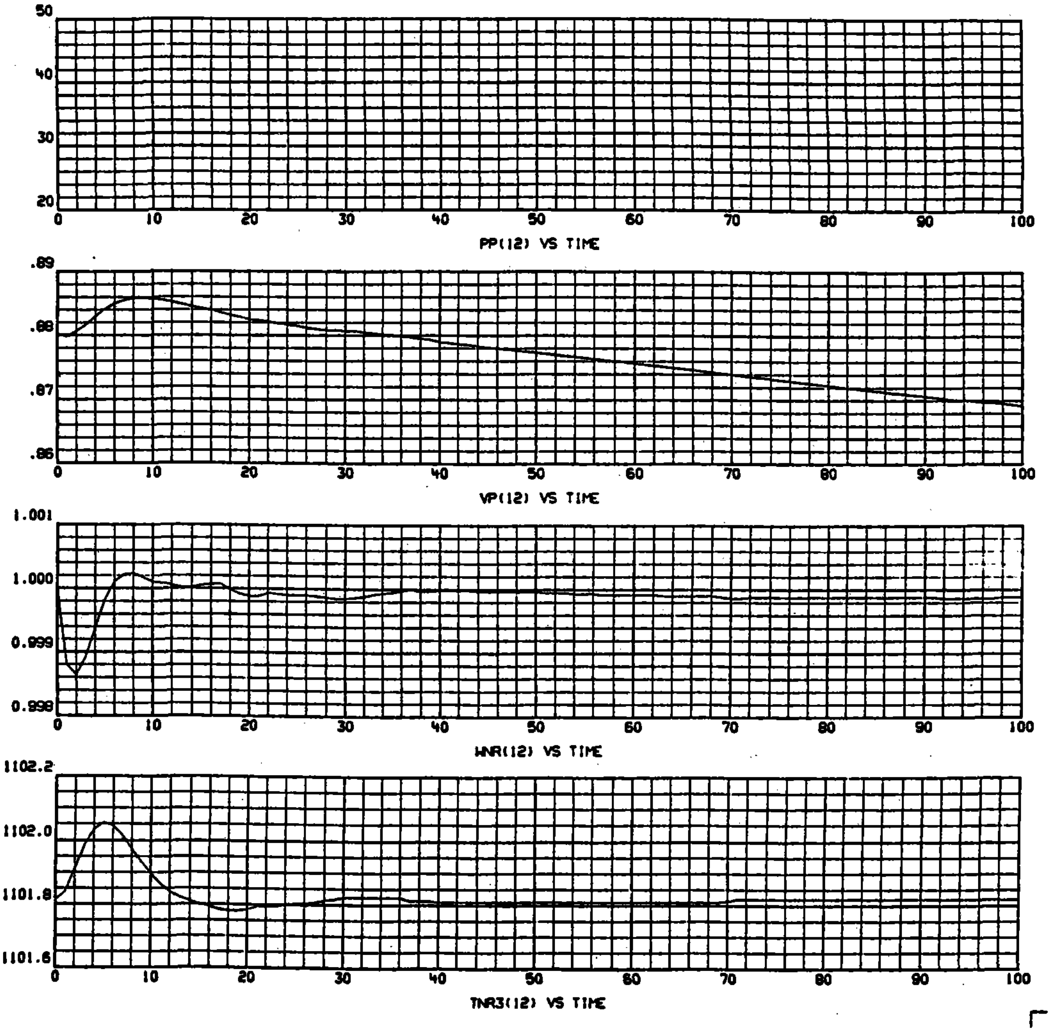
*071758301
070678 0004



109

RUN 04-04 DRAG VALVE FAILS OPEN, NO DEFOCUS, 7-03-78
PP(12) - NORTH PANEL INCIDENT POWER (MWT)
VP(12) - NORTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(12) - NORTH PANEL FLOW (NORMALIZED TO 167.69 LBM/SEC)
TNR3(12) - TEMPERATURE OF SODIUM, NORTH PANEL OUTLET (F)

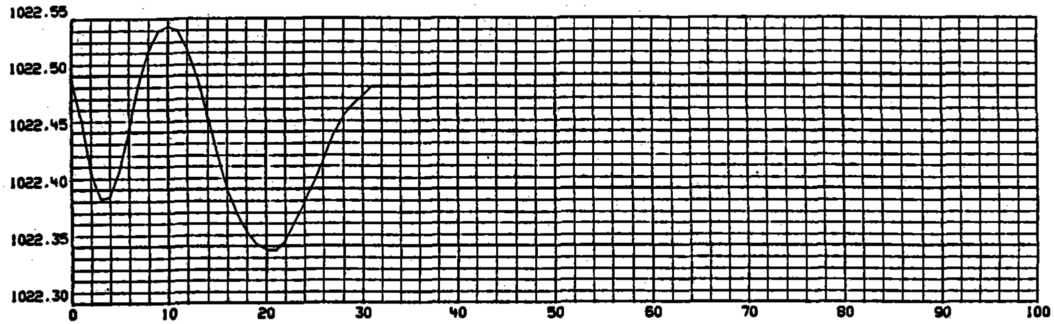
*071758301
070678 0005



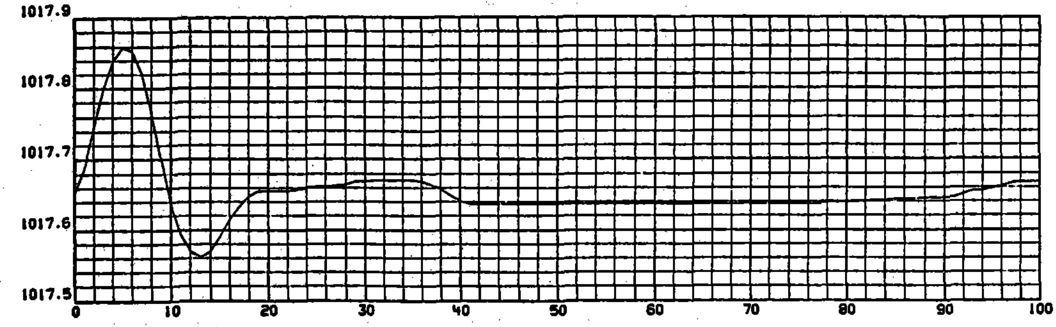
110

RUN 04-04 DRAG VALVE FAILS OPEN, NO DEFOCUS, 7-03-78
TRW2(1) - MEAN WALL TEMPERATURE, MIDPLANE SOUTH PANEL (F)
TRW2(6) - MEAN WALL TEMPERATURE, MIDPLANE WEST PANEL (F)
TRW2(12) - MEAN WALL TEMPERATURE, MIDPLANE NORTH PANEL (F)

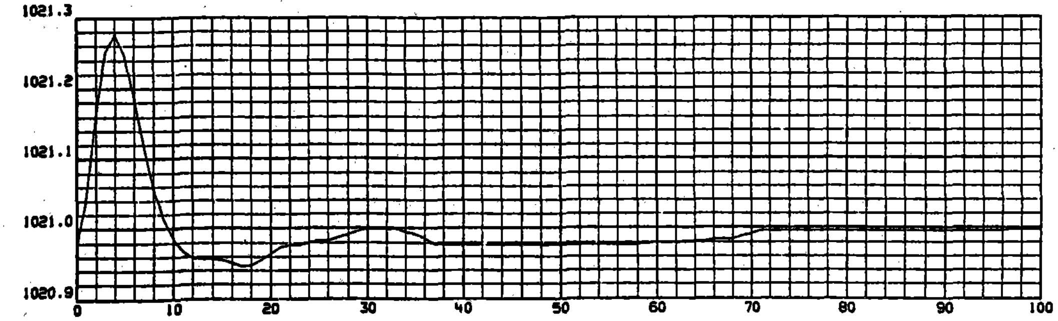
*071758301
070678 0006



TRW2(1) VS TIME



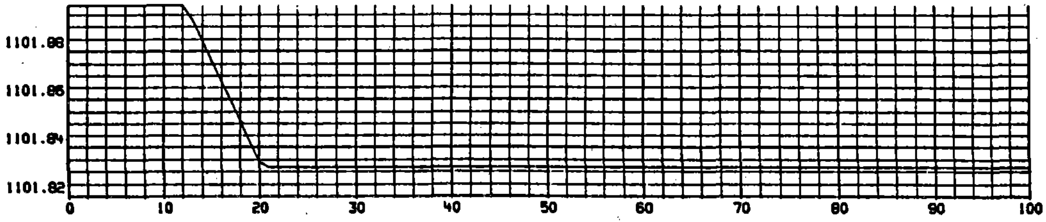
TRW2(6) VS TIME



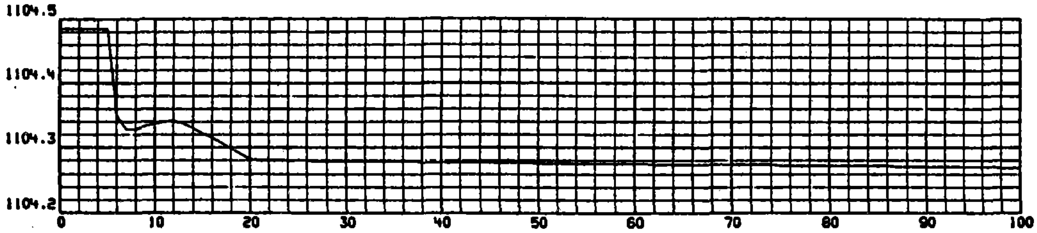
TRW2(12) VS TIME

RUN 04-04 DRAG VALVE FAILS OPEN, NO DEFOCUS, 7-03-78
TNDVI - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE INLET,
TNDVO - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE OUTLET
TNHTI - TEMPERATURE OF SODIUM, HOT TANK INLET (F)
TNHT - TEMPERATURE OF SODIUM, HOT TANK (F)

