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AEC RESEARCH AND DEVELOPMENT REPORT

STEADY-STATE CONTROL CHARACTERISTICS OF CHEMICAL-NUCLEAR AIRCRAFT POWER PLANTS

C. B. Thompson

OAK RIDGE NATIONAL LABORATORY
OPERATED BY
UNION CARBIDE NUCLEAR COMPANY
A Division of Union Carbide and Carbon Corporation
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AIRCRAFT NUCLEAR PROPULSION PROJECT

STEADY STATE CONTROL CHARACTERISTICS OF CHEMICAL NUCLEAR AIRCRAFT POWER PLANTS

C B Thompson*

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STEADY STATE CONTROL CHARACTERISTICS OF CHEMICAL NUCLEAR AIRCRAFT POWER PLANTS

C B Thompson

SUMMARY

It seems reasonable to believe that the simplest control system for the nuclear power source in a combination chemical nuclear aircraft power plant will result if nuclear power delivery during normal operational use can be throttled by variation of a single control quantity Studies to date of the steady state off design point performance characteristics of two such power plants indicate that satisfactory power control can be obtained by bypassing NaK around the engine radiators alone if full range NaK bypass valves can be built and if the fuel temperature at the inlet of the reactor core can be allowed to rise as high as the design point mean fuel temperature If the fuel temperature at the inlet to the reactor core must be limited to some value less than the design point mean fuel temperature the control rod must also be moved as power delivery is varied Possibilities for throttling reactor power delivery by individual variation of reactor fuel flow control rod position NaK flow and radiator air bypass percentage were also considered but each of these alternate schemes is unsatisfactory

Study of the static stability characteristics of a demand sensitive reactor turbojet load combination indicates that such a power plant should operate stably in the high power range At part load operating conditions however the inherent static stability of such a power plant is questionable and appears to depend on the throttling scheme used In the example considered here the NaK bypass throttled power plant was stable at low power part load operating points while the air bypass throttled power plant was not stable

The various engine loads are cross coupled through their common reactor power source If the power delivered to one engine is varied the power delivered to the other engines also changes When NaK bypass throttling is used and the control rod position is constant the magnitude of the coupling effect appears to be relatively small If rod motion with total power level changes is required however cross coupling between engines will be more pronounced and may be large enough to make tedious the independent manual adjustment of power delivery to each load

Automatic control requirements for the nuclear heat source can be determined by considering how the flight engineer might perform typical power plant maneuvers without the help of automatic control equipment Study of the manual operations required indicates that the addition of automatic control equipment for the NaK bypasses is very desirable if not essential to limit movement of the valves in such a way as to maintain the return line NaK temperatures between their upper and lower limits at all times Automatic control equipment is also required for the rod if the fuel temperature at the inlet of the reactor core must be held below the design point mean fuel temperature Such equipment might withdraw the rod to maintain the mean fuel temperature at as high a level as possible as limited by the requirements that both the core fuel inlet temperature and the core fuel outlet temperature be less than or equal to their maximum allowable values

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INTRODUCTION

Most of the control system thinking by the ORNL ANP group has quite naturally been directed toward the problems associated with controlling a circulating fuel reactor which delivers power to a heat dump type of load. This work is of major concern since a large part of the ANP effort at ORNL is now being devoted to the ART.

The control system for the ultimate reactor–turbojet engine power plant will obviously be different from the control system for the ART power plant because both a reactor control system and a properly mated set of chemical turbojet controls will be required. The effectiveness of the ART in clearing up problems associated with controlling the large aircraft power plant depends largely on how well the inherent differences between the control requirements of the ART and those of large aircraft power plants are understood. The work described in this report was carried out to provide some of the information required for studying these differences.

The ultimate power plant will consist of one large reactor coupled to a number of turbojet engines (the number ranging from two to six depending on the type of aircraft being propelled). The over-all steady state performance characteristics of such power plants when manually controlled at part power off-design operating conditions must be thoroughly understood before control system requirements can be determined. This report is concerned chiefly with the over-all steady state manual control characteristics of the following two power plants:

Power Source	Load
60 Mw ART type reactor and chemical burners	2 GE X-61 turbojet engines
60 Mw ART type reactor and chemical burners	4 Allison J-71 turbojet engines

These combinations were selected primarily because of the availability of performance data; it is not believed that they necessarily represent usable systems. They are considered here merely as vehicles for studying control problems.

Detailed characteristics of each of the components of the above power plants are summarized in the next section. Steady state part load performance characteristics derived from these data are then discussed, and the effects of potential throttling parameter variations are described. The static stability of a demand sensitive reactor power source–turbojet engine load combination is then considered, and coupling effects between engines in a multiengine power plant are investigated. Finally, the actions required of the power plant operator in carrying out typical power plant maneuvers without the help of automatic control equipment are outlined to show what types of equipment are needed.

The symbols employed in the calculations are defined below.

NOMENCLATURE

A_{fR} = frontal area of radiator, ft^2

A_{HX} = heat transfer surface area of heat exchanger, ft^2

A_R = heat transfer surface area in radiator, ft^2

C_a = specific heat of air, Btu/lb·°F

C_F = specific heat of circulating fuel, Btu/lb·°F

C_N = specific heat of NaK coolant, Btu/lb·°F

F_N = engine net thrust output, lb

g = gravitational constant

M = flight Mach number

N = engine rotor speed, rpm

P = power, Mw

P_e = power delivered per engine by balanced load, Mw

P_N = power delivered to Nth engine, Mw

P_T = total reactor power, Mw

P_{T6} = total pressure at inlet of exhaust nozzle, lb/ft^2

P_0 = ambient static pressure, lb/ft^2

P_1 = power delivered to engine No. 1, Mw

P_{rF} = Prandtl number of fuel

R = gas constant for air, ft/°R

T_F = mean reactor fuel temperature, °F

T_{FC} = fuel temperature at inlet of reactor core, °F

T_{FH} = fuel temperature at outlet of reactor core, °F

T_{NC} = NaK temperature at inlet of heat exchanger, °F

T[illegible] = NaK tempe ature at outlet of d tor °F

T_{NH} = N K tempe atu e at outlet of heat exchanger (nlet of radiator) °F

T_{T3} = total temperature t omp e sor o tlet °F

T_{T4} = total temperatu e at let of turbine °F

T_{T6} = total temper ture at inlet of exhaust nozzle °F

U_R = over all heat transfe oefficient of r d ator Bt /hr ft^2 °F

U_{HX} = over all heat tr nsfer coefficient fuel to NaK heat exchanger Btu/hr ft^2 °F

V_a = aft velo ity fps

W_a = eng ne a r flow lb/sec

W_{aD} = direct ai flow r te through adiator pe engine lb/ se

W_{aBP} = bypass oi flow rote per eng ne lb/sec

W_F = re to fuel flow rate lb/ sec

W_N = tot l NaK flow rate lb/ sec

W_{NBP} = NaK bypass flow te per eng ne lb/sec

W_{ND} = d rect N K flow rate th o gh adiato pe engine lb/ se

W_{Ne} = NaK flow rate pe engi e lb/ e

X = fr ct on of tot l re ctor power del ve ed to each engine

γ = specific heat r t o for a r

ΔP_R = adi tor p essure d op lb/ ft^2

ΔT_m = log mean tempe ature d ffe ence for the heat exch nger

ΔT_a = air temperature difference $(T_{T4} - T_{T3})$

ΔT_F = fuel tempe t e d ffe ence $(T_{FH} - T_{FC})$

ΔT_N = NaK temperature diffe ence $(T_{NH} - T_{NC})$

η_{HX} = heat exchanger effect veness

η_R = r diator effectiveness

μ_F = s os ty of f el lb/ft se

μ_N = v scosity of NaK lb/ ft se

ρ = average density of ai in adiator lb/ ft^3

ρ_F = density of fuel lb/ ft^3

ρ_N = density of NaK lb/ ft^3

DETAILED POWER PLANT DESCRIPTIONS – COMPONENT CHARACTERISTICS

Detailed performance characteristics of each power plant component must be known before the over all composite behavior of a power plant can be calculated Each of the components of the two power plants under consideration is described in this section

CIRCULATING FUEL REACTOR

An early version of the 60-Mw ART circulating fuel reactor is used here as a basis for control studies Design values for several important re actor and heat exchanger quantities and fuel and NaK physical properties used are tabulated below

Design power Mw	60
Core fuel outlet temperature °F	1600
Mean core fuel temperature °F	1450
Core fuel inlet temperature °F	1300
Fuel flow rate lb/sec	702
Temperature coefficient of reactivity $(\Delta k/k)/°F$	$-5\ 5 \times 10^{-5}$
Heat exchanger NaK nlet tempe a ture °F	1100
Heat exchanger NaK outlet tempera ture °F	1500
Total NaK flow rate lb/sec	569
Total heat exchanger heat transfer area ft^2	1388
Over all heat transfer coefficient at des gn po nt Btu/hr ft^2 °F	1023
Fuel Reynolds number n heat ex- changer at design po nt	3180
Heat-exchanger effect veness at des gn point	0 8
NaK Reynolds number in heat ex changer at design point	125 000
Detailed heat exchanger parameters	
Bundles	24
Tubes per bundle	132
Diameter of tubes in	$\frac{1}{4}$
Spacing between tubes mils	30
Tube length ft	6 67

Equivalent diameter (fuel) in per bundle	0 1328
Free flow area (fuel) in ^{2} per bundle	3 852
Fuel and NaK physical properties (from ART design meeting Jan 7 1955)	
C_F Btu/lb °F	0 27
C_N Btu/lb °F	0 25
μ_F (at 1450°F) lb/ft sec	$3\ 79 \times 10^{-3}$
μ_N lb/ft sec	$0\ 11 \times 10^{-3}$
Pr_F (at 1450°F)	2 475
ρ_F lb/ft^3	200
ρ_N lb/ft^3	46

The heat exchanger design described above was obtained from M M Yarosh This design was prepared some time before detailed heat transfer tests were run and before final heat exchanger designs were completed Heat transfer coefficient estimates fuel property estimates and the design power rating have all been changed since the design described in the above table was made Hence the heat exchanger used here is not the same as the heat exchanger currently planned for the ART However the external performance char acteristics of the design considered here and the current design do not appear to be different enough to change any of the general conclusions drawn from this work

The variation of the over all heat transfer coef ficient of the reactor heat exchanger with changes in fuel flow rate NaK flow rate and mean reactor fuel temperature must be known if the part load steady state performance characteristics of the power plant are to be calculated The variation of this coefficient with changes in fuel flow rate has been estimated for a mean reactor fuel temperature of 1450°F and a midrange NaK flow rate (320 lb/sec) by use of a procedure suggested by Yarosh The result is plotted in Fig 1 Average temperature changes and NaK flow rate changes also affect the over all heat transfer coefficient but these effects are thought to be relatively small for NaK flow rate and average temperature varia tions in the normal safe operating range

[1] J D Goodlette *et al* *Second Summary Report — Nuclear Powered Seaplane Feasibility Study* ER 6621 (Oct 27 1954)

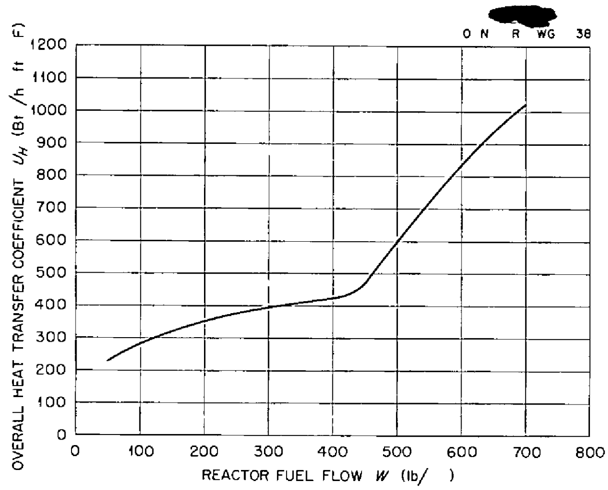

Fig 1 Variation of the Over All Heat Transfer Coefficient of the Main Heat Exchanger with Reactor Fuel Flow Mean temperature 1450°F NaK flow 320 lb/sec

G E X 61 TURBOJET ENGINE

The G E X 61 turbojet engine is described briefly below [1]

Static thrust output per engine at sea level (SL) maximum nterburning lb	23 600
Static thrust output per eng ne at sea level maximum interburning and afterburning lb	33 000
Static thrust output per eng ne at sea level w th 30 Mw power input lb	6 780
Max mum allowable powe nput pe eng ne SL tat c m l ta y Mw	103 5
Max mum turb ne nlet temperatu e °F	1800
Rated a rflow per engine SL static lb/sec	325
Design pressure ratio	8 45 1

Part load engine performance data that describe the variation of the turbojet load imposed on the reactor at off design operating conditions are re quired for over all power plant steady state per formance determination The curves of Figs 2 through 5 show how pertinent off design steady state X-61 engine parameters vary with net thrust output at various altitudes and flight speeds for power inputs less than 30 Mw These curves were calculated from the corrected quantity data of Goodlette [1] Net thrust output and required power input were calculated from

(1) $$P = W_a C_a (T_{T4} - T_{T3})$$

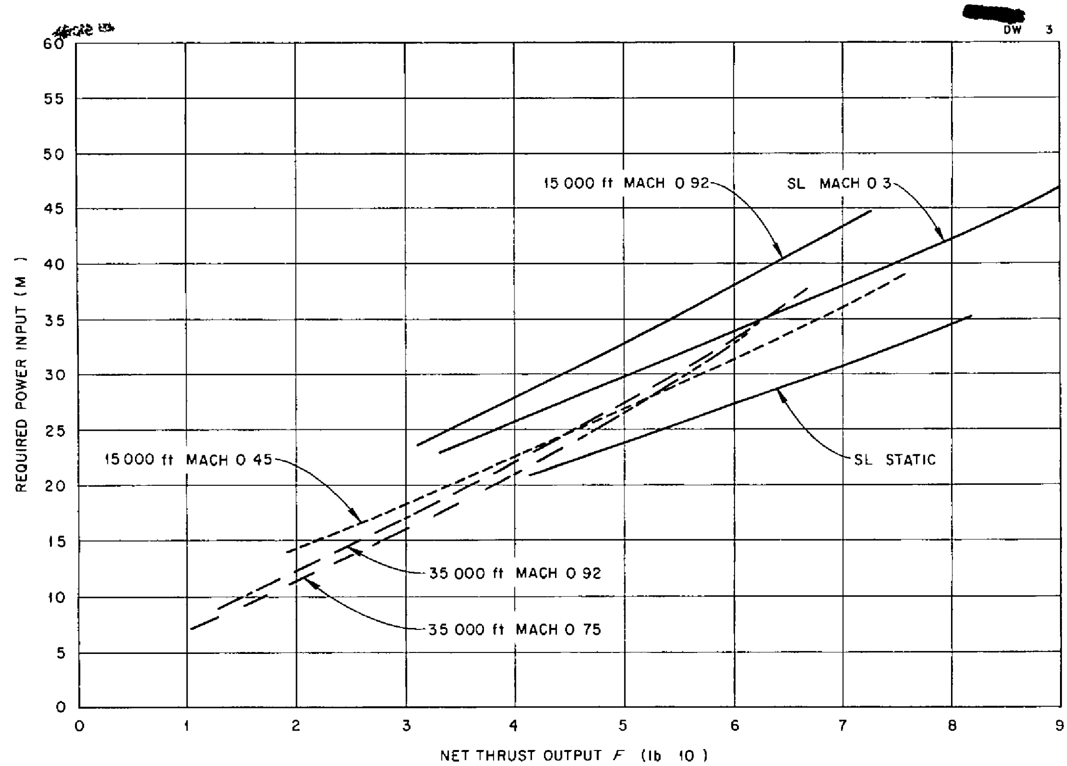

Fig 2 Variation of Steady State Power Input Required with Net Thrust Output for the G E X 61 Engine Exhaust nozzle open