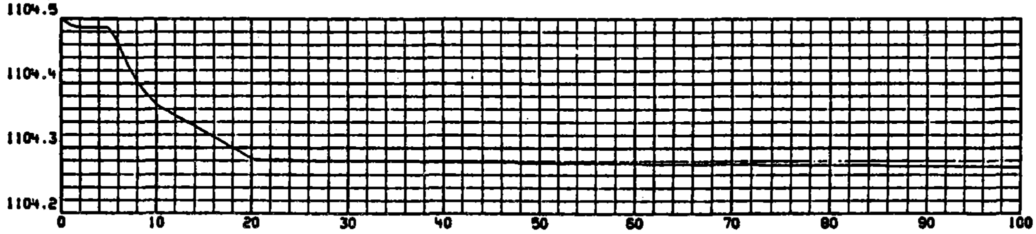
•071758301
070678 0007



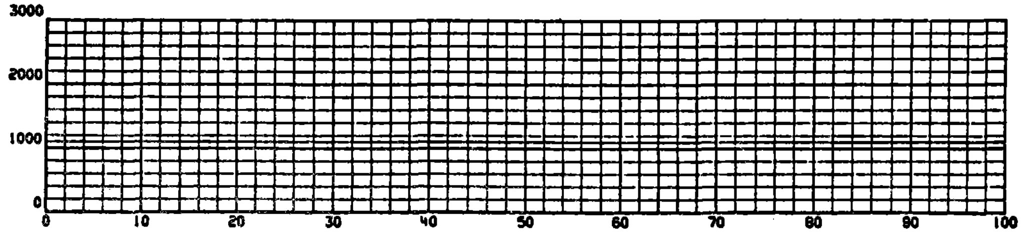
TNDVI VS TIME



TNDVO VS TIME



TNHTI VS TIME



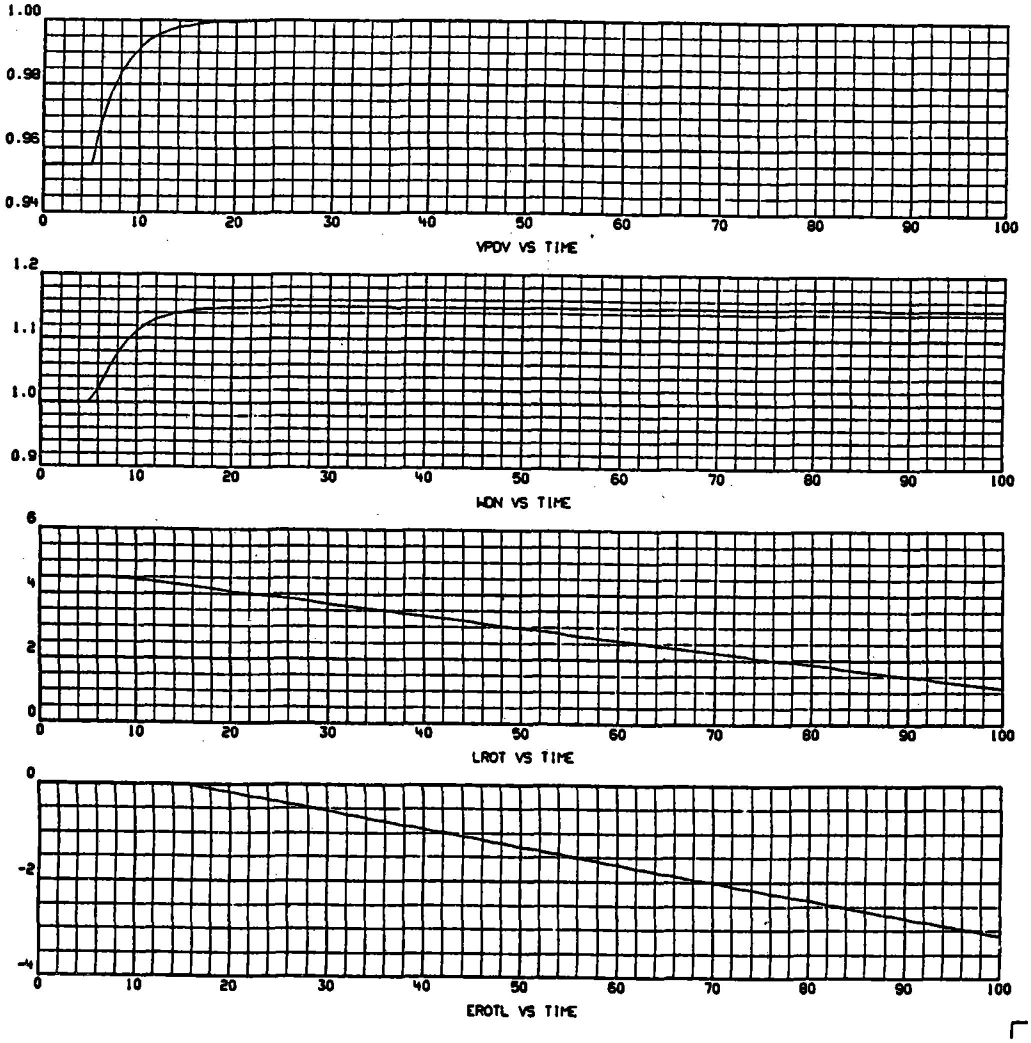
TNHT VS TIME

N272TI000006

112

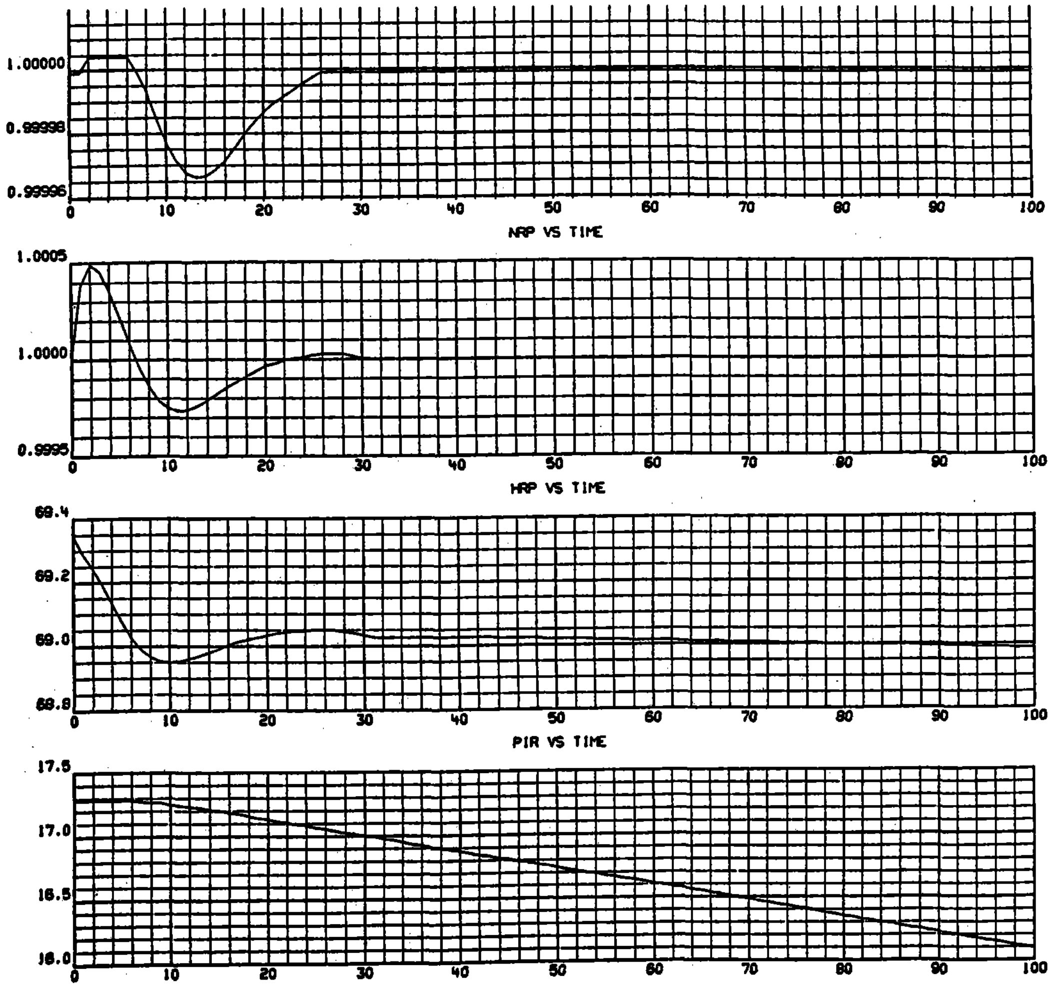
RUN 04-04 DRAG VALVE FAILS OPEN, NO DEFOCUS, 7-03-78
VPDV - PRESSURE REDUCING DEVICE VALVE POSITION (FRACTION OPEN)
HDN - DOWNCOMER FLOW (NORMALIZED TO 2220.1 LBM/SEC)
LROT - RECEIVER OUTLET TANK SODIUM LEVEL (FT)
EROTL - RECEIVER OUTLET TANK SODIUM LEVEL ERROR

•071758301
070678 0008



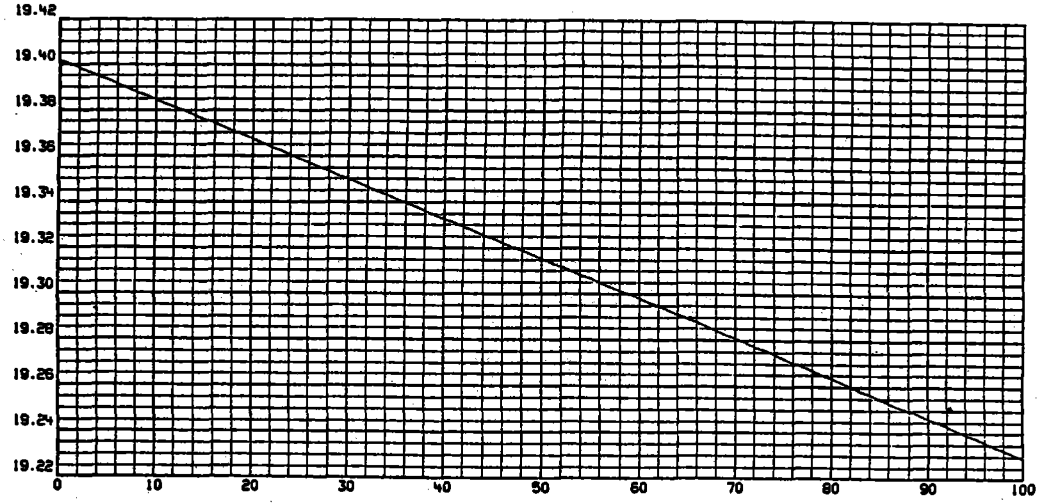
RUN 04-04 DRAG VALVE FAILS OPEN, NO DEFOCUS, 7-03-78
NRP - RECEIVER PUMP SPEED (NORMALIZED TO 700 RPM)
HRP - RECEIVER PUMP HEAD (NORMALIZED TO 824 FT)
PIR - PRESSURE AT RECEIVER INLET (PSIA)
POR - PRESSURE AT RECEIVER OUTLET (PSIA)

*071758301
070678 0009

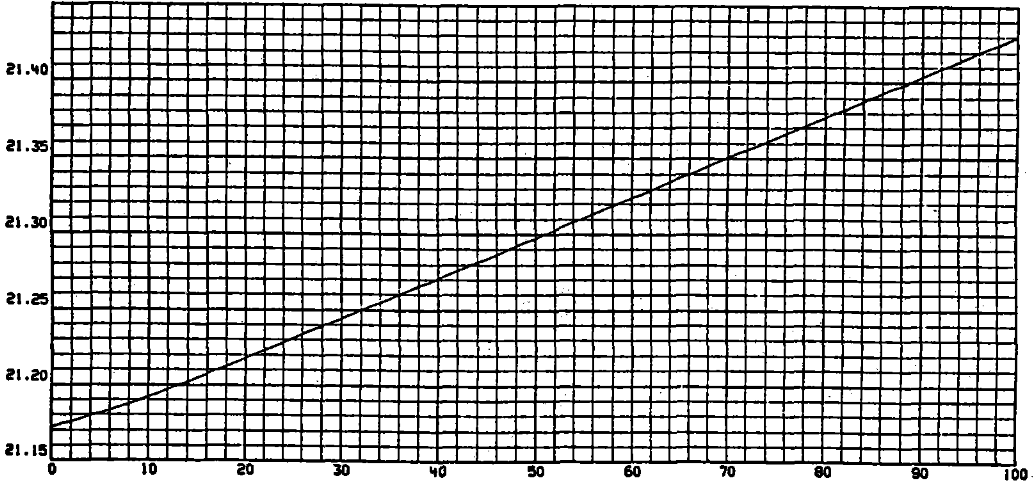


RUN 04-04 DRAG VALVE FAILS OPEN, NO DEFOCUS, 7-03-78
LNACT - LEVEL OF SODIUM IN COLD TANK (FT)
LNAHT - LEVEL OF SODIUM IN COLD TANK (FT)

*071758301
070678 0010



LNACT VS TIME

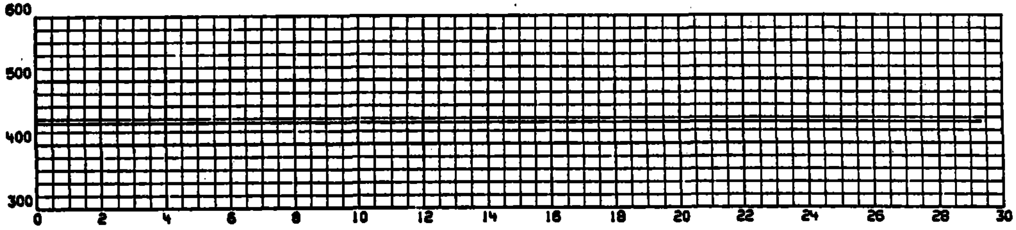


LNAHT VS TIME

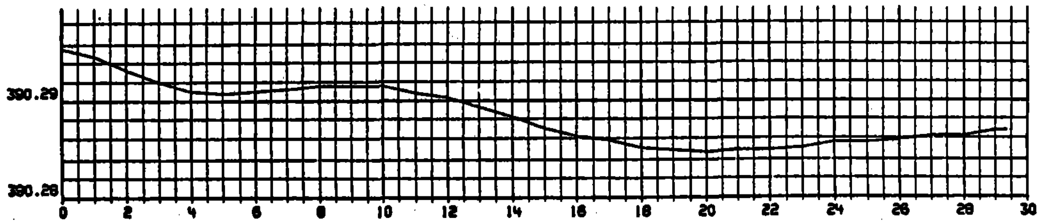
115

RUN 04-05 DRAG VALVE FAILS CLOSED, NO DEFOCUS, 7-03-78
QI - TOTAL INCIDENT SOLAR POWER (MWT)
QA - TOTAL ABSORPED SOLAR POWER (MWT)
WN - TOTAL RECEIVER FLOW (LB/SEC)
TNRO - TEMPERATURE OF SODIUM RECEIVER OUTLET TANK (F)

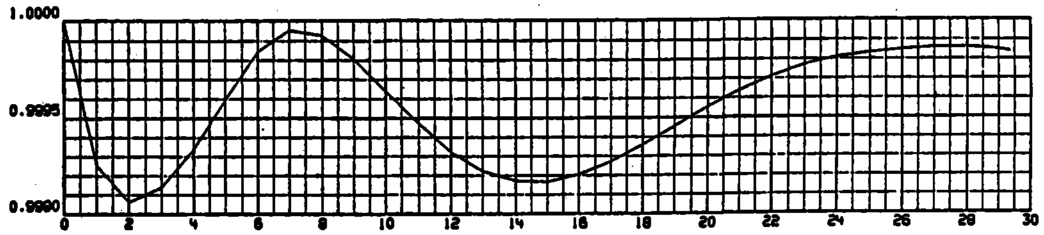
*071758301
070678 0002



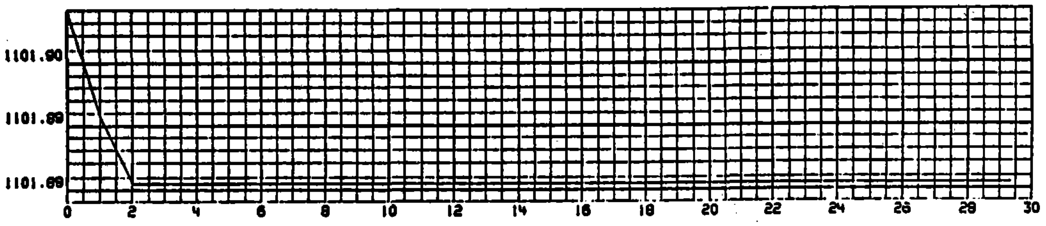
QI VS TIME



QA VS TIME



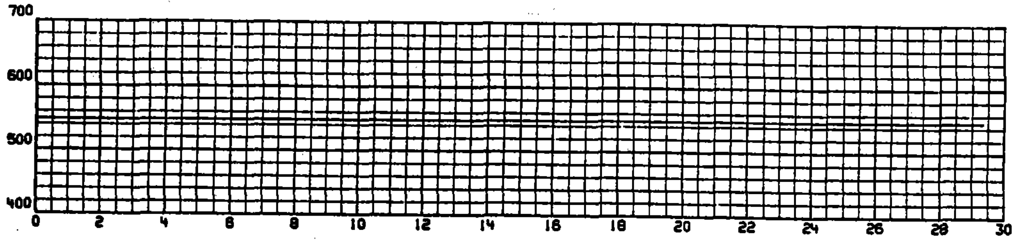
WN VS TIME



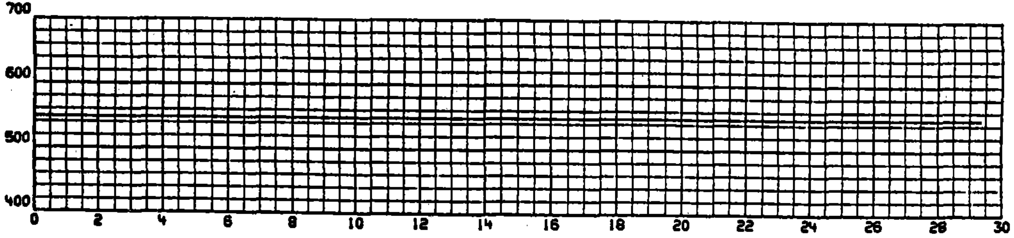
TNRO VS TIME

RUN 04-05 DRAG VALVE FAILS CLOSED, NO DEFOCUS, 7-03-78
TNCT - TEMPERATURE OF SODIUM IN COLD TANK (F)
TNRPUI - TEMPERATURE OF SODIUM, RECEIVER PUMP INLET (F)
TNRPUO - TEMPERATURE OF SODIUM, RECEIVER PUMP OUTLET (F)
TNRI - TEMPERATURE OF SODIUM, RECEIVER INLET (F)

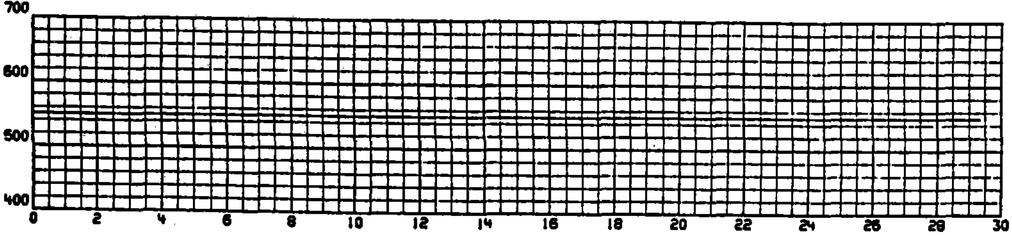
*071758301
070678 0001



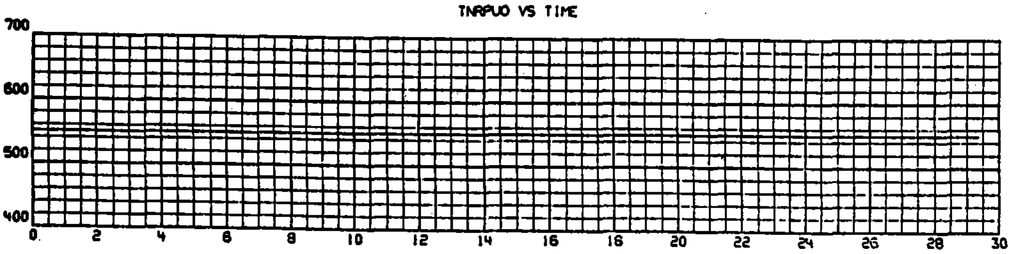
TNCT VS TIME



TNRPUI VS TIME



TNRPUO VS TIME



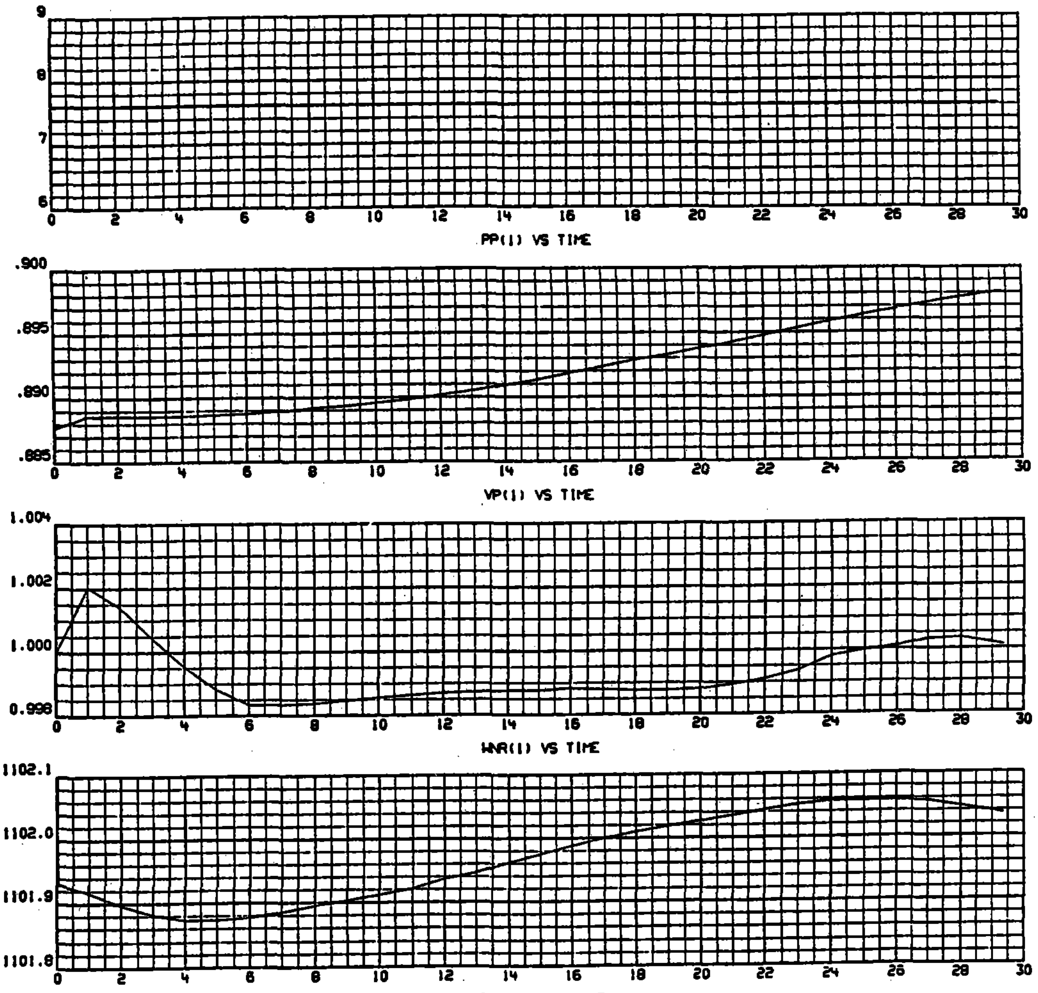
TNRI VS TIME

N272TI000006

//7

RUN 04-05 DRAG VALVE FAILS CLOSED. NO DEFOCUS. 7-03-78
PP(I) - SOUTH PANEL INCIDENT POWER (MWT)
VP(I) - SOUTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(I) - SOUTH PANEL FLOW (NORMALIZED TO 36.17 LBM/SEC)
TNR3(I) -TEMPERATURE OF SODIUM, SOUTH PANEL OUTLET (F)

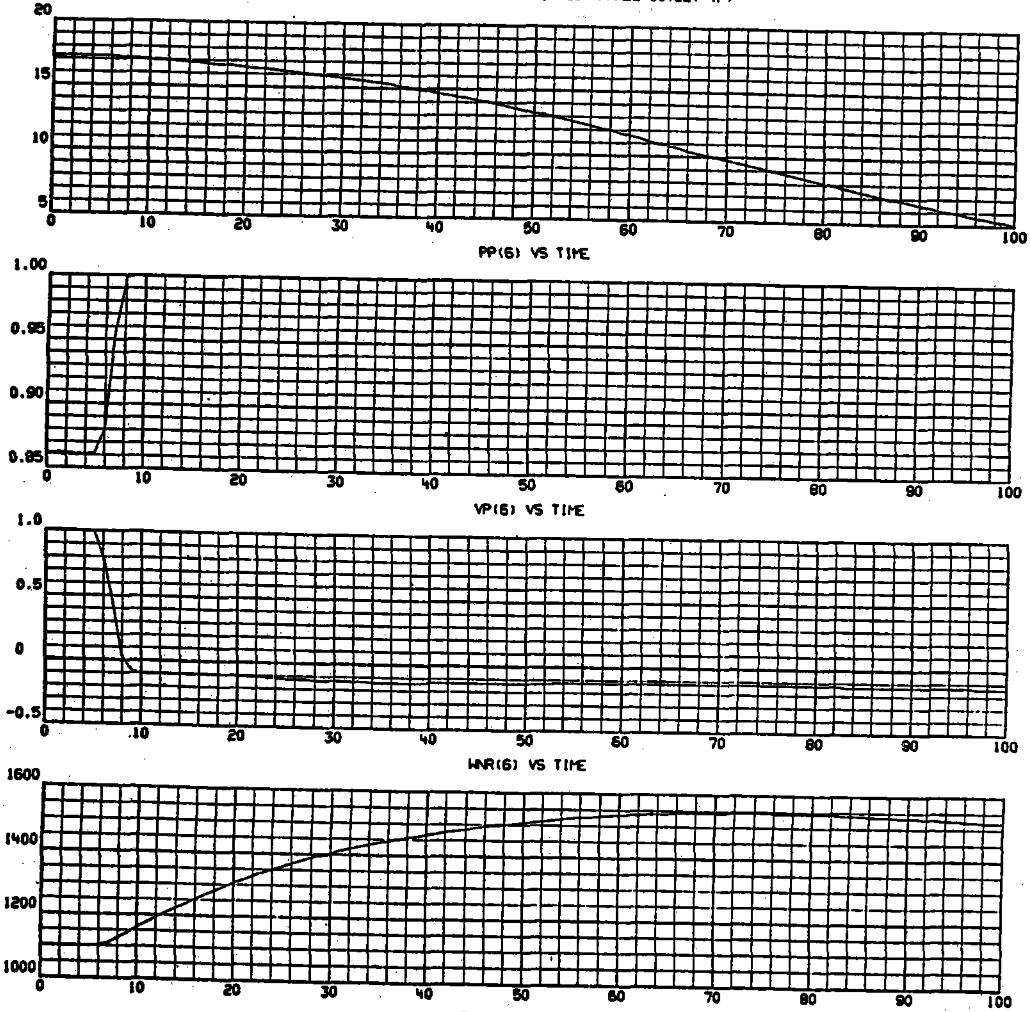
*071758301
070678 0003



N272TI000006
118

RUN 04-038 PUMP TRIP, DEFOCUS, RUNDOWN INC. 7-13-78
PP(6) - WEST PANEL INCEDENT POWER (MWT)
VP(6) - WEST PANEL VALVE POSITION (FRACTION OPEN)
WNR(6) - WEST PANEL FLOW (NORMALIZED 88.15 LBM/SEC)
TNR3(6) -TEMPERATURE OF SODIUM, WEST PANEL OUTLET (F)