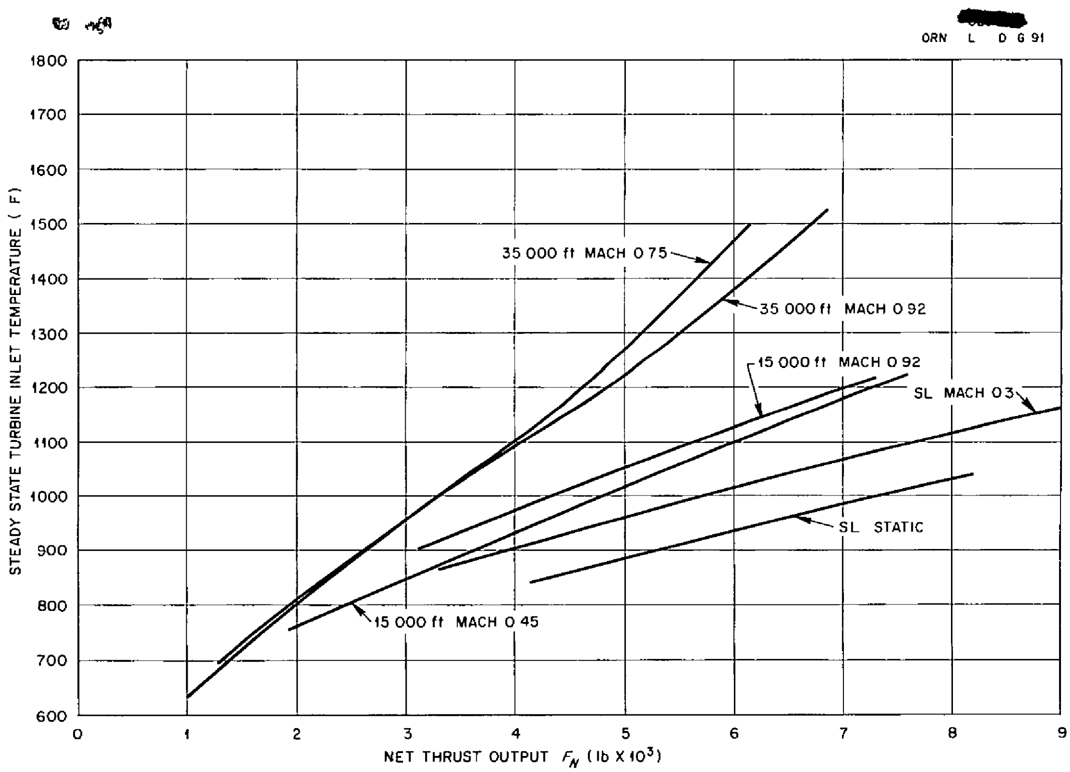

Fig 3 Variation of the Steady-State Turbine Inlet Temperature with Net Thrust Output for the G E X 61 Engine Exhaust nozzle open

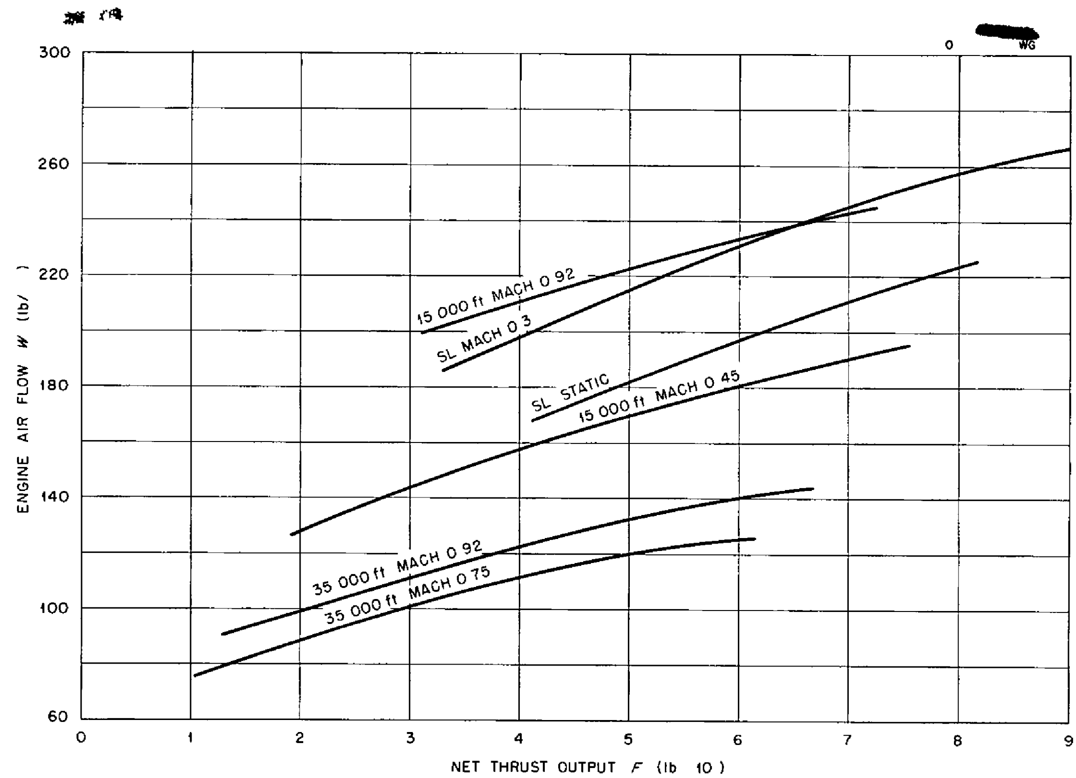

Fig 4 Variation of the Steady State Engine Air Flow with Net Thrust Output for the G E X 61 Engine Exhaust nozzle open

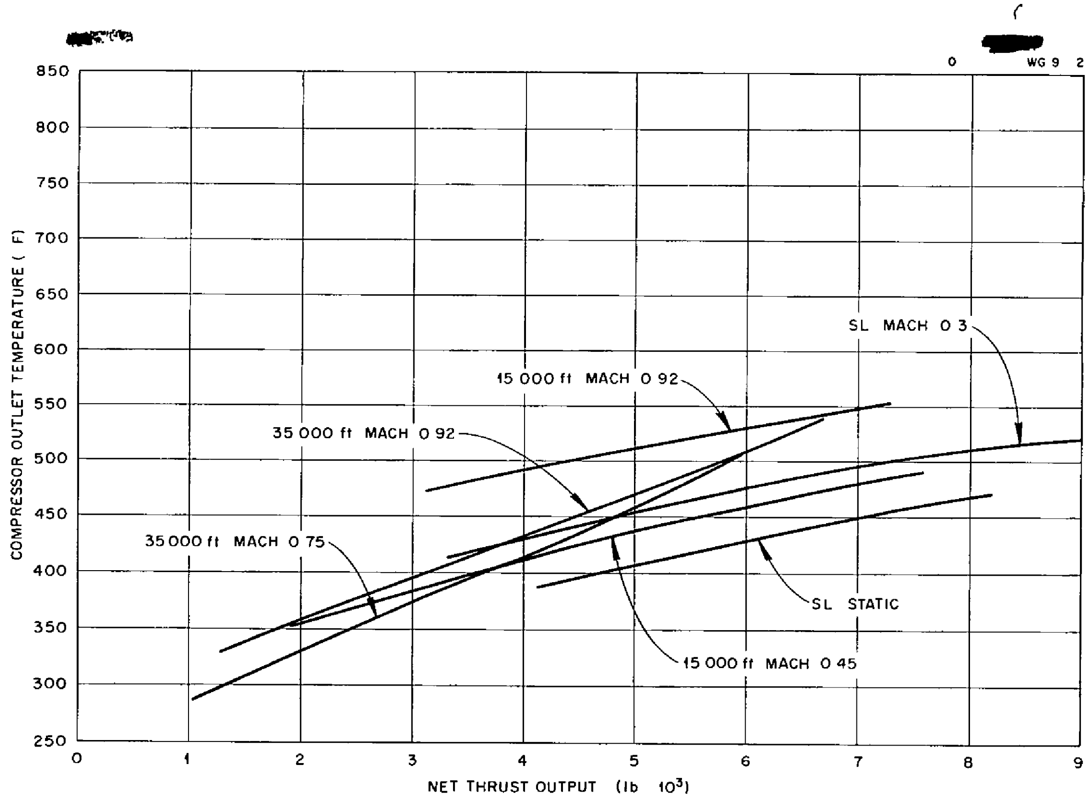

Fig 5 Variation of the Steady State Compressor Outlet Temperature with Net Thrust Output for the G-E X 61 Engine Exhaust nozzle open

The value for C_a was assumed to be constant at 0 26

$$F_N = \underbrace{0.975}_{\text{Nozzle loss coefficient}} \left\{ \underbrace{W_a \sqrt{T_{T6}} \sqrt{2\gamma R/g(\gamma - 1)} \left[1 - \frac{1}{(P_{T6}/P_0)^{(\gamma-1)/\gamma}} \right]}_{\text{Gross thrust for full nozzle expansion}} \right\} - \underbrace{W_a V_a / g}_{\text{Ram drag}} \quad (2)$$

The value for γ was assumed to be constant at 1 35

A hypothetical radiator was designed for the X 61 engine by use of the procedure and basic data outlined in Appendix A which were obtained from R D Schultheiss This radiator was designed to transfer 30 Mw of nuclear power to the engine load imposed during cruise at 35 000 ft Comparison of the total thrust available from two X 61 engines operating at 30 Mw power input at 35 000 ft with the total thrust required by a representative seaplane airframe shows that such an aircraft might be expected to cruise at about Mach 0 87

Radiator and X 61 engine match point and design data are shown in Table 1 The variation of the over all heat transfer coefficient of this radiator with changes in airflow per unit frontal area is shown in Fig 6 The over all heat transfer coefficient also varies with changes in the NaK flow rate and the mean temperature of the radiator but these effects are thought to be small in the normal operating region

The engine performance curves discussed previously (Figs 2 through 5) were worked out for a normal combustion chamber pressure loss between

TABLE 1 RADIATOR AND ENGINE MATCH POINT VALUES

Flight conditions 35 000 ft Mach 0 87 nuclear power only

	G E X-61 Engine	Allison J 71 Engine
Net thrust output lb per engine	5500	2750
Number of engines	2	4
Nuclear power input required Mw per engine	30	15
NaK temperatures °F	1500 to 1100	1500 to 1100
NaK flow rate lb/sec per engine	284 5	142 2
Compressor outlet temperature °F	487	454
Engine air flow lb/sec	132 4	65 7
Turbine inlet temperature °F	1311	1286
Engine speed % of rated	92 6	93 2
Exhaust nozzle area	Open	87 7% closed
Radiator heat-transfer area ft^2	9018	4883
Over all heat transfer coefficient Btu/hr ft^2 °F	31 5	26 8
Radiator frontal area ft^2	16	12
Radiator depth in	19 4	14
Rough estimate of radiator pressure drop % of compressor discharge pressure	6 6	1 8

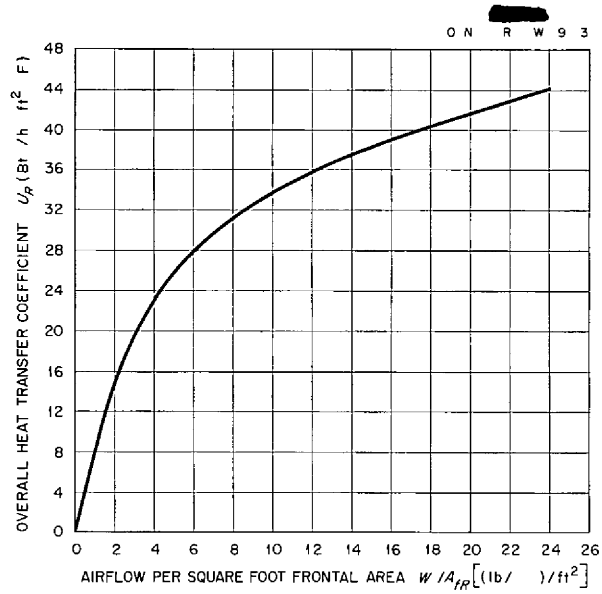

Fig 6 Variation of the Over All Heat Transfer Coefficient of Radiator with Changes in Air Flow per Unit Frontal Area

the compressor and turbine Strictly speaking the increase in pressure loss resulting from the addi tion of a radiator causes all the equilibrium operat ing characteristics of the engine (Figs 2 through 5) to shift Recalculation of the new steady state operating characteristics is a major job however which requires engine component performance maps which are not available

The effects of radiator pressure drop on steady state engine performance are therefore neglected in the calculations that follow This should not cause serious errors in final conclusions because the radiator pressure drop in this case appears to be relatively small The over all trends being sought should still manifest themselves

ALLISON J 71 TURBOJET ENGINE

The J 71 power plant was considered in addition to the X 61 power plant described in the preced ing section because the available X 61 perform ance data are not consistent in the low power operating region the compressor power required does not agree with the turbine power available at

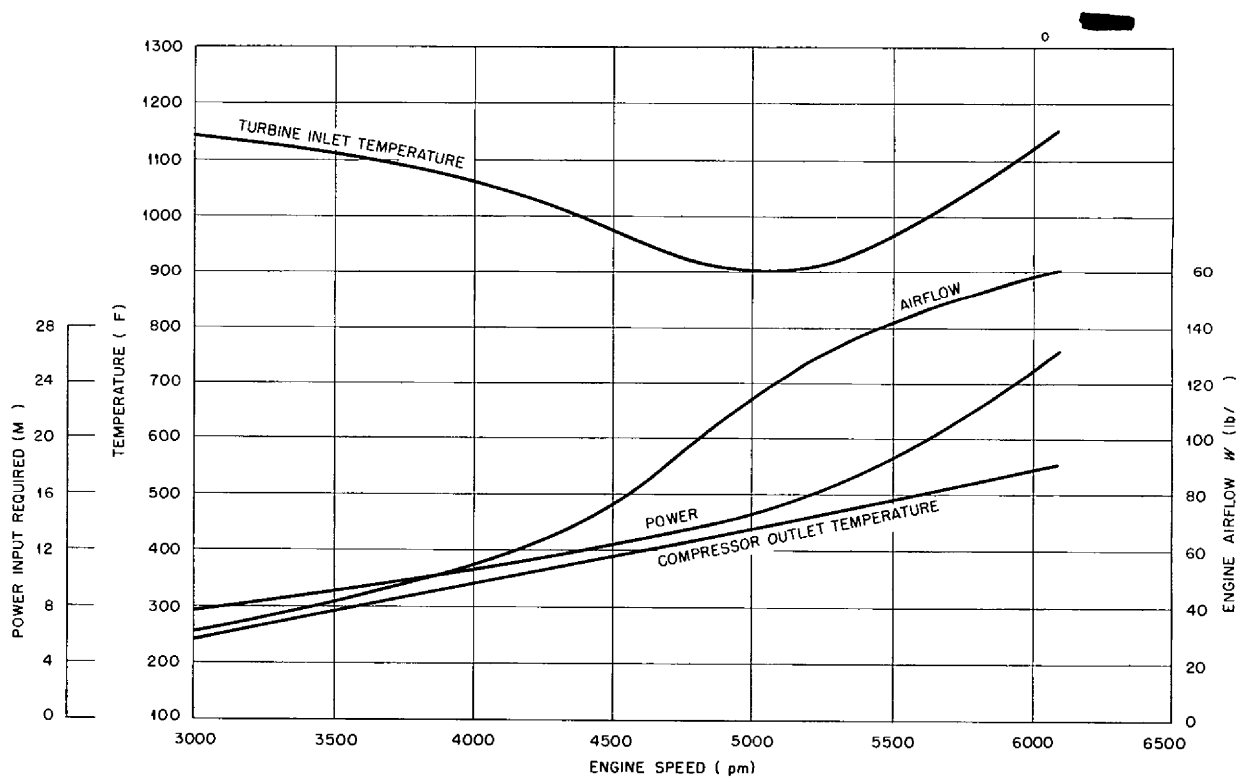

Fig 7 Steady State Performance Characteristics of the Allison J 71 Turbojet Engine at Sea Level (SL) Static conditions exhaust nozzle open

equilibrium points Preliminary estimated per formance data on an early version of the Allison J 71 engine were used so that reactor turbojet behavior in the low power operating range could be studied The J 71 engine is roughly half the size of the X-61 engine Its full power SL static pressure ratio is about 8 5 to 1

Pertinent performance characteristics of this engine at SL static conditions are plotted in Fig 7 Radiator and engine match point values and design data are summarized in Table 1 The basic procedure and data used in designing this radiator are outlined in Appendix A The variation of the over all heat transfer coefficient of the J 71 engine radiator with changes in airflow per unit frontal area is shown in Fig 6