*07175830I
071378 0004



PP(6) VS TIME

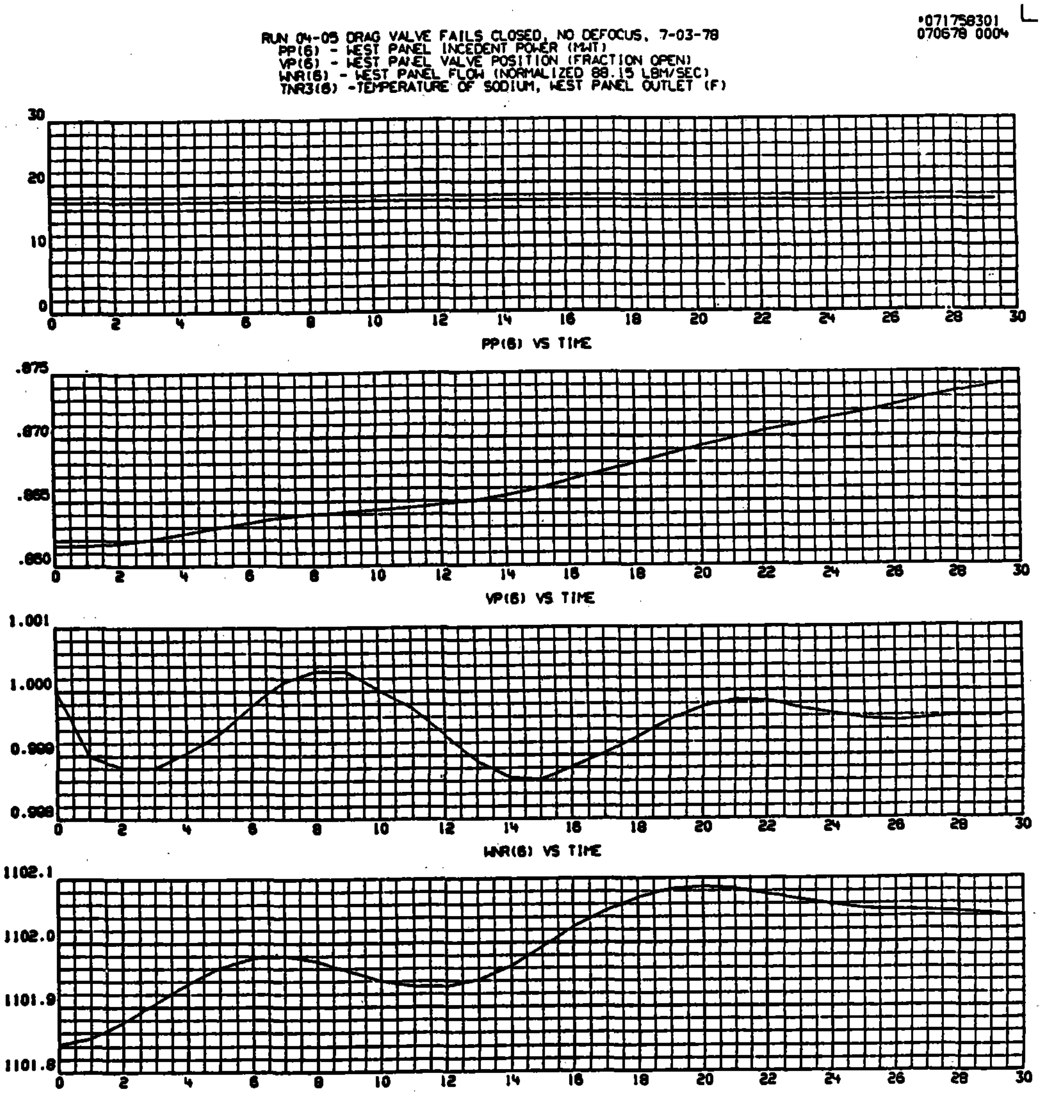
VP(6) VS TIME

WNR(6) VS TIME

TNR3(6) VS TIME

119

RUN 04-05 DRAG VALVE FAILS CLOSED, NO DEFOCUS, 7-03-78
PP(6) - WEST PANEL INCEDENT POWER (MWT)
VP(6) - WEST PANEL VALVE POSITION (FRACTION OPEN)
WNR(6) - WEST PANEL FLOW (NORMALIZED 88.15 LBM/SEC)
TNR3(6) -TEMPERATURE OF SODIUM, WEST PANEL OUTLET (F)

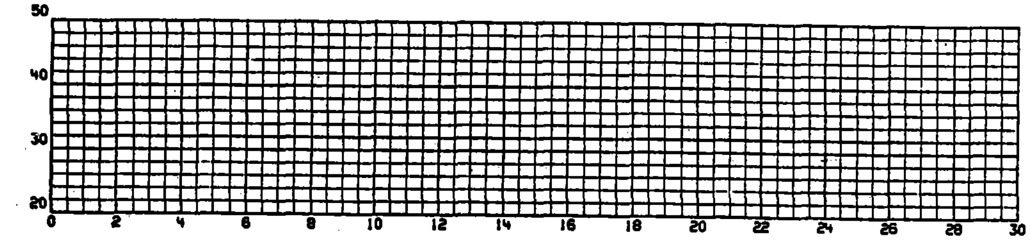


N272TI000006

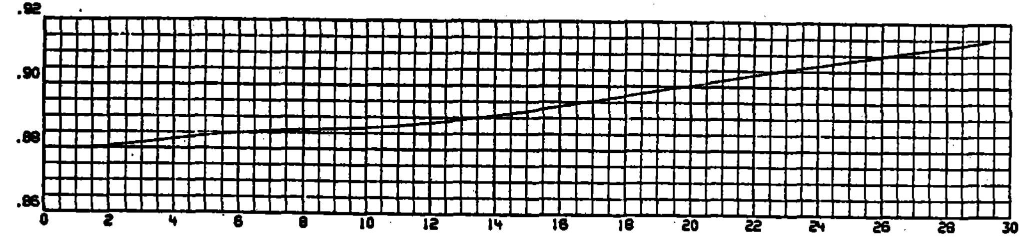
120

RUN 04-05 DRAG VALVE FAILS CLOSED, NO DEFOCUS, 7-03-78
PP(12) - NORTH PANEL INCIDENT POWER (MWT)
VP(12) - NORTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(12) - NORTH PANEL FLOW (NORMALIZED TO 167.69 LBM/SEC)
TNR3(12) - TEMPERATURE OF SODIUM, NORTH PANEL OUTLET (F)

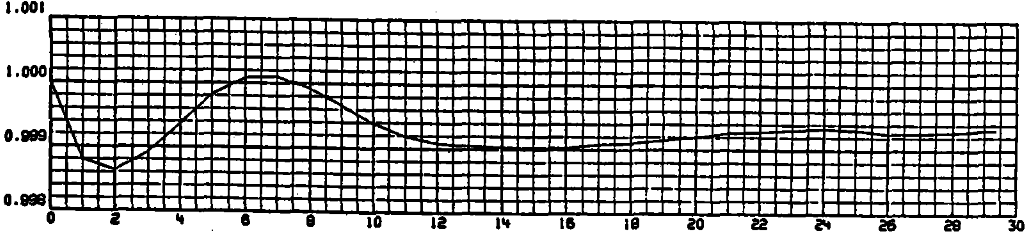
*071758301
070678 0005



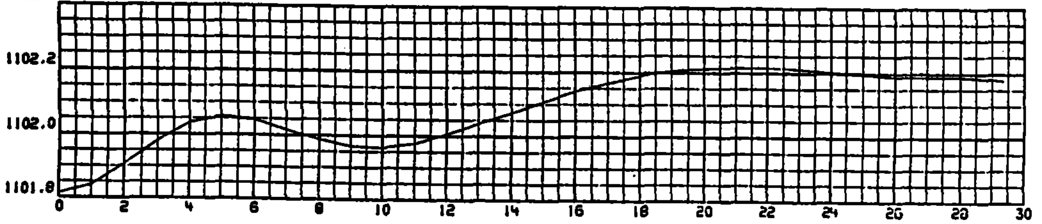
PP(12) VS TIME



VP(12) VS TIME



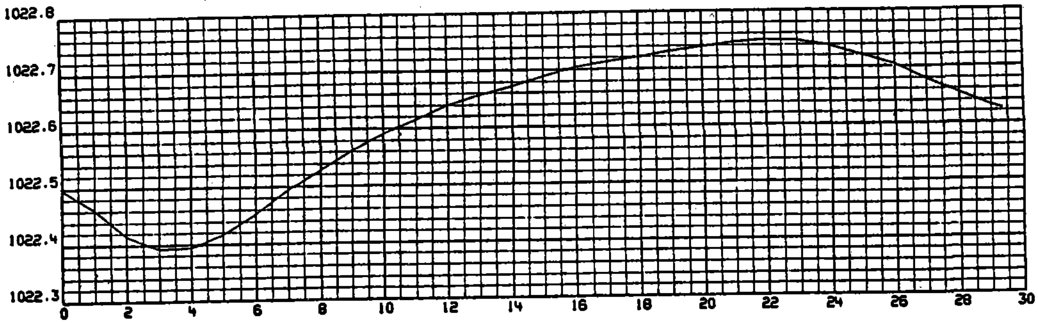
WNR(12) VS TIME



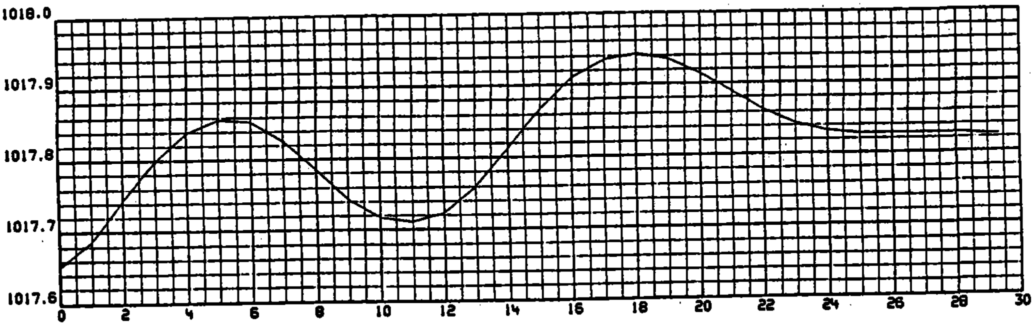
TNR3(12) VS TIME

•071758301
070678 0006

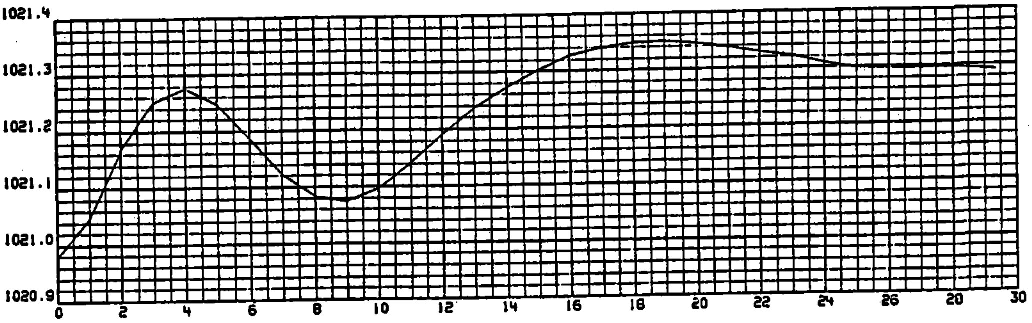
RUN 04-05 DRAG VALVE FAILS CLOSED, NO DEFOCUS, 7-03-78
TRW2(1) - MEAN WALL TEMPERATURE, MIDPLANE SOUTH PANEL (F)
TRW2(6) - MEAN WALL TEMPERATURE, MIDPLANE WEST PANEL (F)
TRW2(12) - MEAN WALL TEMPERATURE, MIDPLANE NORTH PANEL (F)