STEADY STATE POWER PLANT PERFORMANCE CHARACTERISTICS – NUCLEAR POWER ONLY OPERATION

The steady state performance characteristics of the two power plants under consideration during operation on nuclear power only can be calculated by combining the component characteristics sum marized in the preceding section Figure 8 is a schematic diagram showing the parts of the power plants under consideration and the nomenclature used Of particular interest is the behavior of such power plants when throttling in each of the five ways listed below is attempted

Control Rod Throttling

Mean reactor fuel temperature	Variable
Reactor fuel flow and NaK flows	Constont at rated values
Air ond NoK bypasses	Closed

Reactor Fuel Flow Throttling

Reactor fuel flow	Variable
Mean reactor fuel temperature and NaK flow rates	Constant at rated values
A r and NaK bypa se	Clo ed

NaK Flow Th ottling

NaK flow rates	Variable
Mean reactor fuel temperature and reactor fuel flow rate	Constant at rated values
Air and NaK bypasses	Closed

NaK Bypass Throttling

NaK bypass percentage	Variable
Mean reactor fuel temperature reactor fuel flow rate and NaK flow rates	Constont at rated values
Air bypasses	Closed

Air Bypass Throttling

Air bypass percentage	Variable
Mean reactor fuel temperature reactor fuel flow rate and NaK flow rates	Constant at rated values
NaK bypasses	Closed

The behavior of the hypothetical reactor–X 61 power plant when throttled in each of these ways is described in the following paragraphs

CONTROL ROD THROTTLING

The behavior of the reactor–X 61 power plant when throttling by control rod motion is attempted at a typical off design flight condition is shown in Fig 9 A sample calculation illustrating the procedure used to determine these curves is in cluded in Appendix B At this flight condition the radiators have more heat transfer surface area than is required for transferring 30 Mw to each engine If the power transferred to each engine is to be limited to the maximum allowable value of 30 Mw one or more of the potential control quanti ties generally must be reduced with decreasing altitude

Figure 9 shows that the mean reactor fuel tem perature must be reduced to about 1260°F if power delivery is to be limited to 30 Mw during flight at 15 000 ft and Mach 0 45 Under these condi tions the reactor NaK inlet temperature drops to about 900°F Operation of the system at such a low NaK temperature at the inlet of the main heat exchanger is unsafe because of the possibility of local cold spot formation and fuel freezing The situation becomes more unsafe if an attempt is

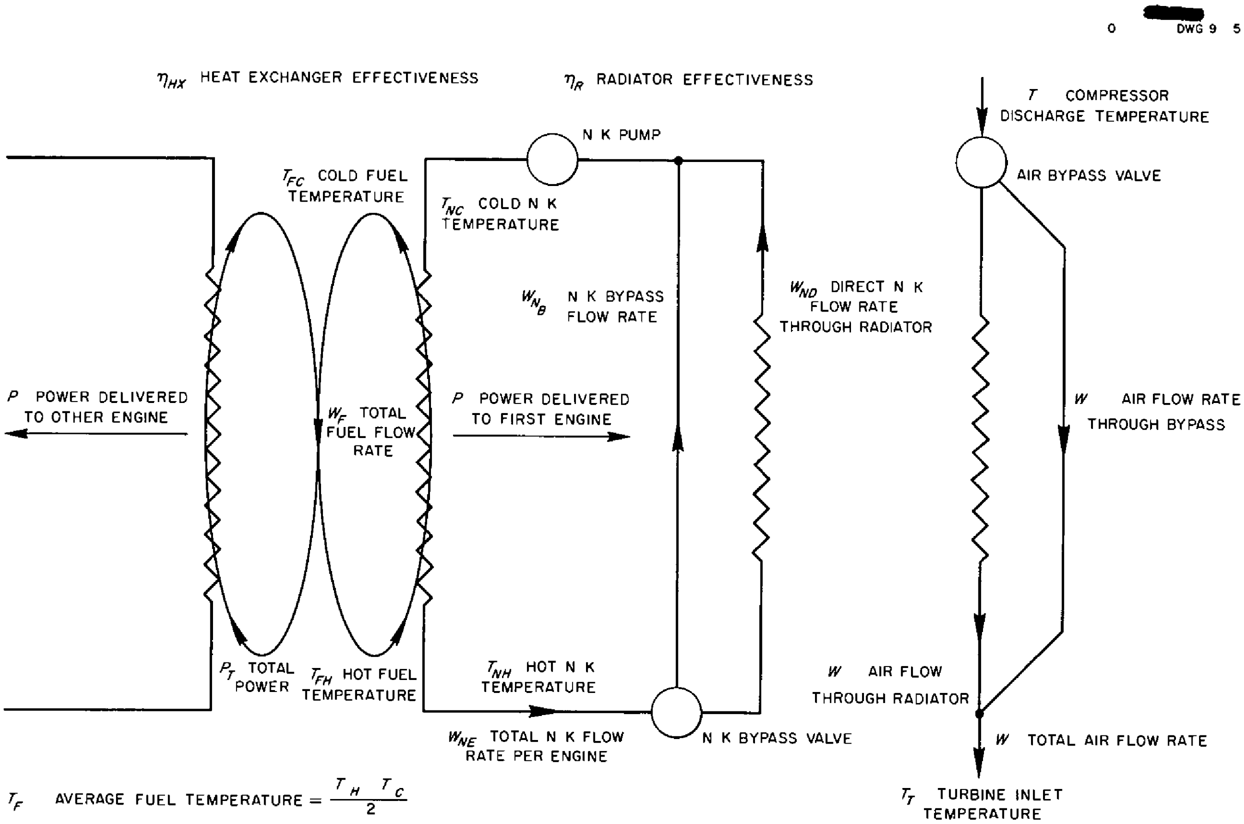

Fig 8 Partial Schematic Diagram of Reactor Turbojet Power Plant

made to reduce power delivery to each engine be low 30 Mw When the rod is inserted far enough to throttle power delivery to only 25 Mw for ex ample the core fuel inlet temperature itself drops to below 1000°F

From the curves of Fig 9 it is apparent that the thrust output of the power plant cannot be throttled safely by moving only the reactor control rod Control rod throttling is also unsuitable if independent variations in power delivery to each of the engines are to be made since motion of the control rod affects all engines in the same way

REACTOR FUEL FLOW THROTTLING

The behavior of the power plant when it is throttled by reactor fuel flow variation with all other quantities at their design point values is shown in Fig 10 At the 15 000 ft Mach 0 45 flight condition reactor fuel flow must be reduced to roughly 60% of its rated value to limit power delivery to each engine to 30 Mw When this is done the fuel temperature at the outlet of the reactor rises to 1700°F and the NaK temperature at the inlet of the reactor falls to 900°F Operation at these temperatures is unsafe if not impossible Further reduction in fuel flow does reduce the power delivered to each engine and reduces the engine thrust outputs but as the fuel flow is reduced the fuel outlet temperature continues to rise and the fuel and NaK inlet temperatures con tinue to fall

Thus reactor fuel flow alone is very unsuitable as a primary power control parameter Virtually all the critical steady state temperature variations which result when such a scheme is used are unsafe and independent adjustment of power delivery to each load is not possible

NaK FLOW THROTTLING

The behavior of the power plant when it is throttled by NaK flow variation alone is shown in Fig 11 The NaK flow must be reduced to 42% of its rated value to limit power delivery to each engine to 30 Mw at the 15 000 ft Mach 0 45 flight

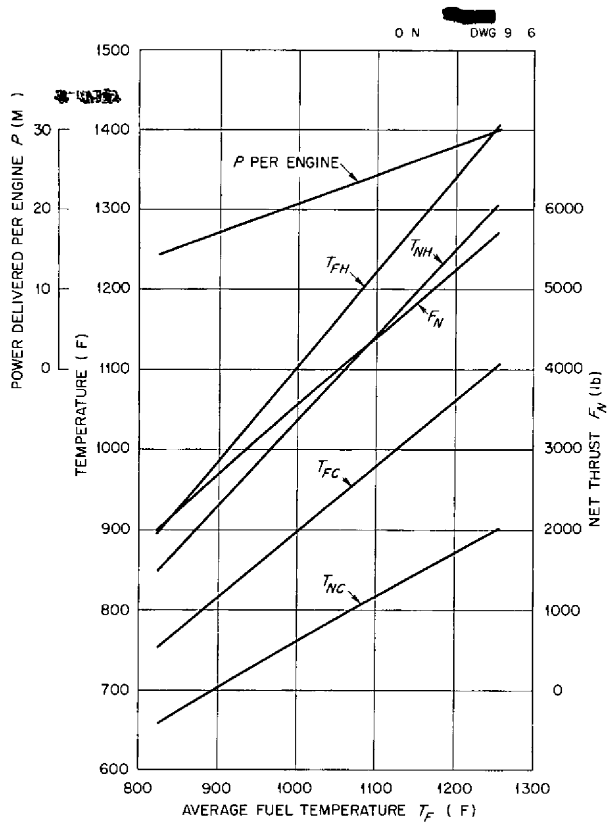

Fig 9 Steady State Performance of Reactor and Two G E X 61 Engines Altitude 15 000 ft Mach 0 45 reactor power delivery throttled by moving the control rod

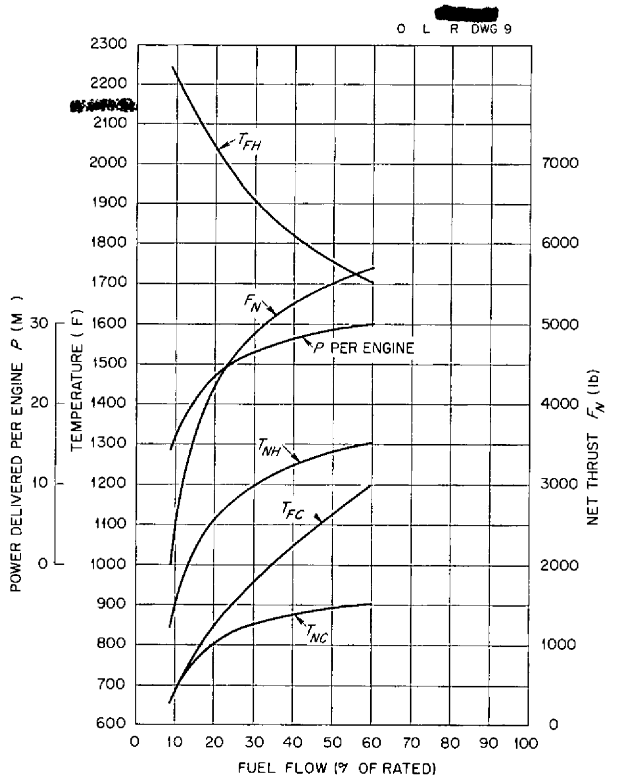

Fig 10 Steady State Performance of Reactor and Two G E X 61 Engines Altitude 15 000 ft Mach 0 45 reactor power delivery throttled by varying the reactor fuel flow

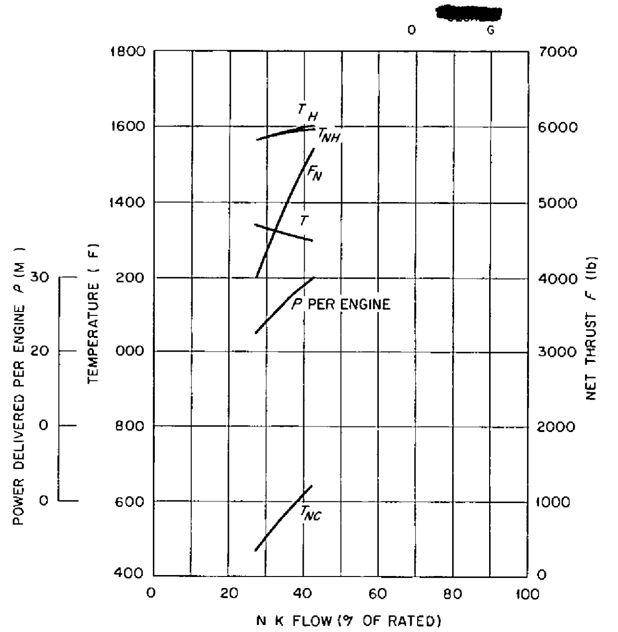

Fig 11 Steady State Performance of Reactor and Two G E X 61 Engines Altitude 15 000 ft Mach 0 45 reactor power delivery throttled by varying the NaK pump speeds

condition Such a NaK flow reduction with all other quantities at their rated values causes the NaK temperature at the inlet of the reactor to drop to around 640°F which is far below the 1050°F safe lower limit Further reduction in NaK flow does reduce power delivery but it causes the return line NaK temperature to drop still lower

Thus NaK flow alone is not a suitable power control quantity because the NaK temperature at the inlet of the reactor drops rapidly to dangerously low values as the flow rate is reduced Some means of protection against return line NaK under cooling must be added if power delivery is to be throttled safely by NaK flow rate reduction

NaK BYPASS THROTTLING

When the reactor–X 61 power plant is throttled by bypassing NaK around the radiators the thrust output of each engine and the reactor power de livered to each engine vary as shown in Figs 12 through 14 Fuel and NaK temperatures vary with power delivery as shown in Fig 15

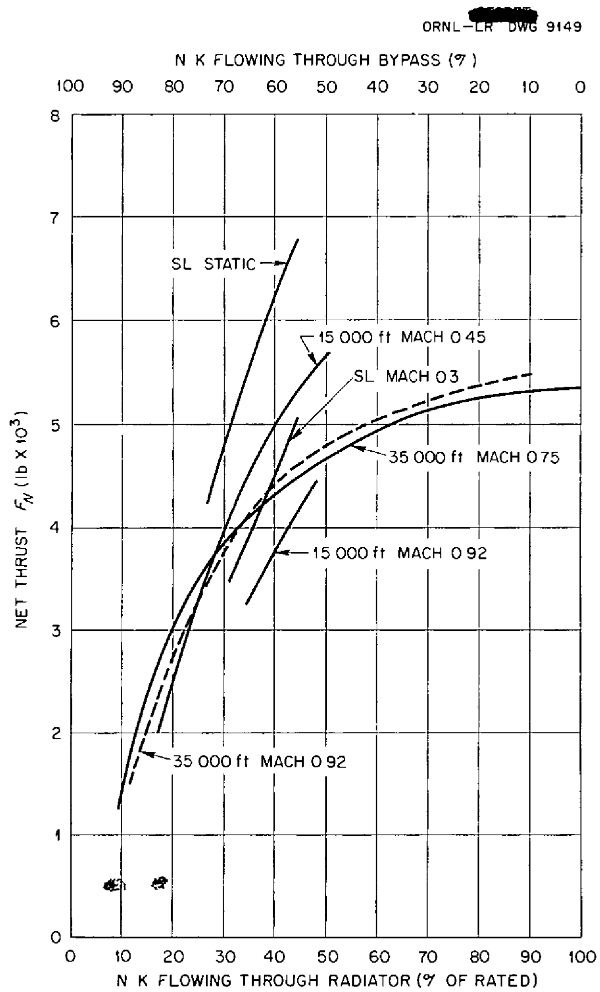

Fig 12 Net Thrust Output per Engine at Various Flight Conditions for Reactor and Two G E X 61 Engines Reactor power delivery throttled with radiator NaK bypasses

Adequate throttling can be obtained through the use of NaK bypass valves alone if the fuel temperature at the inlet of the reactor core can be allowed to rise as high as the design point mean fuel temperature Power delivery and thrust output are relatively insensitive to changes in the NaK bypass percentage in the 50 to 0% bypass range Hence full range NaK bypass valves are required if power delivery is to be throttled in this manner

AIR BYPASS THROTTLING

The behavior of the hypothetical reactor–X 61 engine power plant when it is throttled by by

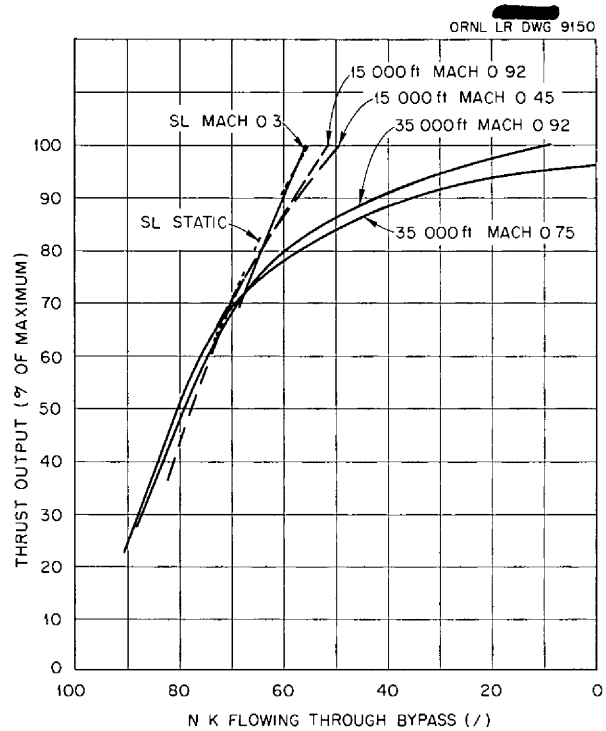

Fig 13 Per Cent of Maximum Thrust Output Attainable with Nuclear Power Only vs Per Cent NaK Bypassed Around Radiator Reactor and two G E X 61 engines

passing air around the engine radiators is shown in Figs 16 through 18 Fuel and NaK temperatures vary with power delivery as shown in Fig 15

These curves show that power plant thrust output can also be throttled safely through the use of air bypasses alone if the fuel temperature at the inlet of the core can be allowed to rise as high as the design point mean fuel temperature

MORE COMPLEX THROTTLING ARRANGEMENTS

It seems reasonable to believe that the simplest over all power plant control system will result when nuclear power delivery is throttled by variation of the fewest possible control quantities The steady state performance characteristics discussed in the preceding paragraphs indicate that power plant thrust output modulation through variation of a single control quantity – NaK bypass percentage or air bypass percentage – appears to be possible if the fuel temperature at the inlet of the reactor core can be allowed to rise as high as the design point mean fuel temperature

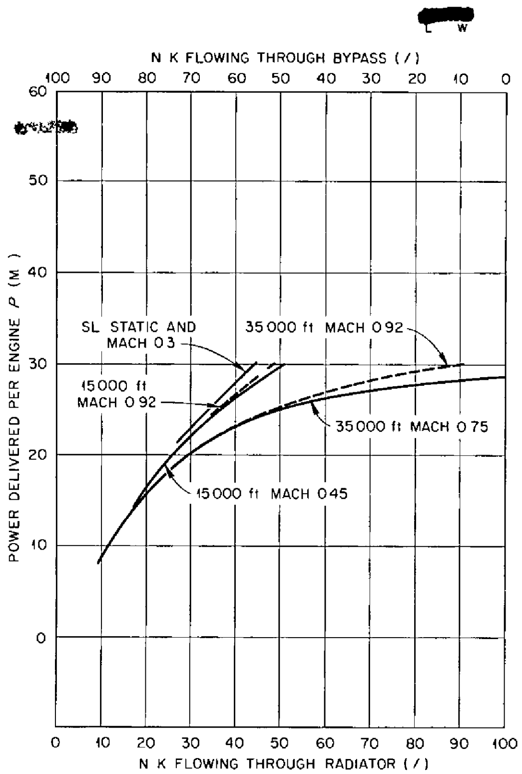

Fig 14 Variation of Reactor Power Delivered to Each Engine with Per Cent NaK Bypassed Around Radiator Reactor and two G E X 61 engines

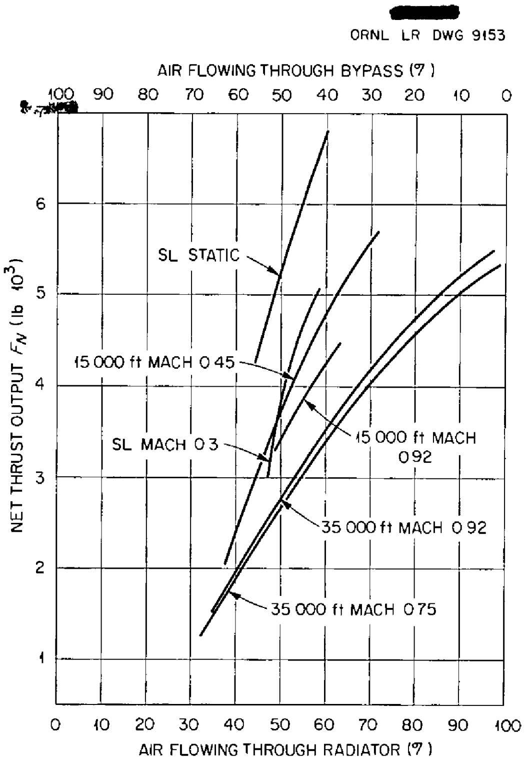

Fig 16 Net Thrust Output per Engine Reactor power delivery throttled with air bypasses Reactor and two G E X 61 engines

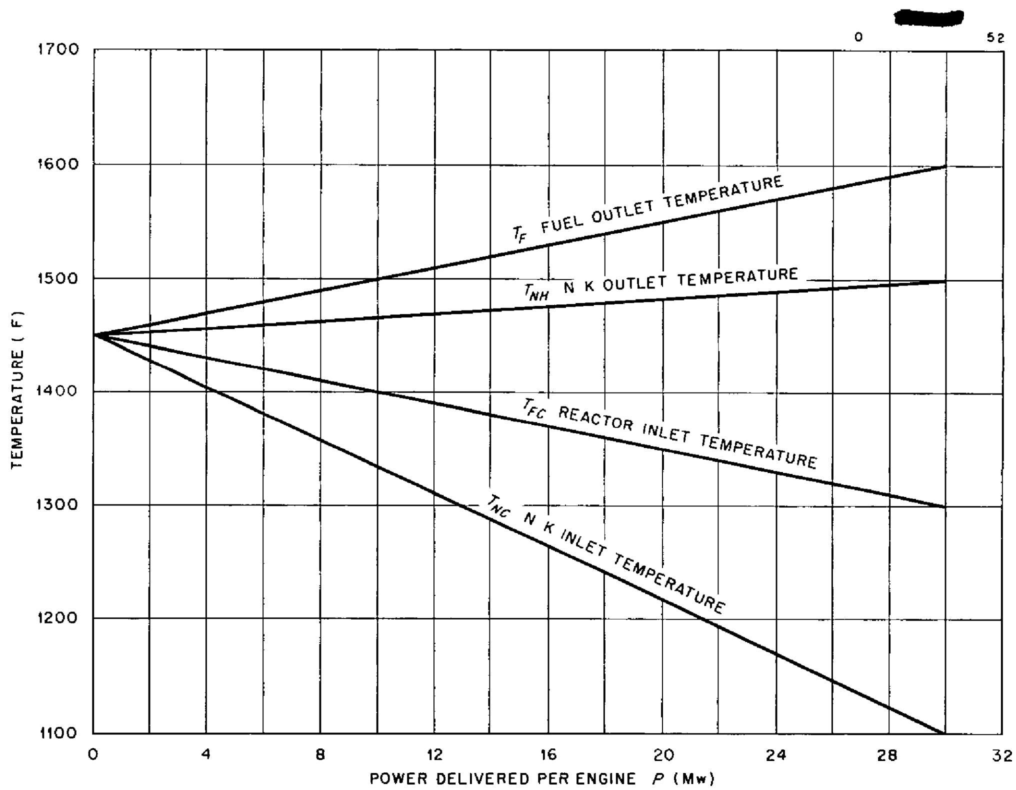

Fig 15 Variations of Reactor Fuel and NaK Temperatures with Power Delivery per Engine Reactor and two G E X 61 engines throttled by NaK bypass or by air bypass

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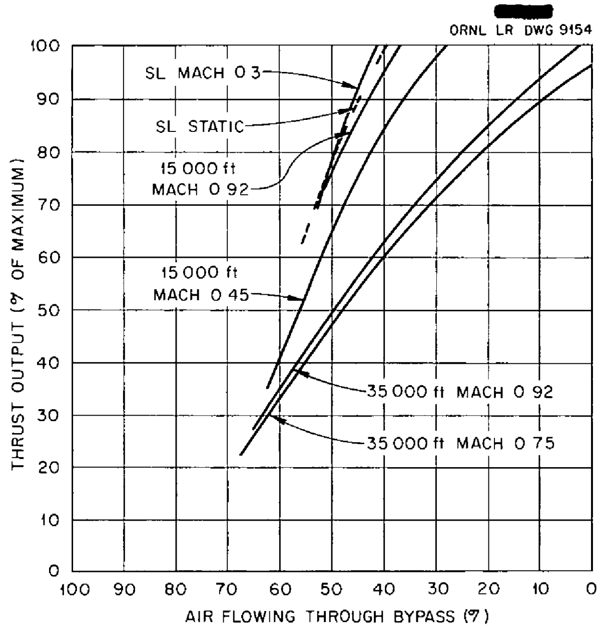

Fig 17 Per Cent of Maximum Thrust Output Attainable with Nuclear Power Only vs Per Cent Air Bypassed Reactor and two G-E X 61 engines

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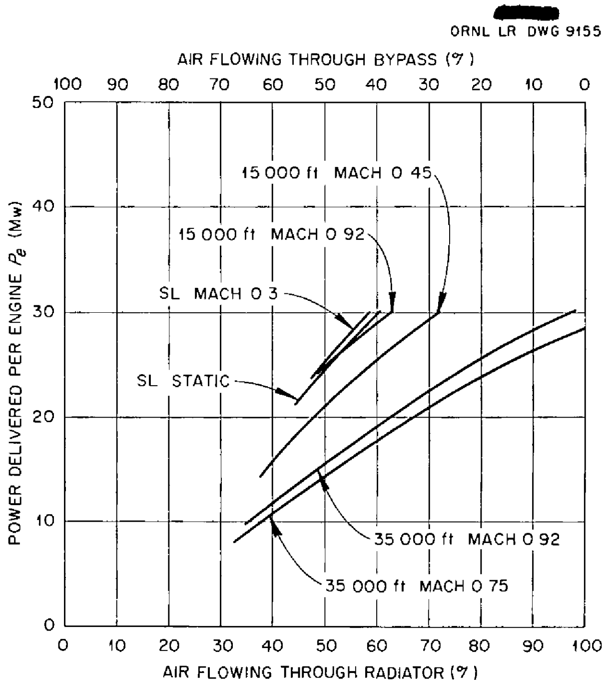

Fig 18 Variation of Reactor Power Delivered to Each Engine with Per Cent Air Bypassed Reactor and two G E X 61 engines

If the fuel temperature at the inlet of the core must be limited to some value less than the design point mean fuel temperature the control rod must also be moved as power delivery is changed If the fuel temperature at the inlet of the reactor core is to be held at 1350°F or less in the reactor–X 61 power plant for example rod insertion is required when total power delivery is reduced to below 40 Mw

As the development of the full scale aircraft power plant progresses it is likely that many situations will arise in power plant design or operation which will make the use of more complex throttling arrangements seem desirable Difficulties in building full range NaK bypass valves for example may make the use of a more complicated throttling arrangement imperative However the effect of increasing the complexity of the control system on the reliability of the over all power plant should be considered carefully before such changes are made

STATIC STABILITY CHARACTERISTICS OF A DEMAND SENSITIVE REACTOR–TURBOJET COMBINATION

Stable operation of a reactor–turbojet engine combination is not assured by a large negative reactor temperature coefficient of reactivity Such a characteristic does undoubtedly simplify the control of the reactor but the demand characteristic of a turbojet load and the demand sensitivity characteristic of a reactor having a large negative temperature coefficient of reactivity are not necessarily compatible

The turbojet load imposed on the nuclear heat source (airflow and radiator inlet temperature) varies in a complicated way with the power delivered to it Changes in power delivery to such a load cause the load characteristics themselves to change Changes in load characteristics however can cause further changes in reactor power delivery because the large negative temperature coefficient of reactivity makes the reactor load sensitive If it is possible for a subsequent change in power delivery to reinforce an original power disturbance the reactor load combination can walk or run away The possibility for an instability of this type does not exist when the reactor is coupled to a heat dump type of load because the load characteristics are externally adjusted by blower speed and louver and bypass opening variation Changes in these external load adjustments do cause the reactor power level to change but changes in the reactor power level cannot in turn cause further changes in the load This is an important basic difference between the two load types

The static stability of a demand sensitive reactor power source and a turbojet load can be studied from plots showing how the steady state power available from the radiator and the steady state power required to run the engine vary with engine speed when the reactor throttling quantities are constant Such plots obviously do not provide a complete picture of the stability of the over all power plant but it does seem that an unstable intersection between a steady state nuclear power available curve and the steady state engine power required curve is a definite indication of trouble

Steady state power required and power available curves for the reactor–J 71 system at SL static operating conditions are shown in Figs 19 and 20 for air and NaK bypass throttling (sample calculations are included in Appendix C) All the potential reactor control quantities with the exception of the bypasses are constant at their rated values The air and NaK bypasses are constant along given power available curves at the values shown

The intersections between the curves of power available at a constant air bypass setting and engine power required are unstable in the low speed range The steady state power available rises faster than the power required as the engine speed increases (air flow and compressor discharge temperature increase)

Idle speed for the J 71 engine is around 3000 rpm Net thrust output at this speed is down to about 3% of the rated SL static value Stable operation at speeds corresponding to less than maximum nuclear power input (5050 rpm 23% of rated SL static net thrust output) does not appear to be possible when the reactor–J 71 power plant is throttled by bypassing air around the radiators This apparent difficulty is a serious disadvantage of the air bypass throttling arrangement When the power plant is throttled with NaK bypasses the nuclear power available curves intersect the engine power required curve stably in the low speed region The power plant behaves differently in each case because of basic differences in the effect of each throttling quantity on radiator performance

The power available from the reactor supplying a number of balanced loads is related to the various engine radiator and reactor parameter values by the following expression

(3) $$P_e = \left[\frac{1}{1/W_{aD} C_a \eta_R + (1 - \eta_{HX})/\eta_{HX} W_{Ne} C_N - 1/2 X W_F C_F} \right] (T_{F\,v} - T_{T3})$$

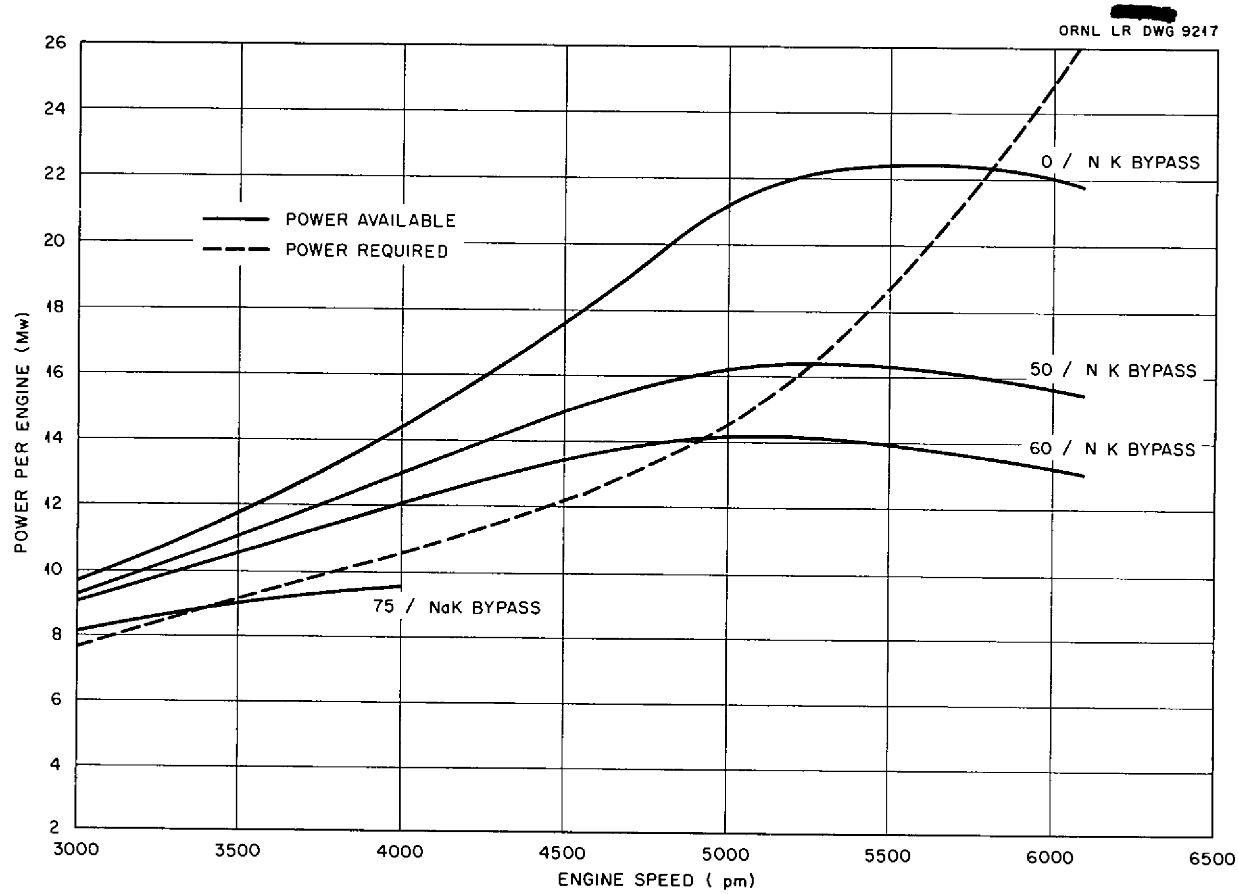

Fig 19 Steady State Power Delivered with NaK Bypass Percentage Constant Steady State Engine Power Required vs Engine Rotor Speed Reactor and four Allison J 71 engines at SL static conditions exhaust nozzle open fuel and NaK pump speeds constant at rated values