TRW2(1) VS TIME



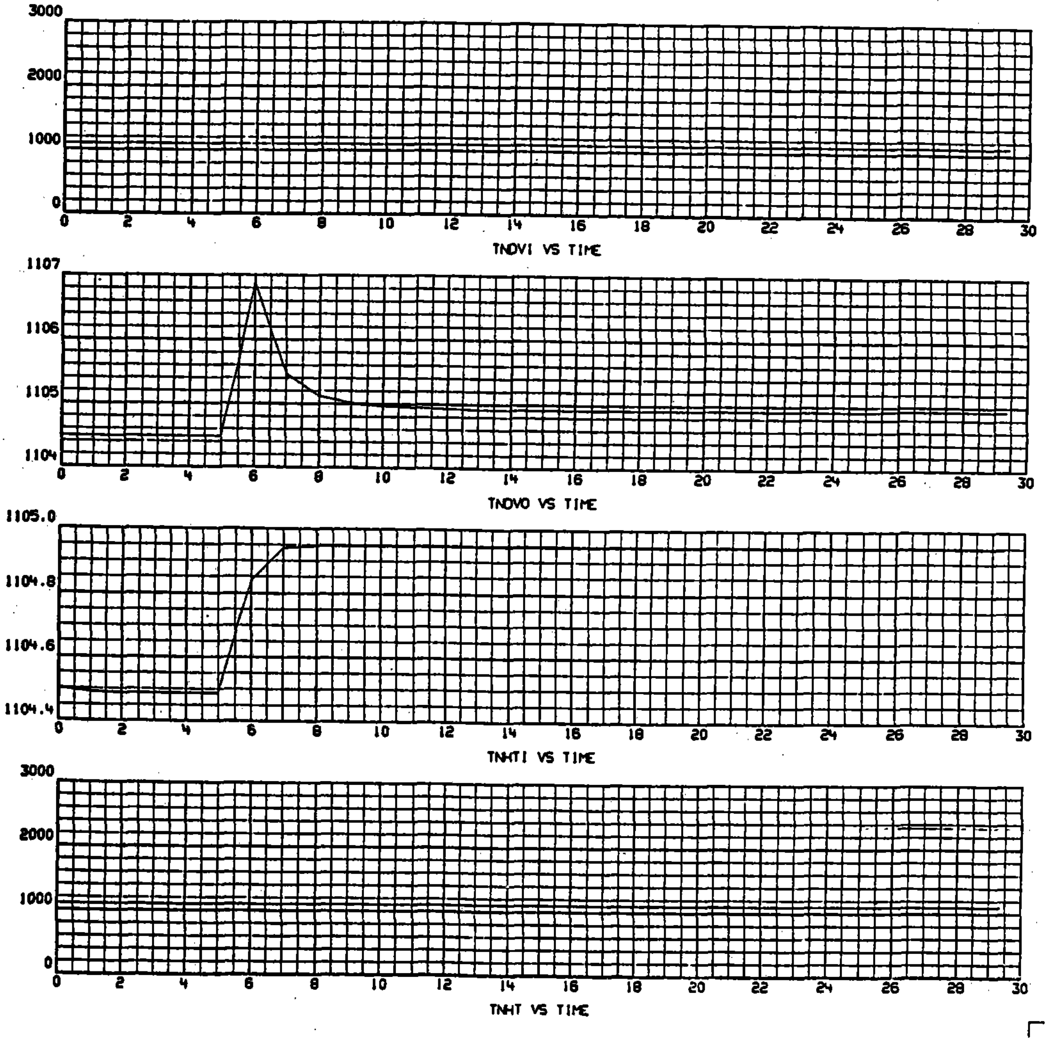
TRW2(6) VS TIME



TRW2(12) VS TIME

RUN 04-05 DRAG VALVE FAILS CLOSED, NO DEFOCUS, 7-03-78
TNDVI - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE INLET,
TNDVO - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE OUTLET
TNHTI - TEMPERATURE OF SODIUM, HOT TANK INLET (F)
TNHT - TEMPERATURE OF SODIUM, HOT TANK (F)

*071758301
070678 0007

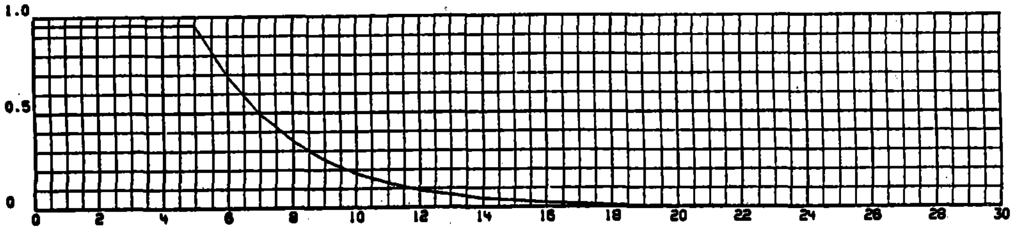


N272TI000006

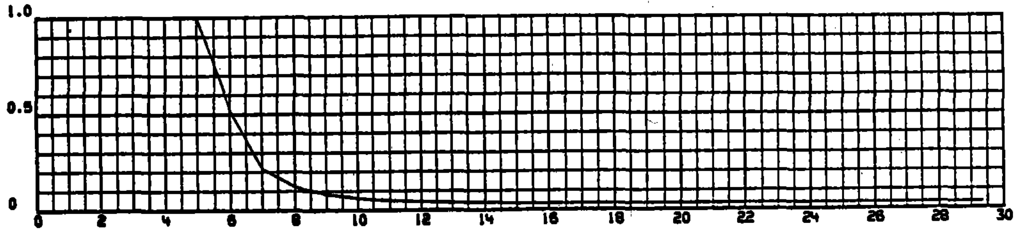
123

RUN 04-05 DRAG VALVE FAILS CLOSED, NO DEFOCUS, 7-03-78
VPDV - PRESSURE REDUCING DEVICE VALVE POSITION (FRACTION OPEN)
WDN - DOWNCOMER FLOW (NORMALIZED TO 2220.1 LBM/SEC)
LROT - RECEIVER OUTLET TANK SODIUM LEVEL (FT)
EROTL - RECEIVER OUTLET TANK SODIUM LEVEL ERROR

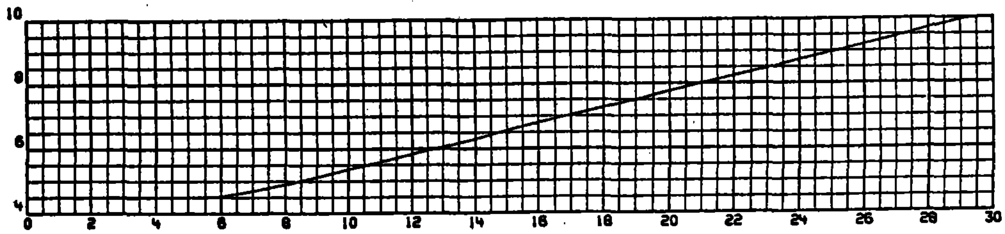
*071758301
070678 0008



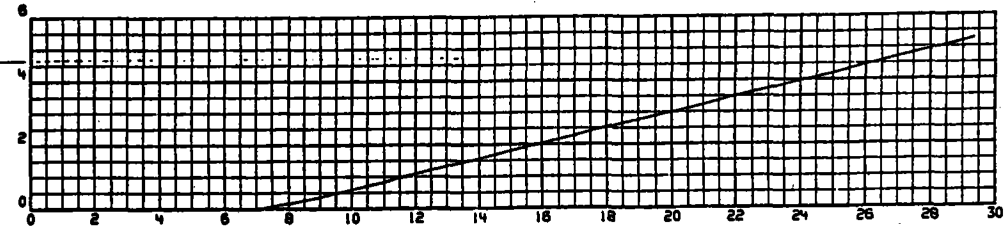
VPDV VS TIME



WDN VS TIME



LROT VS TIME

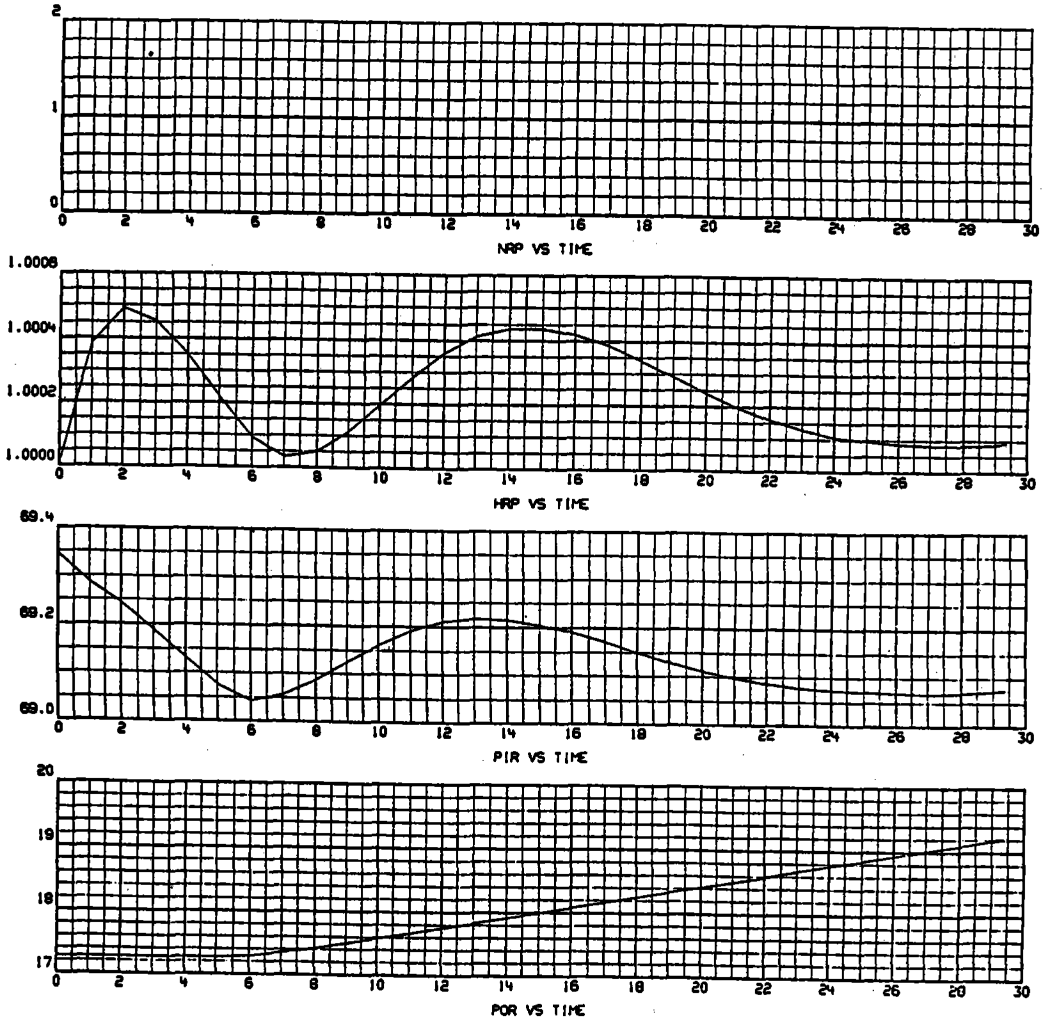


EROTL VS TIME

124

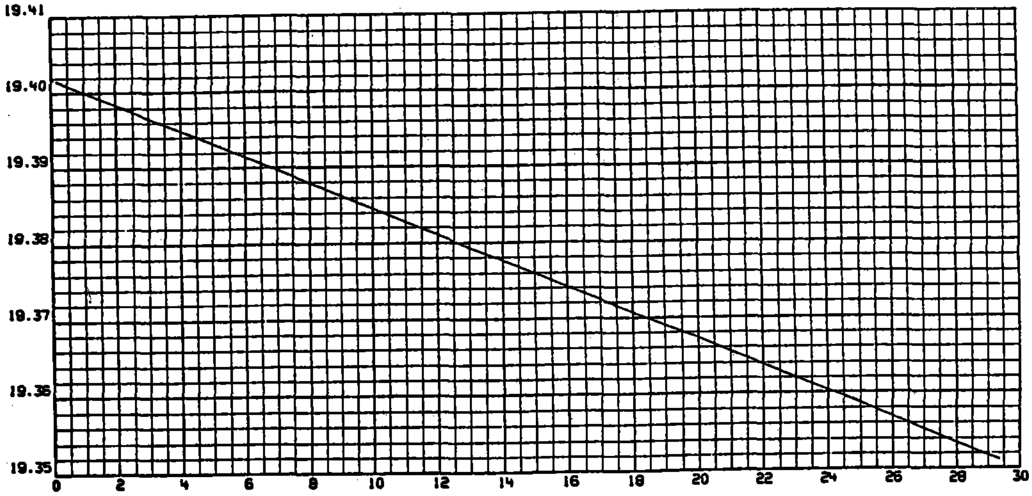
RUN 04-05 DRAG VALVE FAILS CLOSED, NO DEFOCUS, 7-03-78
NRP - RECEIVER PUMP SPEED (NORMALIZED TO 700 RPM)
HRP - RECEIVER PUMP HEAD (NORMALIZED TO 824 FT)
PIR - PRESSURE AT RECEIVER INLET (PSIA)
POR - PRESSURE AT RECEIVER OUTLET (PSIA)

*071758301
070678 0009

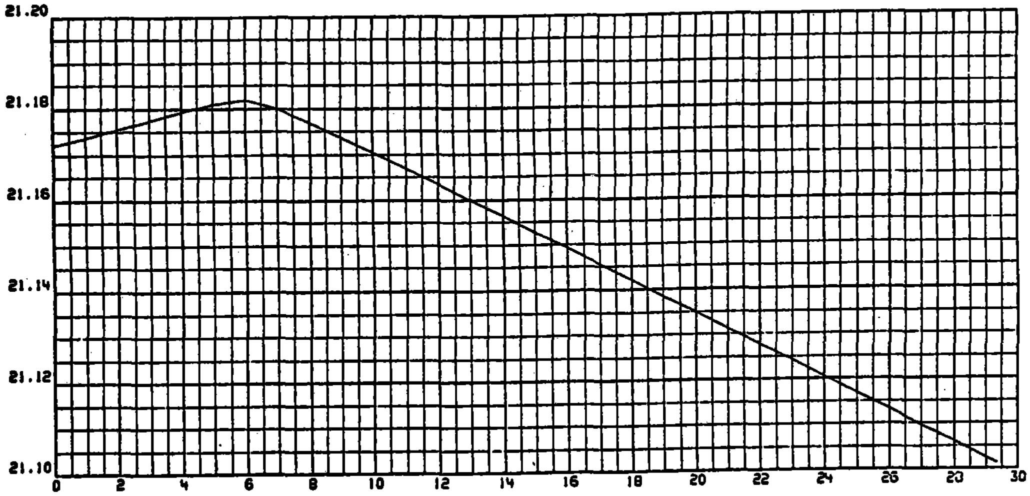


RUN 04-05 DRAG VALVE FAILS CLOSED. NO DEFOCUS. 7-03-78
LNACT - LEVEL OF SODIUM IN COLD TANK (FT)
LNAHT - LEVEL OF SODIUM IN COLD TANK (FT)