When the fuel and NaK flows are constant at their rated values the last two denominator terms are small and tend to cancel The power delivered to each load then is approximately

$$(4) \qquad P_e = \overbrace{W_{aD}\eta_R}^{\text{Destabilizing term}} \overbrace{(T_{Fav} - T_{T3})}^{\text{Stabilizing term}} C_a$$

The second term in the equation describes the stabilizing effect of the increase in compressor outlet temperature which results when engine speed increases This effect alone would cause the power delivered at a constant mean reactor temperature to decrease If power delivery to an engine decreases with an increase in engine speed static stability at least will be assured because the power required increases with increasing speed

The first term in the power delivery expression describes the destabilizing effect of the increase in air flow which results when engine speed increases If the NaK flow rate is constant the effectiveness of the radiator (η_R) decreases as air flow increases but not so rapidly Hence the product ($W_{aD}\eta_R$) increases with increasing air flow This product for the hypothetical J 71 radiator is plotted vs air flow for several constant NaK flow rates in Fig 21

The rapid increase in engine air flow with speed at low speeds causes $W_{aD}\eta_R$ to increase faster than ($T_{Fav} - T_{T3}$) decreases Hence the power delivery curves rise with increasing speed at low speeds At higher speeds however the effect of the increase in radiator inlet temperature predominates (as the compressor outlet temperature moves closer to the mean fuel temperature) and

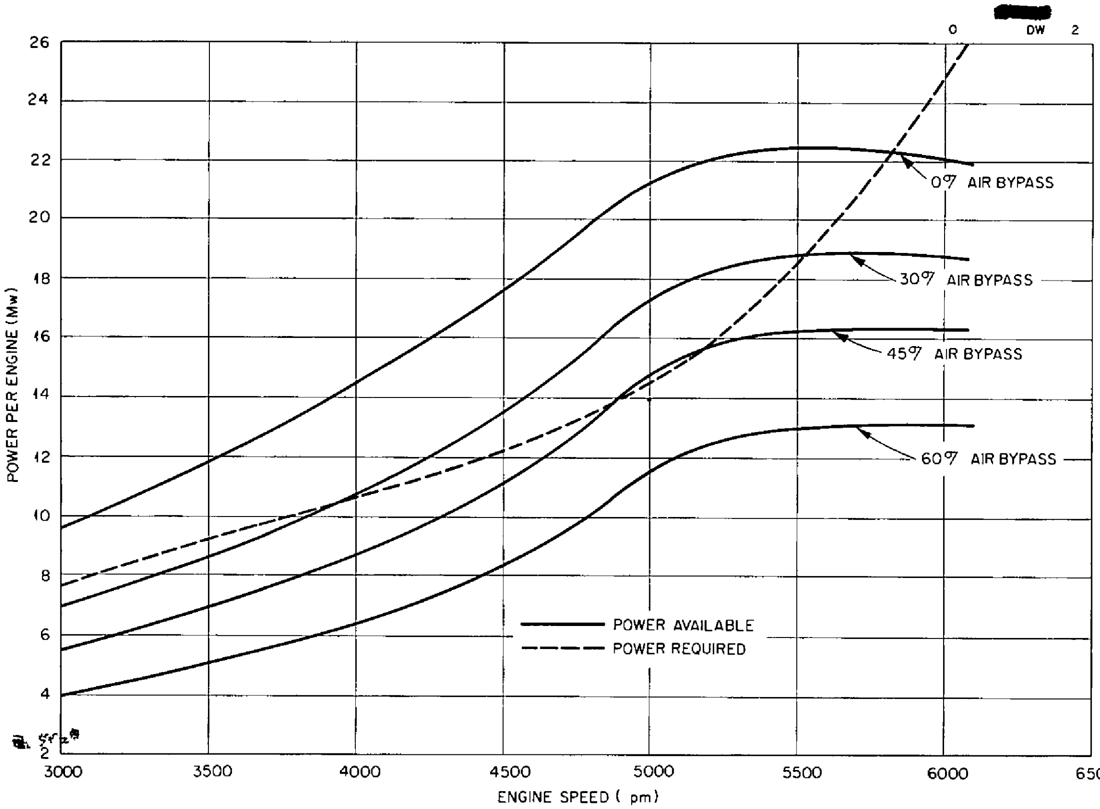

Fig 20 Steady State Power Delivered with Air Bypass Percentage Constant Steady State Engine Power Required vs Engine Rotor Speed Reactor and four Allison J 71 engines at SL static conditions exhaust nozzle open fuel and NaK pump speeds constant at rated values

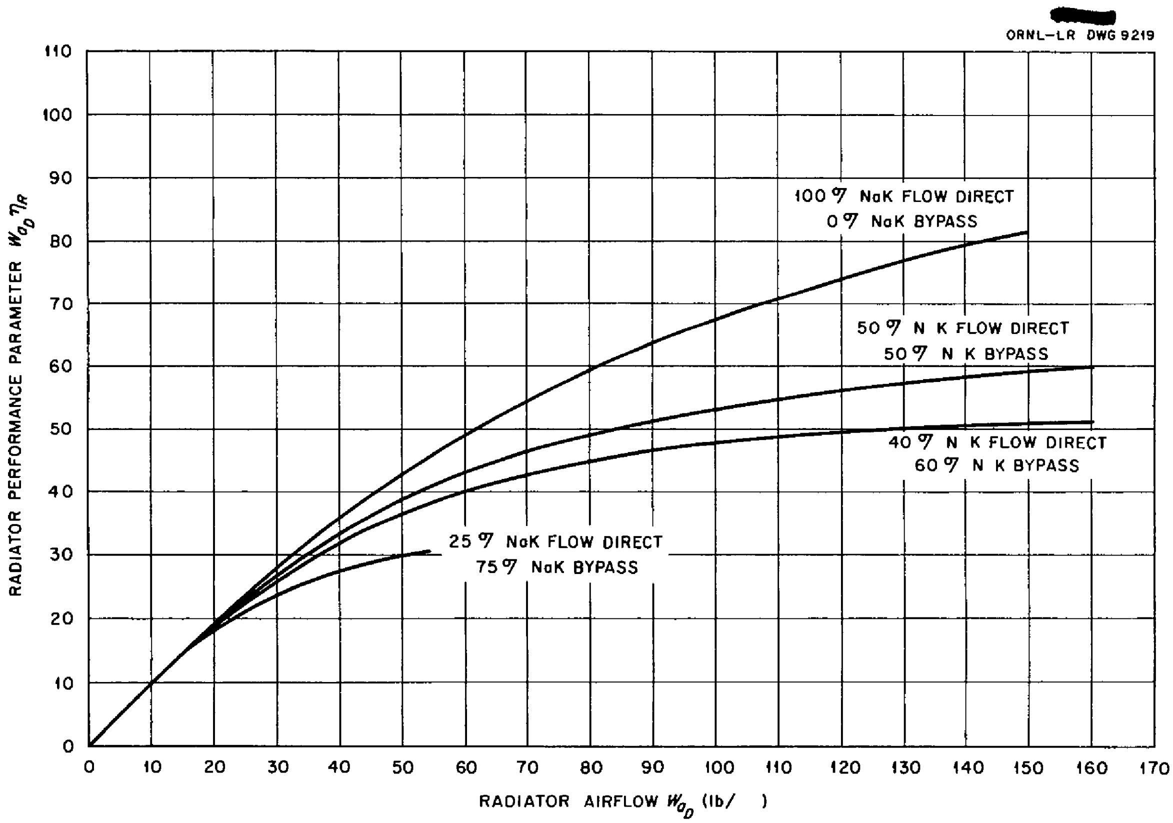

Fig 21 Radiator Performance Parameter for the Allison J 71 Engine

the $W_{aD}\eta_R$ product rises less rapidly These effects cause power delivery to reach a peak and begin to fall in the high speed range The increase in radiator inlet temperature with increasing speed thus causes the steady state power curves to inter sect stably in both cases at high engine speeds in spite of the destabilizing effect of increasing air flow with speed

The relative flatness of the curves showing the variation of the power available with the NaK by pass percentage constant at low speeds can be explained from the $W_{aD}\eta_R$ plot in Fig 19 and from Eq 4 the power delivered equation The differences in the performance characteristics of the air bypass and NaK bypass throttling arrange ments lie in the behavior of the $W_{aD}\eta_R$ product as engine air flow changes since the $(T_{F\ v} - T_{T3})$ term varies with speed in the same way in both cases The power delivery curves rise most slowly with increasing speed when the $W_{aD}\eta_R$ vs W_{aD} curves are flattest The destabilizing effect of an engine air flow change on reactor power de livery is minimized when the variation of $W_{aD}\eta_R$ with changes in air flow is minimized

A study of Fig 19 leads to the conclusion that $W_{aD}\eta_R$ varies least with changes in air flow when the air flow through the radiator is high and when the percentage of NaK flowing through the bypass is large Both these requirements are met best at part load points by the NaK bypass throttling arrangement

The behavior of the NaK bypass throttled power plant at 35 000 ft and Mach 0 87 is shown in Fig 22 The very large amount of NaK bypassing required to throttle the engines at this flight con dition causes the nuclear power delivery curves

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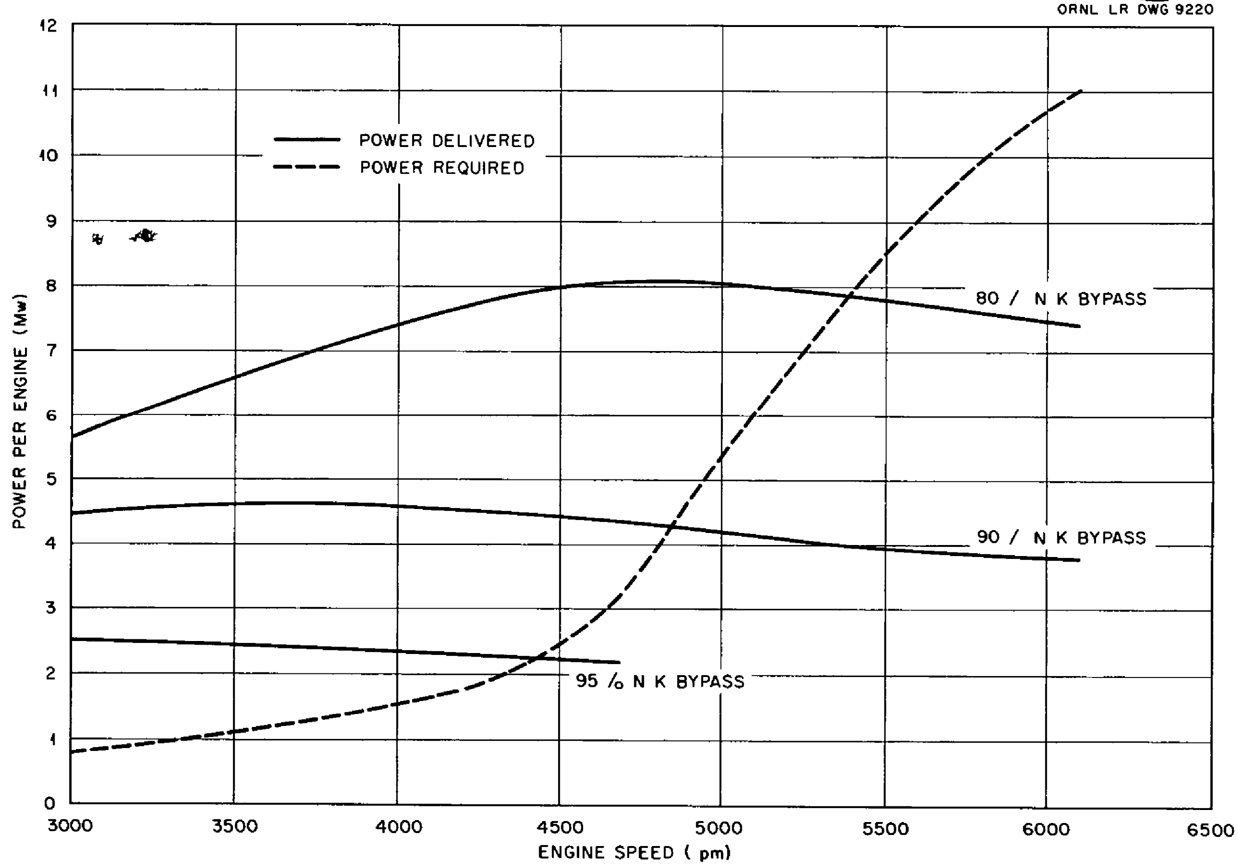

Fig 22. Steady-State Power Delivered with NaK Bypass Percentage Constant Steady State Engine Power Required vs Engine Rotor Speed Reactor and four Allison J 71 engines at 35 000 ft Mach 0 87 exhaust nozzle open fuel and NaK pump speeds constant at rated values

to be quite flat This bears out the conclusion drawn in the preceding paragraph heavy flow of NaK through the bypass results in flat power delivery curves

All the nuclear power delivery variations con sidered so far have been worked out for constant fuel and NaK pump speeds It might be desirable in the interests of simplicity to drive these pumps at engine speed This aggravates the static stability problem however since increasing the pump speeds with engine speed causes power delivery to rise faster with increasing engine speed than when the pump speeds are constant

The behavior of the NaK bypass throttled power plant at SL static conditions when various com binations of pumps are engine driven is shown in Fig 23 (Pump flow rates were assumed to be proportional to pump speed) Driving one or more pumps at speeds proportional to engine speed destroys most of the apparent natural static sta bility of the NaK bypass throttled power plant

Thus from steady state considerations it seems that a turbojet–demand sensitive reactor combina tion should operate stably in the high power range At part load operating conditions however the stability of such a power plant appears to depend