•071758301
070678 0010



LNACT VS TIME



LNAHT VS TIME

APPENDIX G

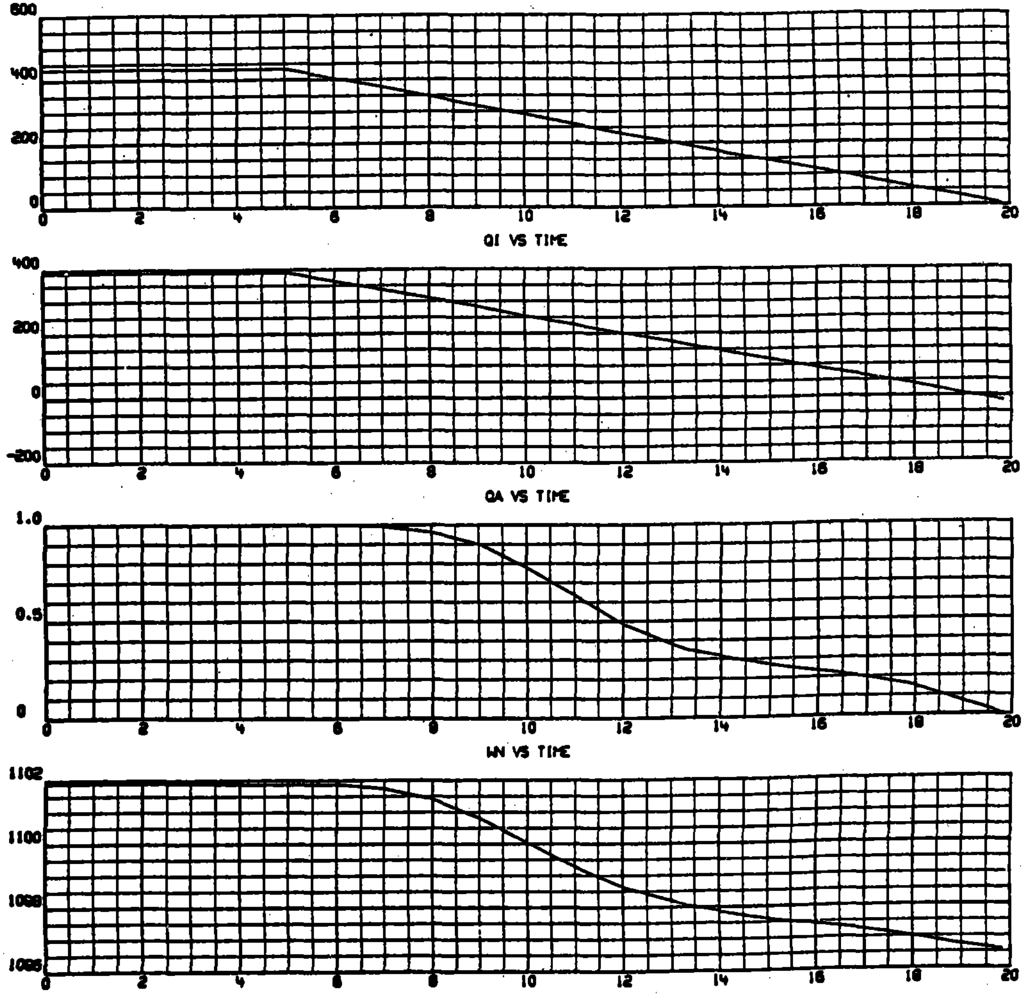
MODEL RESPONSE TO EMERGENCY SHUTDOWN 15-SECOND INCIDENT POWER DECAY RAMP

N272TI000006

127

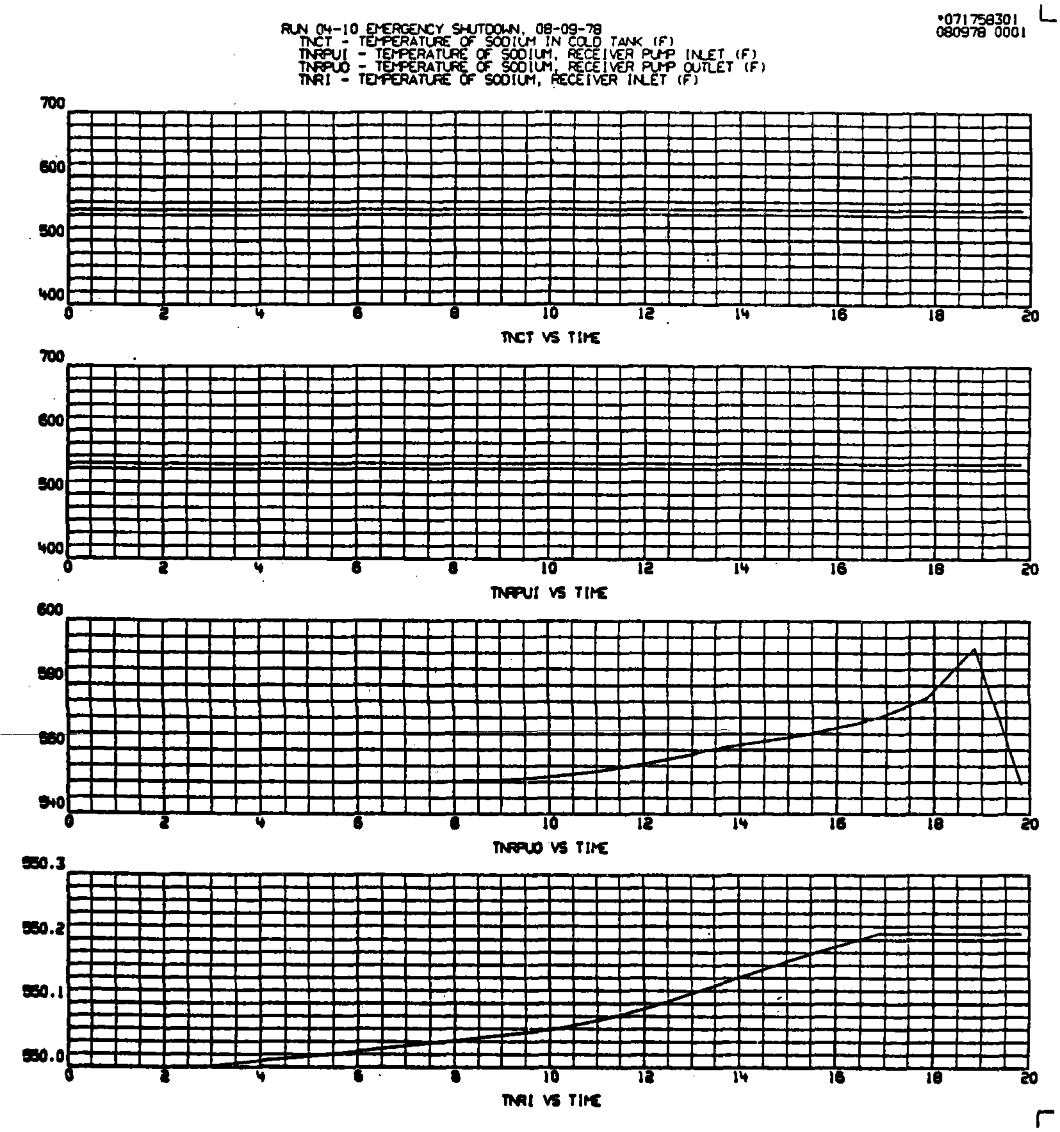
RUN 04-10 EMERGENCY SHUTDOWN 08-09-78
QI - TOTAL INCIDENT SOLAR POWER (MWT)
QA - TOTAL ABSORPED SOLAR POWER (MWT)
WN - TOTAL RECEIVER FLOW (LB/SEC)
TNRO - TEMPERATURE OF SODIUM RECEIVER OUTLET TANK (F)

*071758301
080978 0002

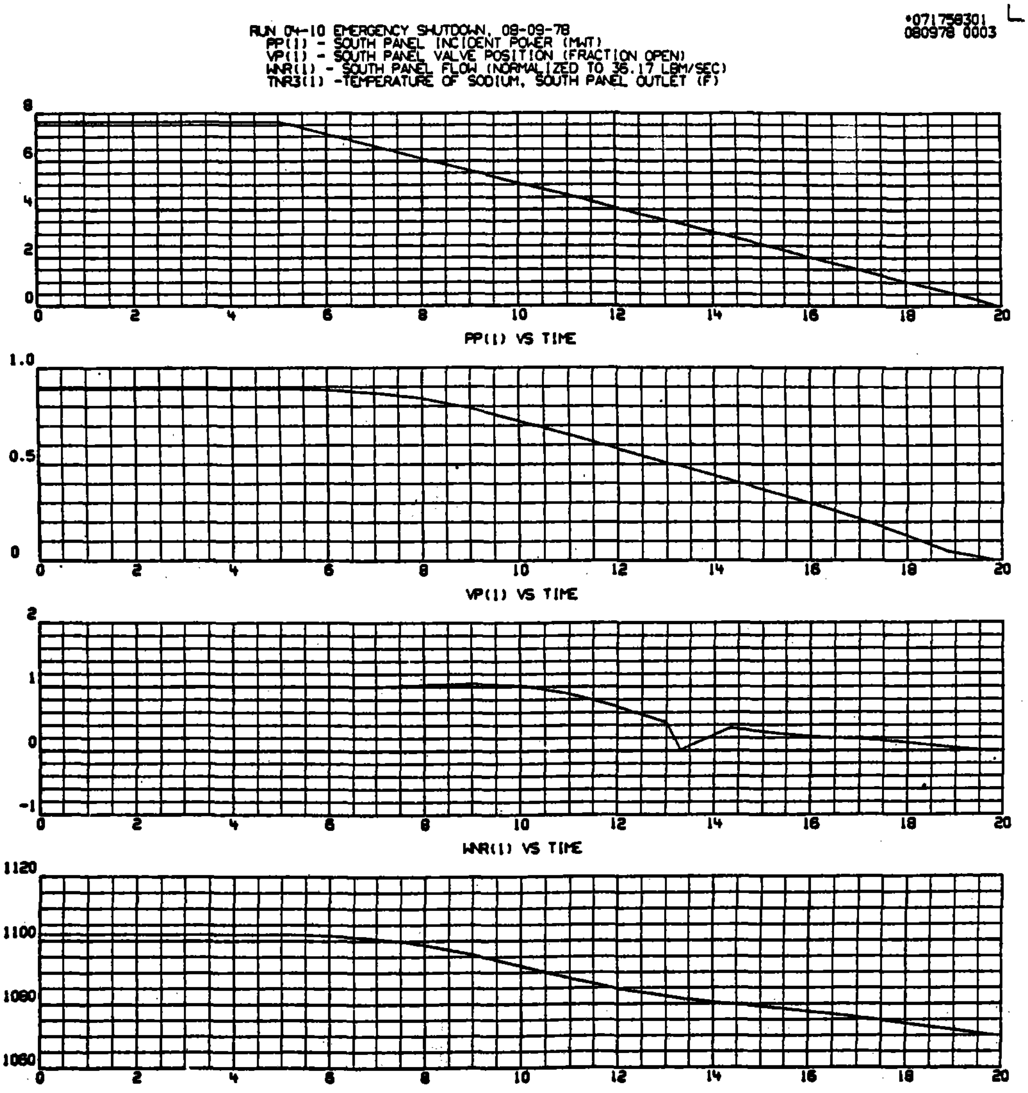


N272TI000006

/28



129



RUN 04-10 EMERGENCY SHUTDOWN, 08-09-78
PP(1) - SOUTH PANEL INCIDENT POWER (MWT)
VP(1) - SOUTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(1) - SOUTH PANEL FLOW (NORMALIZED TO 36.17 LBM/SEC)
TNR3(1) -TEMPERATURE OF SODIUM, SOUTH PANEL OUTLET (F)