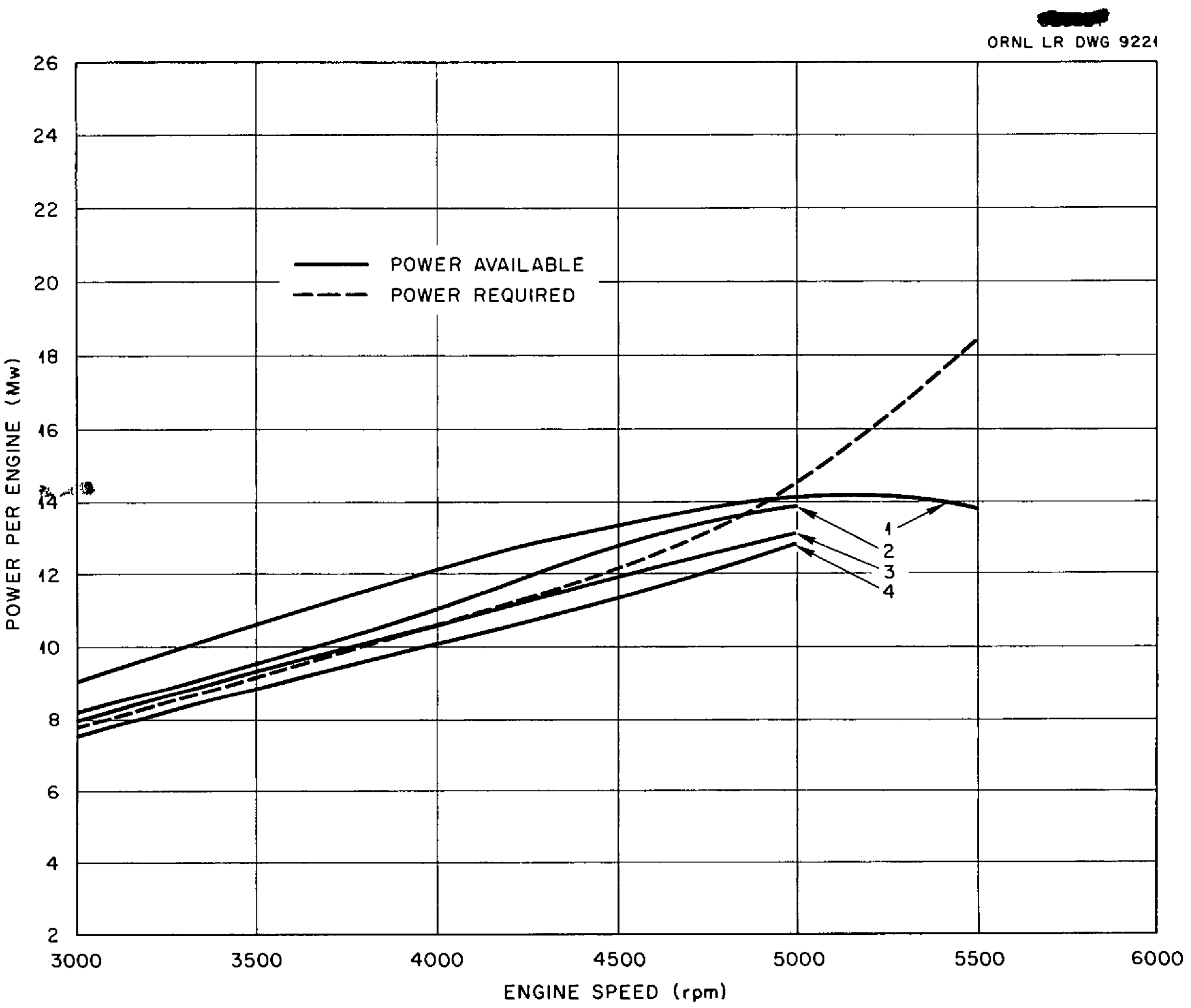

Fig 23 Steady State Power Delivered with 60% NaK Bypassed Steady State Engine Power Required vs Engine Rotor Speed (1) Pump speeds constant at rated values (2) NaK pump speeds constant fuel pumps engine-driven (3) fuel pump speeds constant NaK pumps engine driven (4) fuel and NaK pumps engine driven

on the throttling scheme used Relatively speaking use of a NaK bypass throttling arrangement seems from steady state considerations at least to result in more stable power plant operation than does use of an air bypass throttling arrangement In the example considered the NaK bypass throttled power plant was stable at normal part load operating points when the fuel and NaK pump speeds were constant while the air bypass throttled power plant was not Whether or not a NaK bypass throttled system will be stable in other power plant combinations is difficult to say A detailed check in each particular situation will no doubt be required

If the nuclear power source–turbojet engine load combination is not inherently stable or if the natural stability is not adequate the stability characteristics can be improved by adding the proper control equipment Static power plant stability in the cases considered here for example would be achieved if some sort of power level control system were added to the nuclear heat source to maintain nuclear power delivery to each engine constant at some preset adjustable value The power available from the reactor would then be independent of changes in engine speed or air flow and compressor outlet temperatures and the power available vs speed curves would be horizontal lines

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COUPLING BETWEEN ENGINES IN A MULTIENGINE INSTALLATION

All the steady state performance characteristics considered so far have been worked out for balanced load operation where power delivery to each engine is the same It is also interesting to consider the effects of coupling between engines when the power distribution to the various engines is not symmetrical assuming for the moment that the reactor design and load connection arrangement will allow unbalanced operation The various engine loads are not completely independent They are cross coupled through their common power source If the power delivered to one engine is varied through manipulation of the NaK bypass of that engine the power delivered to the other engines also changes Power delivery to the other engines changes because variation in power delivery to one load causes the reactor outlet temperature to change The power delivered to any given engine load is related to the reactor outlet temperature by

$$(5)\quad P_1 = (T_{FH} - T_{T3}) \times \left[\frac{1}{1/W_{aD}C_a\eta_R + (1 - \eta_{HX})/\eta_{HX}W_{Ne}C_N}\right]$$

The magnitude of the cross coupling effect when the control rod position is constant has been determined for the NaK bypass throttled reactor–X 61 engine power plant operating at 35 000 ft at Mach 0 92 The results which are plotted in Fig 24 show how the per cent of full nuclear power delivered to an engine load with a constant NaK bypass setting varies with power delivery to a second engine load In the event of complete failure of the second engine the power delivered

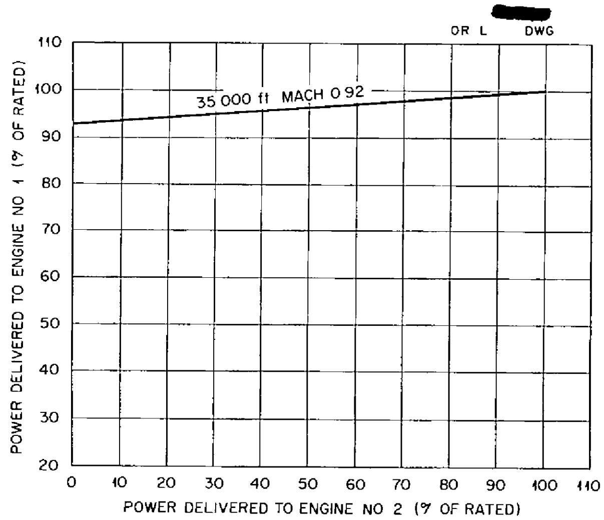

Fig 24 Steady State Coupling Between Engines Reactor and two G E X 61 engines altitude 35 000 ft Mach 0 92 No 1 engine NaK bypass constant at 9 5% No 2 engine NaK bypass varied from 9 5 to 100%

to the first engine drops to 93% of its rated value If this lost power is to be regained the bypass on the first engine must be readjusted if possible or the control rod must be withdrawn slightly

Cross coupling between engines can be eliminated by the addition of automatic control equipment When the control rod position is constant and NaK bypass throttling is used however the magnitude of the coupling effect does not appear to be great enough to justify much complication of the control system for its elimination If rod motion with total power level changes is required cross coupling between engines will be more pronounced than in the example considered here and the coupling effects between engines may be so large that independent manual power delivery adjustments to each load will be tedious

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NUCLEAR POWER SOURCE CONTROL REQUIREMENTS

Automatic control requirements for the nuclear heat source in a combination chemical nuclear aircraft power plant of the type discussed in the preceding sections can be determined by con sidering how the flight engineer might perform typical power plant maneuvers without the help of automatic control equipment The numerous altitudes flight speeds and ambient temperatures at which such a power plant might be operated can be grouped into three categories for purposes of discussion those flight conditions at which the radiators are (1) larger than they need be (2) just large enough and (3) too small to transfer rated nuclear power to each engine If the radi ators are designed to transfer rated nuclear power to each engine at the nuclear cruise flight condition (Mach 0 9 at 35 000 ft in the example considered here) excess radiator capacity is generally avail able during flight at altitudes below the nuclear cruise design altitude and the radiators will generally be too small to transfer rated nuclear power to each engine during operation at altitudes above the nuclear cruise design altitude

Manual operation of the nuclear part of the reactor–X 61 power plant in each of these situ ations is described in the paragraphs which follow Throttling by means of radiator NaK bypass valves is assumed and fuel and NaK flow rates are assumed to be constant at their rated values Startup and shutdown problems ground handling problems and sodium coolant temperature control problems are not considered

MANUAL OPERATION AT FLIGHT CONDITIONS WHERE RADIATOR CAPACITY IS EXCESSIVE

The radiators will generally be large enough to transfer more than rated nuclear power to each engine load at altitudes below the design nuclear cruise altitude Power plant maneuvers which might be performed in this operating range include engine startup operation on nuclear power only and operation on chemical plus nuclear power

The engines will probably be started on chemical power only The higher turbine inlet temperatures obtainable with the chemical power sources should result in the lowest possible engine firing speeds and cranking powers The chemical power sources are also more maneuverable than the nuclear power source which probably will be advantageous during the critical starting and accelerating period

Once the engines have been started nuclear power delivery can be initiated by diverting NaK through the engine radiators It is assumed that the reactor has already been brought critical and is known to be delivering power at some low level Care must be exercised in closing the NaK bypass valves to avoid transient undercooling of the NaK returning to the reactor Enough hot NaK must be allowed to flow through the bypass valves to ensure that the return line NaK temperatures will remain above their lower limits at all times

Full closure of the NaK bypass valves is not permissible even during steady state operation at flight conditions where excess radiator capacity is available Rated nuclear power is delivered to each engine in the reactor–X 61 power plant during static operation at sea level, for example when only 45% of the total rated NaK flow passes through the radiators (Figs 12 through 15) If the NaK bypass valves are fully closed at such operating conditions excess power demands will be set up and return line NaK undercooling and reactor fuel overheating will result

Care must also be exercised in opening the NaK bypass valves to reduce nuclear power delivery The return line NaK temperature should not be allowed to rise above the value at which isothermal idling of the reactor is desired when power delivery has been reduced virtually to zero Limiting the return line NaK temperature rise during load removal ensures that the load will be removed slowly enough to prevent reactor overheating

If the reactor design is such that the fuel temperature at the inlet of the reactor core must be limited to some value less than the design point mean fuel temperature control rod withdrawal is required as nuclear power delivery is increased Since the reactor fuel inlet temperature approaches the mean fuel temperature as power delivery is reduced the rod must be inserted to lower the mean fuel temperature during operation at low powers if the reactor fuel inlet temperature is to be maintained below the design point mean fuel temperature Subsequent rod withdrawal to raise the mean fuel temperature to the design point value cannot be initiated until some load has been reapplied

If operation on chemical plus nuclear power is desired engine fuel flows and exhaust nozzle areas must be controlled Control requirements for the turbojet section of the power plant during operation on chemical plus nuclear power will not be considered here For purposes of this discussion it is assumed that the automatic control equipment required is available

Each time chemical power delivery to the engines is varied or the engine exhaust nozzle areas are changed the rate of nuclear heat delivery will also change The changes in compressor outlet temperatures and in air flow resulting from the changes in chemical fuel flows or nozzle areas upset previously established heat transfer balances in the radiators If nuclear power delivery is to be held constant NaK bypasses must be readjusted each time the engine thrust outputs are changed during operation on chemical plus maximum nuclear power

Continuous readjustment of the bypass valve positions is also required if nuclear power delivery is to be maintained constant as the aircraft altitude and flight speed change since the engine air flows and compressor outlet temperatures are also functions of the engine inlet total temperature total pressure and flight Mach number The demand sensitivity of the reactor makes continual NaK bypass readjustment necessary if power delivery is to be held constant as the load characteristics change Constant power delivery to a turbojet load is not necessarily desirable except when nuclear power only flight at the highest speed possible is to be maintained Operation in this manner will probably be required for a large percentage of the time during typical missions

MANUAL OPERATION AT RADIATOR DESIGN FLIGHT CONDITIONS

The manual control operations required in the execution of typical power plant maneuvers at flight conditions when the radiators are just large enough to transfer rated nuclear power to each engine are quite similar to those described in the preceding section except that full closure of the NaK bypass valves is now permissible during steady state operation Return line NaK undercooling and overheating must be guarded against during transients but the radiators are not large enough to cause undercooling during steady state operation at such flight conditions Full nuclear power delivery to each engine results when the bypasses are fully closed Rod control requirements are the same as those discussed in the preceding section Rod withdrawal or insertion during power level changes is required if the fuel temperature at the inlet of the reactor core must be held below the design point mean fuel temperature

MANUAL OPERATION AT FLIGHT CONDITIONS WHERE RADIATOR CAPACITY IS INADEQUATE

Radiator capacity will be inadequate at some flight conditions because the engine air flows and compressor outlet temperatures are such that the available heat transfer surface area is not sufficient to transfer rated nuclear power During dash for example only 71% of rated nuclear power can be delivered to each engine in the X 61 power plant even though the NaK bypasses are fully closed and the mean reactor fuel temperature is at its design point value This operating condition is described in Table 2

Since rated nuclear power is not being delivered the fuel temperature at the outlet of the reactor core is less than the 1600°F upper limit Some increase in nuclear power delivery thus can be effected by further withdrawal of the control rod

TABLE 2. DASH OPERATION (55 000 ft Mach 2 0) OF G E X 61 ENGINE

	T_F at Des gn Po nt Value	T_{FH} at Maximum Value
T_{Fav} °F	1450	1489
T_{FH} °F	1557	1600
T_{FC} °F	1343	1378
NaK byp %	0	0
Pump speeds	R ted	Rated
Nuclea power delivered per engine Mw	21 4	22 3
Chemical power delivered per eng ne Mw	40 9	40 0
Total power del vered per engine Mw	62 3	62 3
Chemical power reduct on effected by moving control rod %		2 2

to raise this temperature The operating conditions described in the last column of Table 2 prevail after such action is taken Nuclear power delivery to each engine is increased to 74% of rated power and chemical fuel consumption is reduced by about 2 2% under these conditions

If the fuel temperature at the inlet of the core must be limited to 1350°F however rod withdrawal to the extent shown in the last column of Table 2 is not permissible and the potential advantages to be gained in raising the mean fuel temperature during operation at such a flight condition are not so great as those described in this column

The discussion in the preceding paragraphs leads to the conclusion that some sort of automatic control equipment to raise the reactor mean fuel temperature to its maximum allowable value during operation at radiator limited flight conditions is desirable but that equipment performing this function alone is not essential to power plant operation The potential advantages to be gained do not appear to be great enough to justify much complication of the control system unless such equipment is also needed for other reasons such as controlling rod withdrawal during power increases

AUTOMATIC CONTROL REQUIREMENTS DURING OPERATION IN THE POWER RANGE

The foregoing discussion indicates that some sort of automatic control equipment is required for the NaK bypasses Automatic control equipment is also required for the control rod if the fuel temperature at the inlet of the reactor core must be held below the design point mean fuel temperature If the reactor can be designed to operate isothermally at the design point mean fuel temperature however a reasonably conventional manual type rod control will probably suffice

Movement of the NaK bypasses must be limited to maintain the return line NaK temperatures between their upper and lower limits at all times The lower limit for steady state operation is the temperature at which rated nuclear power is delivered to each engine The upper limit is the temperature at which steady state isothermal reactor idling is desired

In simplest form the controls for the NaK bypass valves might be remote positioning servos with return line NaK temperature overrides and underrides to limit bypass valve openings to those values that will result in temperatures in the safe range Further studies of reactor and engine control integration may show that a more complex arrangement is needed

If the reactor cannot be operated isothermally at the design point mean fuel temperature rod insertion with power reduction is required to limit the core inlet fuel temperature rise Rod withdrawal with increasing power delivery is required either to restore the mean fuel temperature to its design point value or to raise the reactor fuel outlet temperature to its maximum value The discussion in the preceding section showed that a slight advantage would be gained during the dash if the

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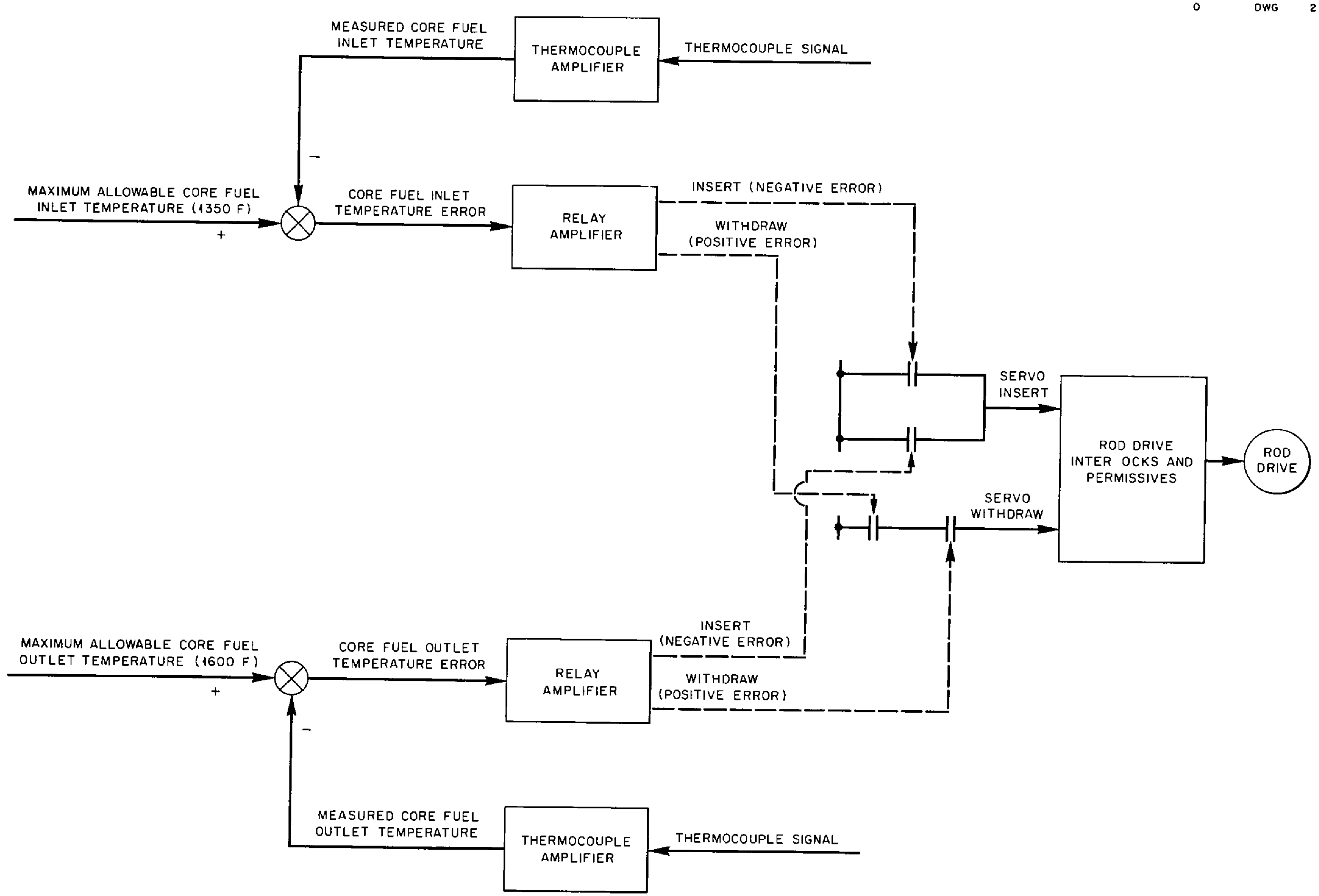

Fig 25 Schematic Diagram of Rod Servo

rod were withdrawn to raise the fuel outlet temperature to its maximum value rather than to raise the mean temperature to its design point value Hence one simple type of rod control for the reactor–X 61 power plant would be one which operates as follows

1 withdraws the rod if the reactor core fuel inlet temperature is less than 1345°F *and* the reactor core fuel outlet temperature is less than 1590°F
2 inserts the rod if the reactor core fuel inlet temperature exceeds 1355°F *or* the reactor core fuel outlet temperature exceeds 1600°F

The basic form of such a control system is outlined in Fig 25 Further study may show that additional stabilizing signals are required but this question will not be considered here The diagram is intended to be schematic only and does not necessarily represent the best way to do the job

The fuel temperatures resulting from the use of such a control scheme are shown in Fig 26 Either the core fuel inlet temperature or the core fuel outlet temperature is held at its upper limit at all times Operation with the fuel outlet temperature at its maximum value is possible only when power delivery exceeds 83 4% of the rated value The fuel inlet temperature limiting requirement does not allow the maximum fuel outlet temperature to be reached when power delivery is less than 83 4% of rated power

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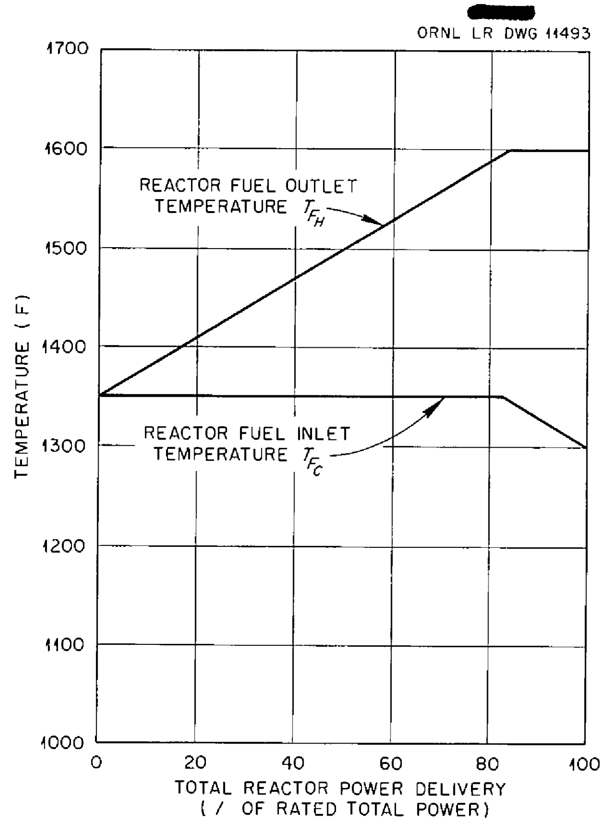


Fig 26 Fuel Temperature Variations Resulting from Use of Rod Servo

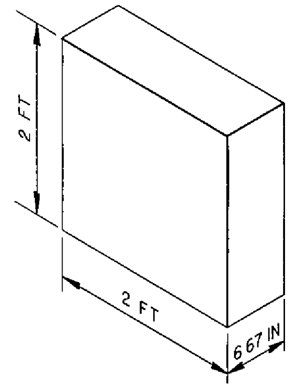
ACKNOWLEDGMENTS

The writer wishes to express appreciation for help received from A P Fraas M M Yarosh and R D Schultheiss of ORNL and from J Bendot of The Glenn L Martin Company

APPENDIX A

RADIATOR DESIGN PROCEDURE

The basic radiator unit from which the engine radiators discussed in this report were composed, was designed by R D Schultheiss A sketch of this unit is shown



This unit has 776 ft^2 of heat transfer area and the variation of its over all heat transfer coefficient U_R with changes in air flow per unit frontal area W_a/A_{fR} is as shown in Fig 6 The pro cedure followed in assembling a hypothetical radiator for the X 61 engine is outlined below

1 An engine radiator design point flight condition is chosen, and the engine load requirements at this flight condition are determined The 35 000 ft Mach 0 87 nuclear power only cruise flight condition was chosen as the radiator engine design point for the reactor–X 61 power plant and the accompanying load re quirements are shown below

T_{NC} (1100°F) ⟵〰〰⟵ T_{NH} (1500°F)

P_e = 30 Mw

W_a = 132 4 lb/ e

T_{T3} (487°F) ⟶〰〰⟶ T_{T4} (1311°F)

2 The required value for the product $U_R A_R$ (total heat transfer area–over all heat transfer coefficient) is then calculated as follows

$$\text{Log mean temperature difference} = \frac{(1100 - 487) - (1500 - 1311)}{\ln (1100 - 487)/(1500 - 1311)} = 360°F$$

$$U_R A_R = \frac{P_e}{\Delta T_{me}} = \frac{28\ 425}{360} = 78\ 9 \text{ Btu/sec °F}$$

3 The engine air flow per unit frontal area of the radiator W_a/A_{fR} is calculated from W_a which is known and A_{fR} which is determined from the engine design In this case A_{fR} was arbitrarily chosen as 16 ft^2 so

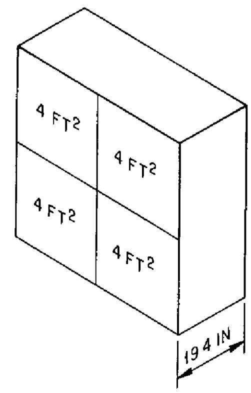
$$\frac{W_a}{A_{fR}} = \frac{132\ 4}{16} = 8\ 275 \text{ lb/sec ft}^2$$

4 A value for U_R is read from the curve in Fig 6 with the use of W_a/A_{fR} found in step 3 and the required heat transfer surface area A_R, is calculated

$$U_R = 31\ 5 \text{ Btu/hr ft}^2 \text{ °F}$$

$$A_R = \frac{U_R A_R}{U_R} = \frac{(78\ 9)(3600)}{31\ 5} = 9018 \text{ ft}^2$$

5 Next a number of the basic radiator units are stacked to provide the required frontal area Four units are needed in this example Since each basic unit contains 776 ft^2 of heat transfer area the stacked array contains 3104 ft^2 of heat transfer surface The array must therefore be lengthened to provide the required over all heat transfer surface Since a 6 67 in deep stacked unit contains 3104 ft^2 and since 9018 ft^2 is required the depth must be increased to



$$\frac{9018}{3104} \times 6\ 67 = 19\ 4 \text{ in}$$

The pressure drop can be estimated by multiplying the calculations of Schultheiss by the proper ratios Under the following operating conditions

$$\frac{W_a}{A_{fR}} = 5\ 79 \text{ lb/sec ft}^2 \qquad \rho = 0\ 0434 \qquad \text{radiator depth} = 6\ 67 \text{ in}$$

Schultheiss has calculated that the pressure drop of this type of radiator is

$$\Delta P_R = 28\ 5 \text{ in } H_2O$$

At other operating conditions the pressure drop is estimated to be

$$\Delta P_R = 28\ 5 \left(\frac{W_a/A_{fR}}{5\ 79}\right)\left(\frac{0\ 0434}{\rho_v}\right)\left(\frac{\text{radiator depth}}{6\ 67}\right)$$

For the G E X 61 case

$$\Delta P_R = 82\ 16 \text{ in } H_2O = 426\ 8 \text{ lb/ft}^2$$

At the design point (described in step 1) this pressure drop is (426 8/6470) = 6 6% of the com pressor discharge pressure The same procedure was used in assembling the hypothetical Allison J 71 radiators

APPENDIX B

STEADY STATE PERFORMANCE CALCULATIONS

Control parameter values required to yield given engine thrust outputs during steady state operation at specified flight conditions can be determined by working backwards through the engine and reactor performance characteristics The engine load imposed on the reactor (as described by power compressor outlet temperature turbine inlet temperature and airflow) is first determined from Figs 2 through 5 When these load quantities are known and when values for all but one of the unknown potential throttling quantities are specified the value which the remaining unknown throttling quantity must have in order to meet the load conditions can then be calculated by use of one of the procedures outlined below For purposes of illustration it is assumed in each case that the throttling quantity value required to deliver 4000 lb of thrust output per engine during flight at 15 000 ft at a speed of Mach 0 45 is to be determined

Example 1 – Control Rod Throttling

The engine load quantities resulting when 4000 lb of thrust is delivered during flight at 15 000 ft and Mach 0 45 are (from Figs 2 through 5)

$$T_{T3} = 411°\text{F} \qquad W_a = 157 \text{ lb/sec} \qquad T_{T4} = 931°\text{F}$$

$$P_e = 22\ 5 \text{ Mw} = 21\ 300 \text{ Btu/sec}$$

Effectiveness values for both the heat exchanger and the engine radiators will be required for calculation of the unknown quantities T_F v T_{FH} T_{FC} T_{NH} T_{NC} These effectiveness values depend on the fluid flow rates and the over all heat transfer coefficients which are also functions of the flow rates

$$\eta_{HX} = \frac{1 - e^{(U_{HX}A_{HX}/W_N C_N)[(W_N C_N/W_F C_F)-1]}}{1 - (W_N C_N/W_F C_F)\, e^{(U_{HX}A_{HX}/W_N C_N)[(W_N C_N/W_F C_F)-1]}}$$

$$\eta_R = \frac{1 - e^{(U_R A_R/W_a C_a)[(W_a C_a/W_N C_N)-1]}}{1 - (W_a C_a/W_N C_N)\, e^{(U_R A_R/W_a C_a)[(W_a C_a/W_N C_N)-1]}}$$

Since the flow rates in the main heat exchanger are constant at design point values in this example the heat exchanger effectiveness is 0 8 as shown on page 3 The effectiveness of the radiator at this operating condition is found by substituting the following values into the effectiveness expression

$$W_a = 157 \text{ lb/sec} \qquad A_R = 9018 \text{ ft}^2$$

$$U_R = 33\ 6 \text{ Btu/hr ft}^2\ °\text{F} \quad \left(\text{from } \frac{W_a}{A_{fR}} = \frac{157}{16} = 9\ 81 \text{ and Fig } 6\right)$$

$$W_N = 284\ 3 \text{ lb/sec} \qquad C_a = 0\ 26 \qquad C_N = 0\ 25$$

This substitution shows that the radiator effectiveness η_R is 0 768

Values for all the unknowns desired can now be determined from the following series of calculations

NaK Temperature at Outlet of Heat Exchanger (T_{NH}) – By definition

$$\eta_R = \frac{T_{T4} - T_{T3}}{T_{NH} - T_{T3}}$$

or

$$T_{NH} = \frac{T_{T4} - T_{T3}}{\eta_R} + T_{T3} = \frac{931 - 411}{0\ 768} + 411 = 1088°F$$

NaK Temperature at Inlet of Heat Exchanger (T_{NC}) –

$$T_{NC} = T_{NH} - (T_{NH} - T_{NC}) = T_{NH} - \frac{P_e}{W_{Ne}C_N} = 1088 - \frac{21{,}300}{(284\ 3)(0\ 25)} = 790°F$$

Fuel Temperature at Outlet of Reactor Core (T_{FH}) – By definition

$$\eta_{HX} = \frac{T_{NH} - T_{NC}}{T_{FH} - T_{NC}}$$

or

$$T_{FH} = \frac{T_{NH} - T_{NC}}{\eta_{HX}} + T_{NC} = \frac{1088 - 790}{0\ 8} + 790 = 1162°F$$

Fuel Temperature at Inlet of Reactor Core (T_{FC}) –

$$T_{FC} = T_{FH} - (T_{FH} - T_{FC}) = T_{FH} - \frac{2P_e}{W_F C_F} = 1162 - \frac{42\ 600}{(702)(0\ 27)} = 938°F$$

Twice the power delivered to one engine is used in the above expression since reactor power delivery to two engine loads has been assumed

Thus if 4000 lb of thrust is to be delivered by each engine during flight at 15 000 ft and Mach 0 45 the control rod must be set to lower the mean fuel temperature to 1051°F if throttling is to be by means of control rod motion alone

Example 2 – Reactor Fuel Flow Throttling

The engine load quantities at the 15 000 ft Mach 0 45 4000 lb thrust output flight condition were given in the preceding example The radiator effectiveness in this case is also the same as the effectiveness calculated in example 1 (η_R = 0 768) since the air and NaK flow rates are the same It is assumed in this example that the control rod is adjusted to hold the mean fuel temperature at its design point value T_F = 1450°F

The unknown quantities to be calculated are W_F T_{FH} T_{FC} T_{NH} and T_{NC} The unknown NaK temperatures are the same as those calculated in example 1 since the load characteristics are the same and the radiator effectiveness is the same The fuel flow rate required to satisfy heat balances in the main heat exchanger can be calculated as outlined below

The power transferred from the main heat exchanger is

$$P_T = 2W_F C_F (T_{FH} - T_{F\ v}) = 2W_F C_f \left(\frac{\Delta T_N}{\eta_{HX}} + T_{NC} - T_F \right)$$

If the power delivery to the two engines is the same

$$P_e = \frac{P_T}{2} = 0\ 27\, W_F \left(\frac{299}{\eta_{HX}} + 790 - 1450 \right) = W_F \left(\frac{80\ 6}{\eta_{HX}} - 178\ 3 \right)$$

Since P_e is known from the engine load requirements and η_{HX} is a function of W_F (since the NaK flow rate is constant) the above expression might be solved directly for W_F However the complexity of the η_{HX} to W_F relationship makes solution by trial and error more attractive One procedure for solving this equation involves assuming a value for W_F calculating the associated value of η_{HX} and calculating a value for P_e The process is repeated until the calculated power per engine is equal to the required power per engine At the 15 000 ft Mach 0 45 4000 lb thrust output flight condition W_F = 125 lb/sec satisfies the power delivery requirement