*071758301
080978 0003

PP(1) VS TIME

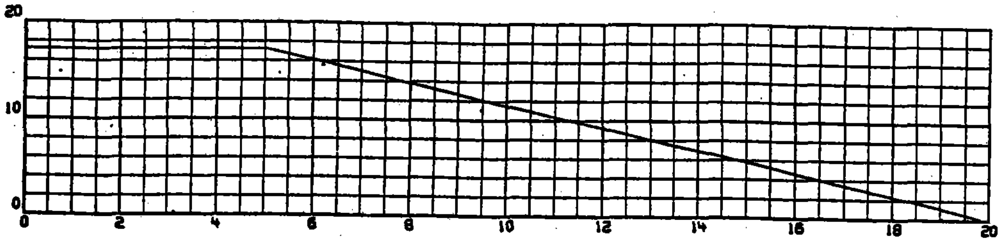
VP(1) VS TIME

WNR(1) VS TIME

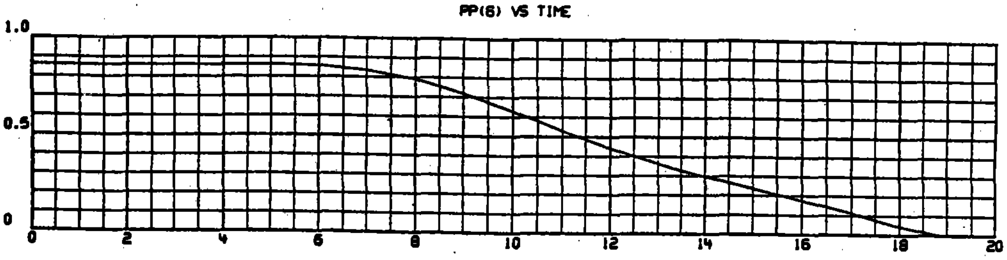
TNR3(1) VS TIME

RUN 04-10 EMERGENCY SHUTDOWN, 08-09-78
PP(6) - WEST PANEL INCEDENT POWER (MWT)
VP(6) - WEST PANEL VALVE POSITION (FRACTION OPEN)
WNR(6) - WEST PANEL FLOW (NORMALIZED 88.15 LBM/SEC)
TNR3(6) -TEMPERATURE OF SODIUM, WEST PANEL OUTLET (F)

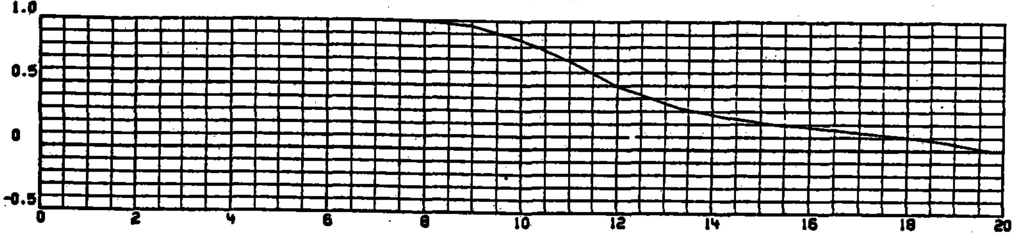
*071758301
080978 0004



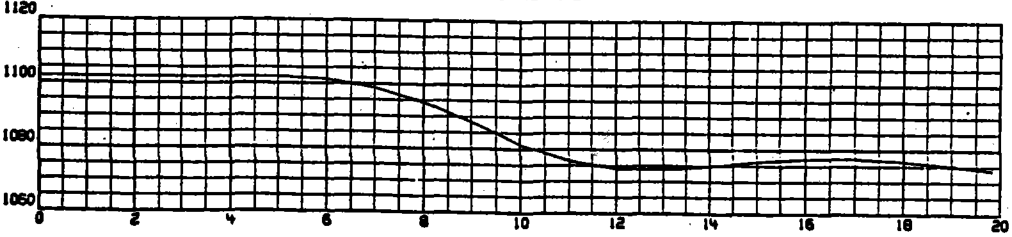
PP(6) VS TIME



VP(6) VS TIME



WNR(6) VS TIME



TNR3(6) VS TIME

/3/

RUN 04-10 EMERGENCY SHUTDOWN, 08-09-78
PP(12) - NORTH PANEL INCIDENT POWER (MWT)
VP(12) - NORTH PANEL VALVE POSITION (FRACTION OPEN)
WNR(12) - NORTH PANEL FLOW (NORMALIZED TO 167.69 LBM/SEC)
TNR3(12) - TEMPERATURE OF SODIUM, NORTH PANEL OUTLET (F)

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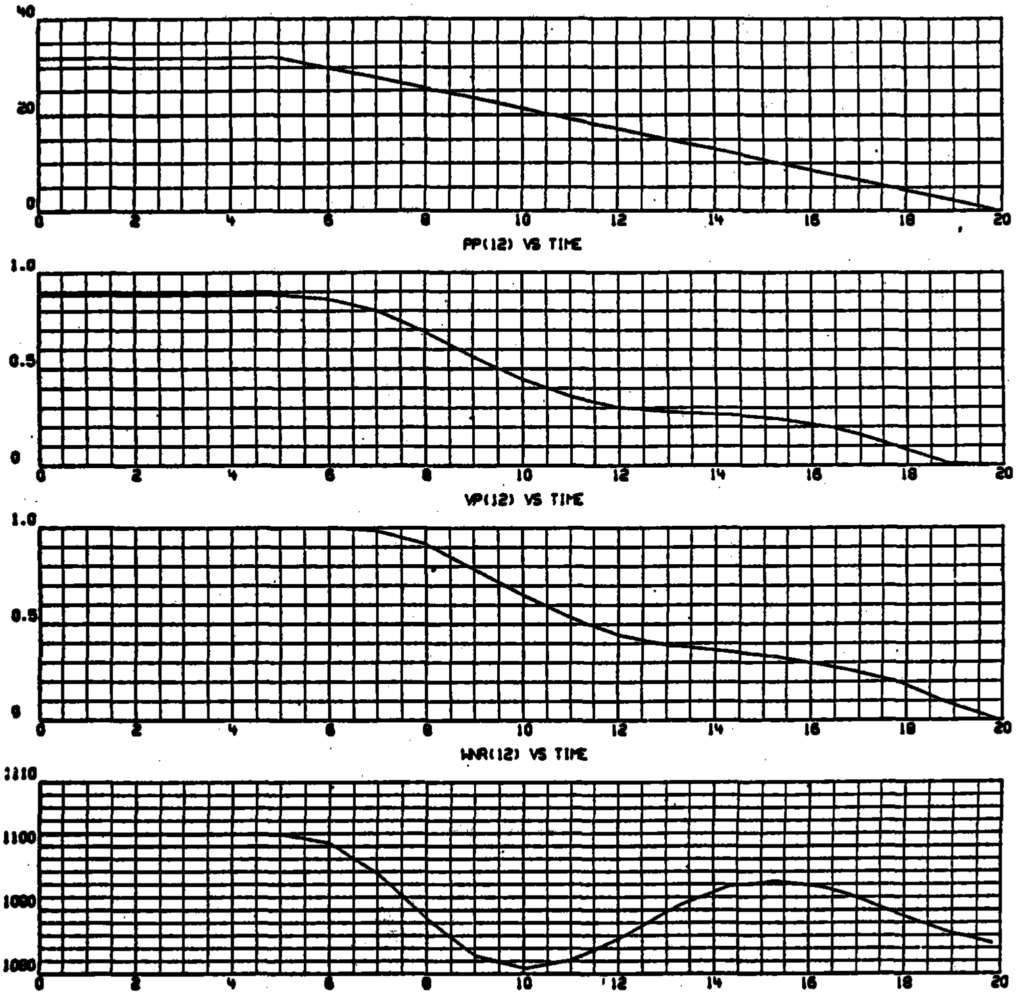

PP(12) VS TIME

VP(12) VS TIME

WNR(12) VS TIME

TNR3(12) VS TIME

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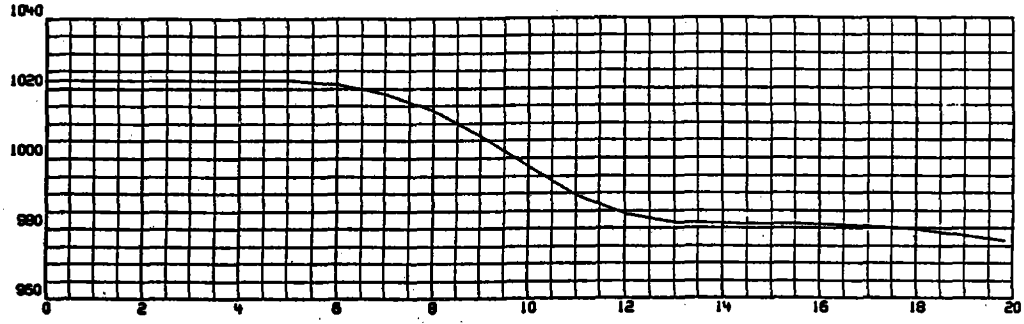
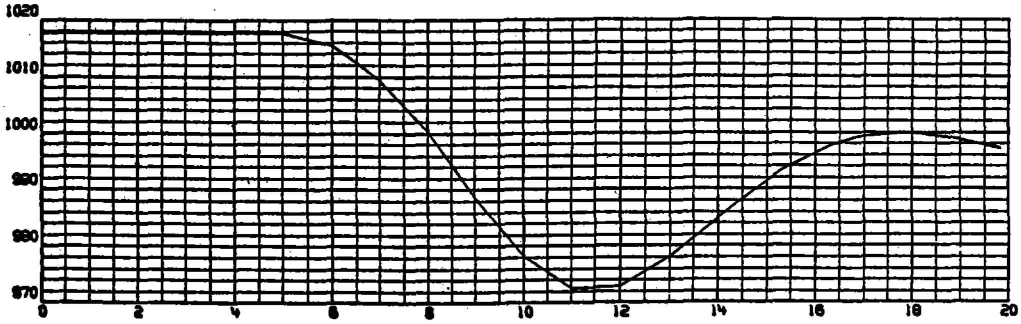
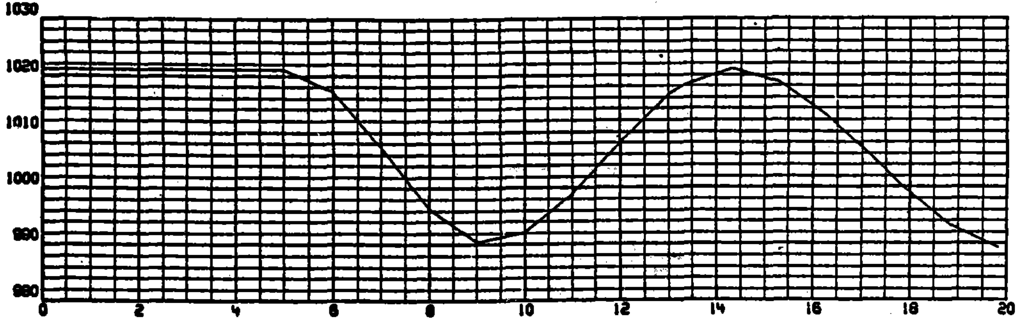
RUN 04-10 EMERGENCY SHUTDOWN, 08-09-78
TRW2(1) - MEAN WALL TEMPERATURE, MIDPLANE SOUTH PANEL (F)
TRW2(6) - MEAN WALL TEMPERATURE, MIDPLANE WEST PANEL (F)
TRW2(12) - MEAN WALL TEMPERATURE, MIDPLANE NORTH PANEL (F)



TRW2(1) VS TIME



TRW2(6) VS TIME



TRW2(12) VS TIME

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RUN 04-10 EMERGENCY SHUTDOWN, 08-09-78
TNDVI - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE INLET,
TNDVO - TEMPERATURE OF SODIUM, PRESSURE REDUCING DEVICE OUTLET
TNHTI - TEMPERATURE OF SODIUM, HOT TANK INLET (F)
TNHT - TEMPERATURE OF SODIUM, HOT TANK (F)

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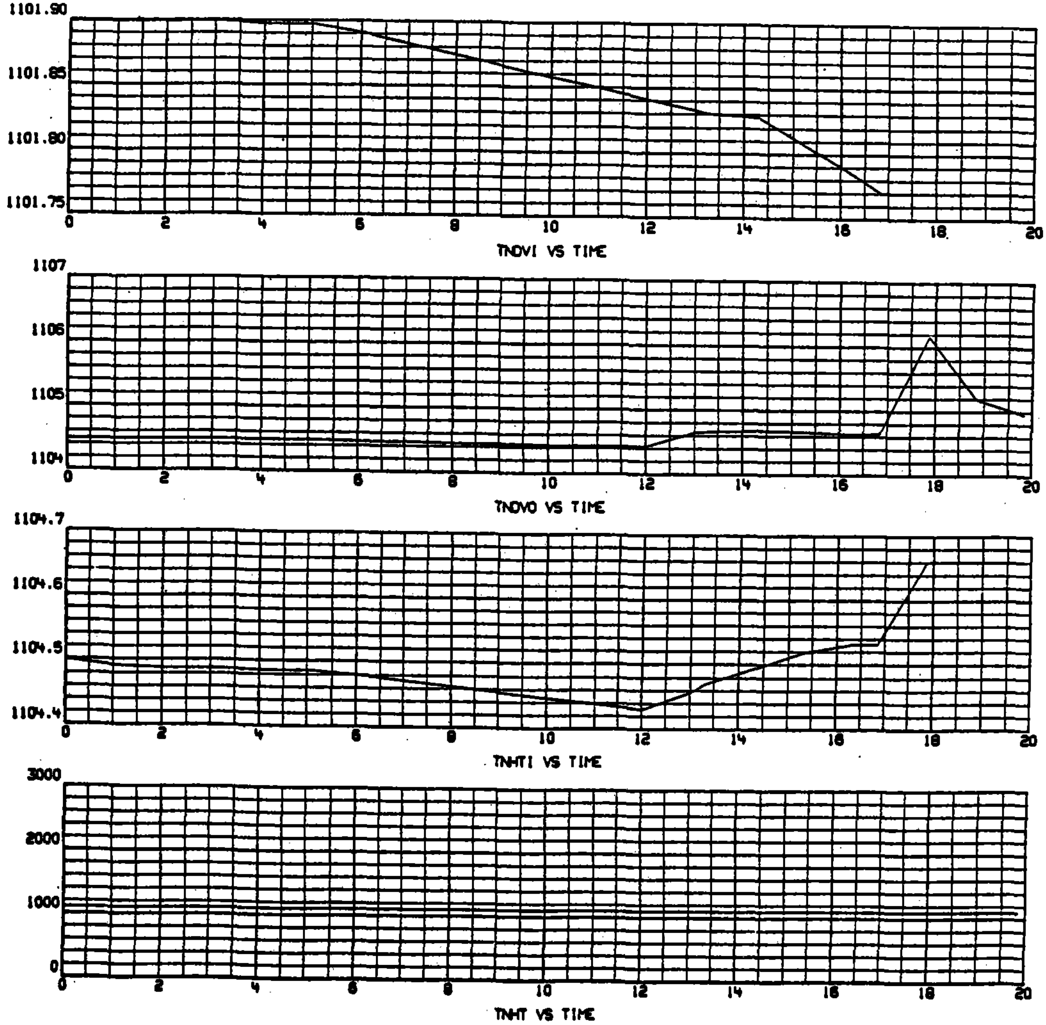