Fuel temperatures are then calculated from

$$T_{FH} - T_{FC} = \frac{P_T}{W_F C_F} = \frac{42\ 600}{(125)(0\ 27)} = 1257°\text{F}$$

$$T_{FH} = T_{F} + \frac{T_{FH} - T_{FC}}{2} = 1450 + \frac{1257}{2} = 2079°\text{F}$$

$$T_{FC} = T_{F\ v} - \frac{T_{FH} - T_{FC}}{2} = 1450 - \frac{1257}{2} = 822°\text{F}$$

Example 3 – NaK Flow Throttling

The engine load quantities are again the same as those shown in example 1 since the aircraft flight condition and engine thrust outputs desired are the same In this example the fuel flow rate W_F, and the mean fuel temperature $T_{F\ v}$ are constant at their rated values (702 lb/sec and 1450°F respectively)

The unknown quantities to be calculated in this case are W_{Ne} T_{FH} T_{FC} T_{NH} and T_{NC} The reactor fuel temperatures are found easily from

$$T_{FH} - T_{FC} = \frac{P_T}{W_F C_F} = \frac{42\ 600}{(702)(0\ 27)} = 224°\text{F}$$

$$T_{FH} = T_{F} + \frac{T_{FH} - T_{FC}}{2} = 1450 + \frac{224}{2} = 1562°\text{F}$$

$$T_{FC} = T_{F\ v} - \frac{T_{FH} - T_{FC}}{2} = 1450 - \frac{224}{2} = 1338°\text{F}$$

The NaK flow rate needed for delivering the power required by each engine at the specified load conditions can be found by a trial and error process The right trial is outlined below

A value for W_{Ne} is assumed and the resulting η_{HX} is calculated If W_{Ne} is 155 4 lb/sec η_{HX} is 1 0 as calculated from the known fuel flow rate the over-all heat transfer coefficient and the assumed NaK flow rate The resulting NaK temperatures are then calculated From the definition of main heat exchanger effectiveness

$$T_{NC} = T_{FH} - \frac{T_{NH} - T_{NC}}{\eta_{HX}} = T_{FH} - \frac{P_e}{W_{Ne} C_N \eta_{HX}} = 1562 - \frac{21\ 300}{(155\ 4)(0\ 25)(1\ 0)} = 1012°\text{F}$$

and

$$T_{NH} = T_{NC} + (T_{NH} - T_{NC}) = T_{NC} + \frac{P_e}{W_{Ne}C_N} = 1012 + \frac{21\,300}{(155\ 4)(0\ 25)} = 1562°F$$

An alternate expression for the radiator effectiveness is

$$\eta_R = \frac{1 - e^{(U_R A_R/W_a C_a)[(\Delta T_N/\Delta T_a)-1]}}{1 - (\Delta T_N/\Delta T_a)\, e^{(U_R A_R/W_a C_a)[(\Delta T_N/\Delta T_a)-1]}}$$

Substitution of the following quantities into this expression yields a value for radiator effectiveness which exists when the NaK flow rate is 155 4 lb/sec as was originally assumed

$$\frac{W_a}{A_{fR}} = \frac{157}{16} = 9\ 81 \qquad U_R = 33\ 6\ \text{Btu/hr ft}^2\ °\text{F (Fig 6)}$$

$$\frac{\Delta T_N}{\Delta T_a} = \frac{1092}{520} = 2\ 10 \qquad \frac{U_R A_R}{W_a C_a} = \frac{(33\ 6)(9018)}{(157)(0\ 26)(3600)} = 2\ 063$$

$$\eta_R = \frac{1 - e^{2\ 063(2\ 10-1)}}{1 - 2\ 10\, e^{2\ 063(2\ 10-1)}} = 0\ 450$$

The radiator effectiveness required to satisfy the load requirement is

$$\eta_R = \frac{T_{T4} - T_{T3}}{T_{NH} - T_{T3}} = \frac{520}{1562 - 411} = 0\ 452$$

If these two effectiveness calculations had not yielded the same result a different NaK flow rate would have been assumed and the calculations would have been repeated

Example 4 – NaK Bypass Throttling

The engine load quantities are again the same as those shown in example 1 and in this case the fuel flow rate total NaK flow rate main heat exchanger effectiveness and mean fuel temperature are assumed to be constant at their rated values

The unknown quantities to be calculated are W_{NBP_1} W_{ND_1} T_{FH} T_{FC} T_{NH} T_{NC} and T_{NC}

Fuel Temperature at Outlet of Reactor Core (T_{FH}) –

$$T_{FH} = T_F + \frac{T_{FH} - T_{FC}}{2} = 1450 + \frac{224}{2} = 1562°F$$

Fuel Temperature at Inlet of Reactor Core (T_{FC}) –

$$T_{FC} = T_{Fav} - \frac{T_{FH} - T_{FC}}{2} = 1450 - \frac{224}{2} = 1338°F$$

NaK Temperature at Inlet of Heat Exchanger (T_{NC}) – From the definition of heat exchanger effectiveness

$$T_{NC} = T_{FH} - \frac{T_{NH} - T_{NC}}{\eta_{HX}} = 1562 - \frac{299}{0\ 8} = 1189°F$$

NaK Temperature at Outlet of Heat Exchanger (T_{NH}) –

$$T_{NH} = T_{NC} + (T_{NH} - T_{NC}) = T_{NC} + \frac{P_e}{W_{Ne}C_N} = 1189 + \frac{21\ 300}{(284\ 3)(0\ 25)}$$

$$T_{NH} = 1189 + 299 = 1488°F$$

NaK Temperature at Outlet of Radiator (T_{NC}) – Values for the following constants are first obtained

$$\eta_R = \frac{T_{T4} - T_{T3}}{T_{NH} - T_{T3}} = \frac{931 - 411}{1488 - 411} = 0\ 483$$

$$\frac{U_R A_R}{W_a C_a} = \frac{(33\ 6)(9018)}{(157)(0\ 26)(3600)} = 2\ 063$$

Substitution of these constants into the alternate radiator effectiveness expression given in example 3 yields

$$0\ 483 = \frac{1 - e^{2\ 063\{[(T_{NH}-T_{NC})/(T_{T4}-T_{T3})]-1\}}}{1 - [(T_{NH} - T_{NC})/(T_{T4} - T_{T3})]\,e^{2\ 063\{[(T_{NH}-T_{NC})/(T_{T4}-T_{T3})]-1\}}}$$

Solving for $(T_{NH} - T_{NC})/(T_{T4} - T_{T3})$

$$\frac{T_{NH} - T_{NC}}{T_{T4} - T_{T3}} = 1\ 90$$

Thus

$$T_{NC} = T_{NH} - 1\ 90(T_{T4} - T_{T3}) = 1488 - 1\ 90(931 - 411) = 500°F$$

at the outlet of the radiator

Direct NaK Flow Rate per Engine Through Radiator (W_{ND}) –

$$W_{ND} = \frac{P_e}{(T_{NH} - T_{NC})C_N} = \frac{21\ 300}{(1488 - 500)(0\ 25)} = 85\ 9\ \text{lb/sec}$$

NaK Bypass Flow Rate per Engine (W_{NBP}) –

$$W_{NBP} = W_{Ne} - W_{ND_1} = 284\ 3 - 85\ 9 = 198\ 4\ \text{lb/sec}$$

or

$$\frac{198\ 4}{284\ 3} \times 100 = 69\ 8\%$$

Example 5 – Air Bypass Throttling

The engine load quantities are given in example 1 and the fuel flow rate NaK flow rate heat exchanger effectiveness and mean fuel temperature are assumed to be constant at their rated values

The unknowns to be calculated in this case are W_{aBP} W_{aD} T_{FH} T_{FC} T_{NH} and T_{NC} The fuel and NaK temperatures are the same as those calculated in example 4 and are repeated here for reference

$$T_{FH} = 1562°F \qquad T_{FC} = 1338°F \qquad T_{NH} = 1488°F \qquad T_{NC} = 1189°F$$

The remaining unknowns W_{aD} and W_{aBP} are calculated in the following way

Direct Radiator Air Flow Rate per Engine (W_{aD}) – The radiator effectiveness is

$$\eta_R = \frac{T_{T4} - T_{T3}}{T_{NH} - T_{T3}}$$

Radiator power delivery is

$$P_e = W_a C_a (T_{T4} - T_{T3})$$

Combination of these expressions yields

$$W_{aD}\eta_R = \frac{P_e}{C_a(T_{NH} - T_{T3})} = \frac{21\ 300}{(0\ 26)(1488 - 411)} = 75\ 8$$

The $W_{aD}\eta_R$ product is also given by

$$W_{aD}\eta_R = W_{aD}\left\{\frac{1 - e^{(U_R A_R/W_{aD}C_a)[(W_{aD}C_a/W_N C_N)-1]}}{1 - (W_{aD}C_a/W_N C_N)\, e^{(U_R A_R/W_{aD}C_a)[(W_{aD}C_a/W_N C_N)-1]}}\right\}$$

This expression might be solved for W_{aD} (inserting the known value of $W_{aD}\eta_R$ product from above) since the NaK flow rate is constant and the over all heat transfer coefficient U_R is a function of W_{aD} The complexity of the right side of the above expressions makes direct solution difficult however The value of W_{aD} resulting in a $W_{aD}\eta_R$ product of 75 8 can be found graphically by plotting the right side of the above expression for $W_{aD}\eta_R$ as a function of W_{aD} Such a plot is shown in Fig B 1 This plot shows that the required $W_{aD}\eta_R$ value (75 8) results when W_{aD} is 83 lb/sec

Bypass Air Flow Rate per Engine (W_{aBP}) –

$$W_{aBP} = W_a - W_{aD} = 157 - 83 = 74 \text{ lb/sec}$$

$$\%\text{ air bypass} = \frac{74}{157} \times 100 = 47\%$$

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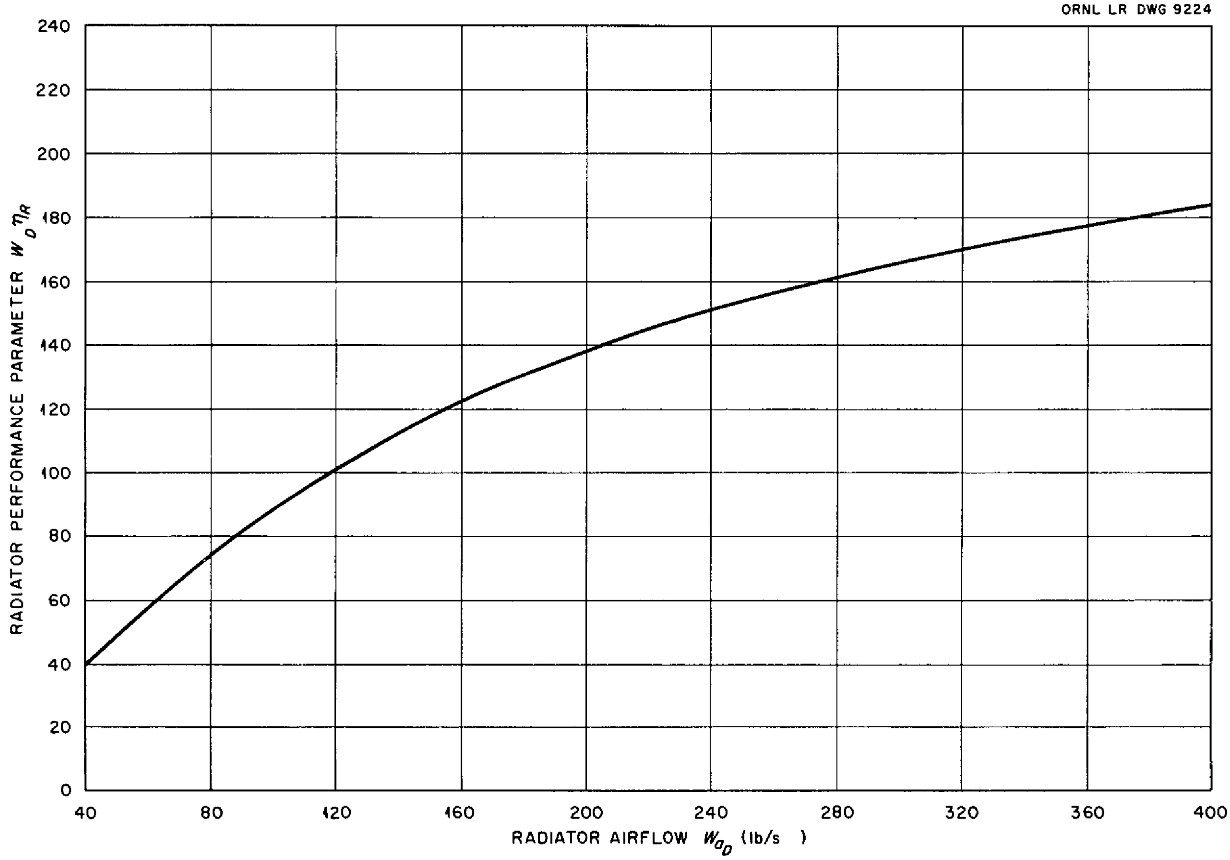

Fig B 1 Performance Parameter for X 61 Engine Radiator

APPENDIX C

STATIC STABILITY CALCULATIONS

The steady state power delivered by the reactor is related to the engine load quantities in the following way

(C 1) $$P_e = \frac{1}{1/W_{aD}C_a\eta_R + (1 - \eta_{HX})/\eta_{HX}W_{Ne}C_N - 1/2XW_FC_F}(T_{F\,v} - T_{T3})$$

Condition 1 – Variation of steady state power delivery with changes in engine speed when reactor control quantities are constant and throttling is by air bypass with pump speeds constant

In this case the quantities listed below are constant at the values shown in the reactor–J 71 engine power plant

η_{HX} = 0 8	X = 0 25
W_{Ne} = 142 2 lb/sec	W_F = 702 lb/sec
C_N = 0 25 Btu/lb °F	C_F = 0 27 Btu/lb °F
C_a = 0 26 Btu/lb °F	T_{Fav} = 1450°F

Substitution of these values into Eq C 1 yields

(C 2) $$P_e = \frac{1}{(3\,846/W_{aD}\eta_R) - 0\,003517}(1450 - T_{T3})$$

The $W_{aD}\eta_R$ product is a function of the total engine air flow which is a function of speed (Fig 7) and the air bypass percentage The variation of $W_{aD}\eta_R$ with W_{aD} at rated NaK flow is shown in Fig 21 Steady state compressor outlet temperature variation with speed is shown in Fig 7 Substitution of values for $W_{aD}\eta_R$ and T_{T3} at each speed into Eq C 2 yields the power delivery curves of Fig 20

Condition 2 – Variation of steady state power delivery with changes in engine speed when reactor control quantities are constant throttling is by NaK bypass and all pump speeds are constant

Equation C 2 applies in this case also The value for W_{aD} is the same as that for W_a (the total engine air flow) Variations of the $W_{aD}\eta_R$ product with W_{aD} at constant NaK bypass per centages are shown in Fig 21 The variations of T_{T3} and W_a with engine speed are shown in Fig 7 Substitution of these values into Eq C 2 yields the constant NaK bypass power delivery curves of Fig 19

Condition 3 – Variation of steady state power delivery with changes in engine speed when reactor control quantities are constant throttling is by NaK bypass and one or more pump speeds are proportioned to engine speed

Equation C 1 applies to this case The value for W_{aD} is equal to that for W_a (the total engine air flow) the variation of $W_{aD}\eta_R$ with radiator air flow is shown in Fig 21 variations of W_a and T_{T3} with engine speed are shown in Fig 7 and heat exchanger effectiveness values are calcu lated from the fuel and NaK flow rates and the heat exchanger effectiveness equation given on page 29

In calculating the power delivery curves of Fig 23 it was furthermore assumed that the mean fuel temperature T_{Fav} was held constant at 1450°F at all times by rod motion if necessary

[redacted]

and that the pump flows were proportional to the pump speeds Thus

$$W_F = \frac{702}{5680} N$$

$$W_{Ne} = \frac{142\ 4}{5680} N$$

Substitution of these expressions into Eq C 1 yields the desired relationship between power delivery and engine speed which is plotted for various pump drive combinations in Fig 23

[redacted]