/34

RUN 04-10 EMERGENCY SHUTDOWN, 08-09-78
VPDV - PRESSURE REDUCING DEVICE VALVE POSITION (FRACTION OPEN)
WDN - DOWNCOMER FLOW (NORMALIZED TO 2220.1 LBM/SEC)
LROT - RECEIVER OUTLET TANK SODIUM LEVEL (FT)
EROTL - RECEIVER OUTLET TANK SODIUM LEVEL ERROR

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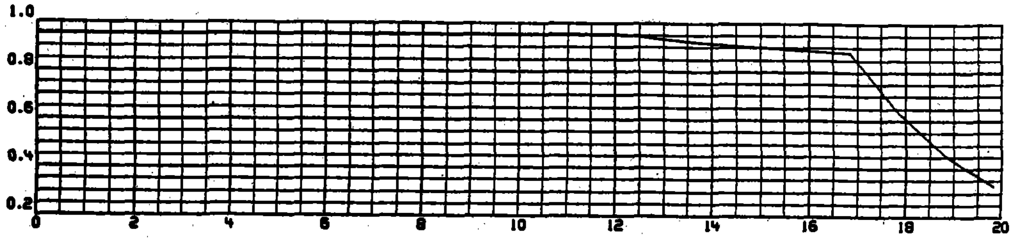
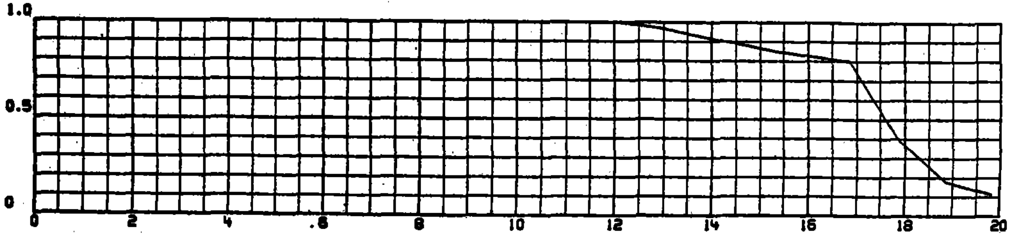
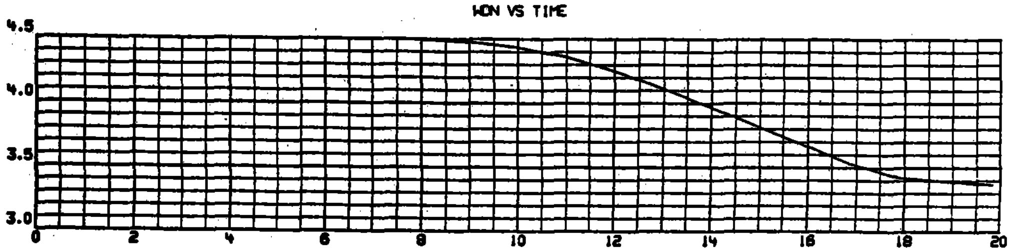


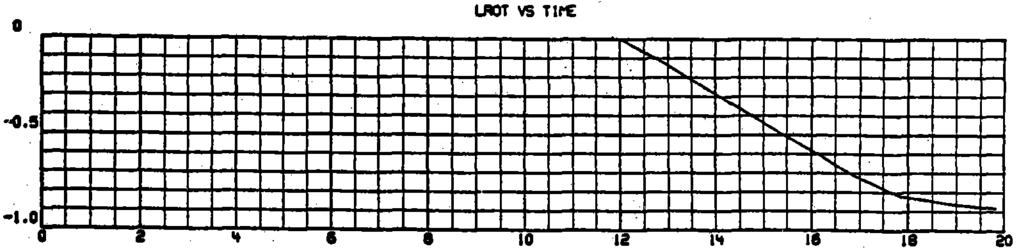
VPDV VS TIME



WDN VS TIME



LROT VS TIME



EROTL VS TIME

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RUN 04-10 EMERGENCY SHUTDOWN, 08-09-78
NRP - RECEIVER PUMP SPEED (NORMALIZED TO 700 RPM)
HRP - RECEIVER PUMP HEAD (NORMALIZED TO 824 FT)
PIR - PRESSURE AT RECEIVER INLET (PSIA)
POR - PRESSURE AT RECEIVER OUTLET (PSIA)

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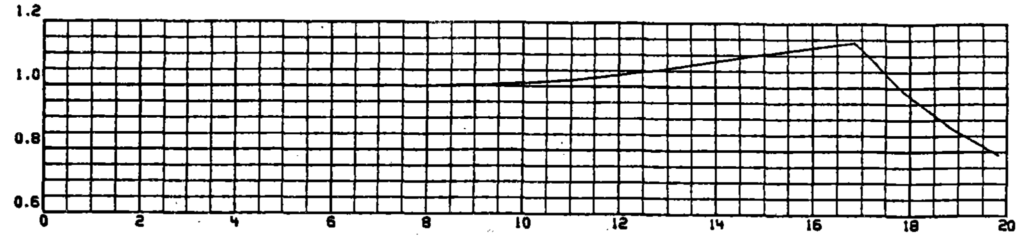
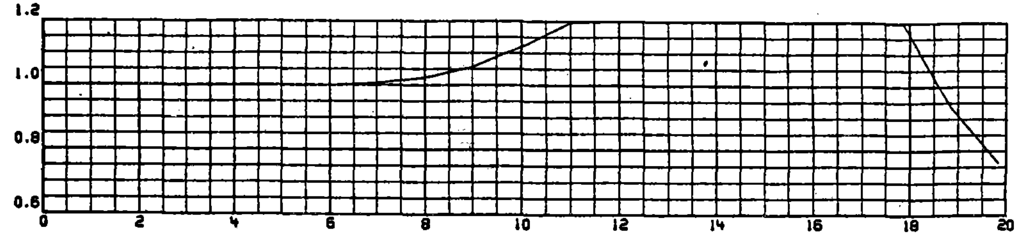
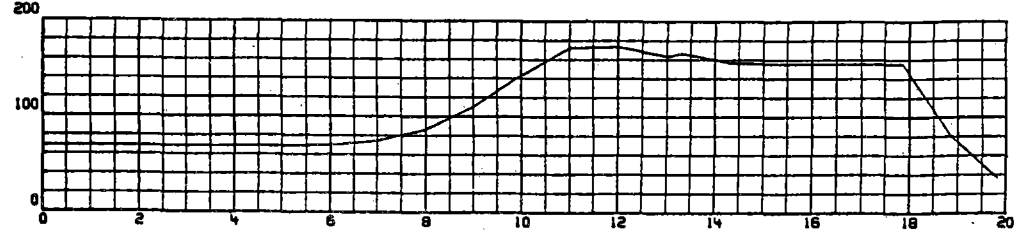


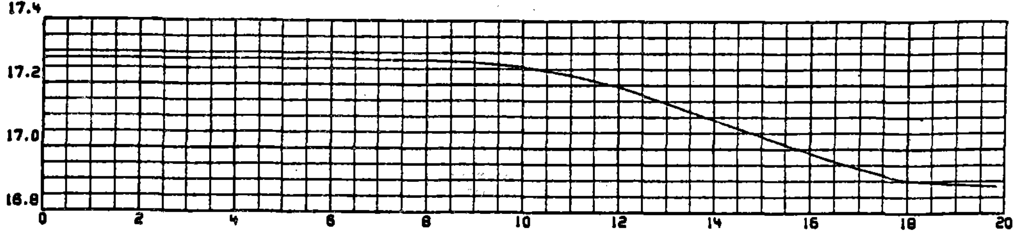
NRP VS TIME



HRP VS TIME



PIR VS TIME



POR VS TIME

RUN 04-10 EMERGENCY SHUTDOWN, 08-09-78
LNACT - LEVEL OF SODIUM IN COLD TANK (FT)
LNAHT - LEVEL OF SODIUM IN COLD TANK (FT).

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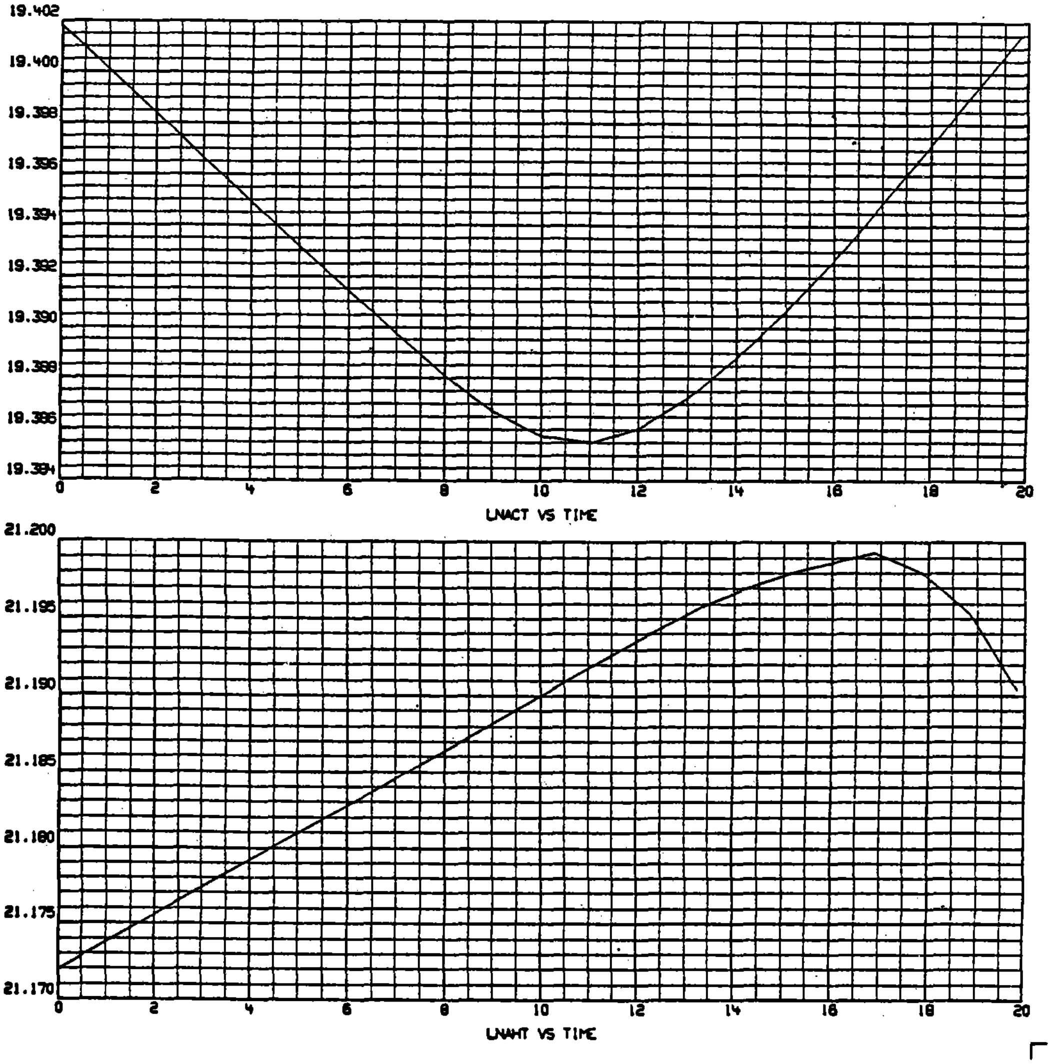

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