LOW PRESSURE OXYGEN-HYDROGEN AUXILIARY PROPULSION SUBSYSTEMS

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INTRODUCTION

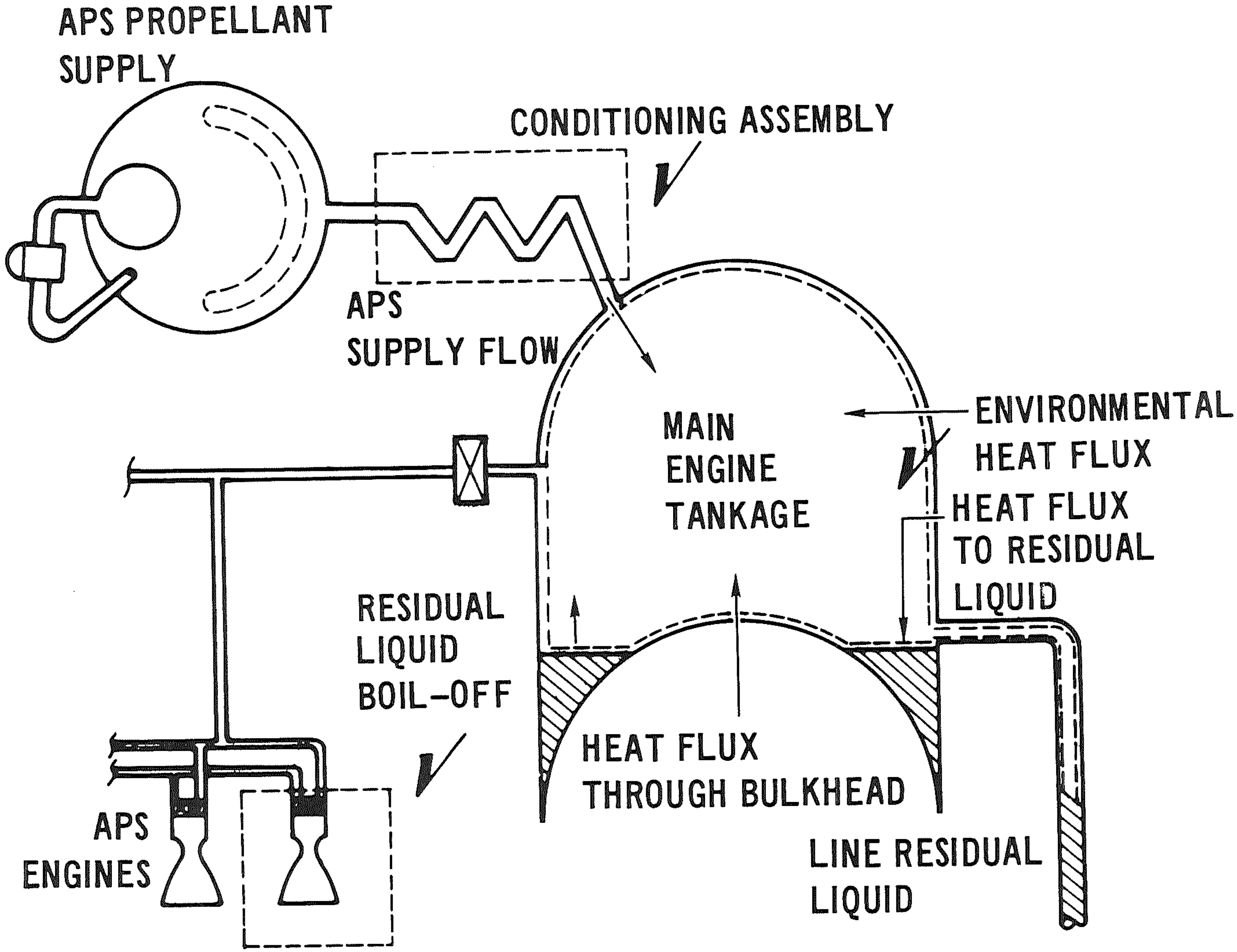
A PRIME CANDIDATE FOR THE AUXILIARY PROPULSION SUBSYSTEM OF THE SPACE SHUTTLE VEHICLE IS THE LOW PRESSURE CONCEPT WHICH TAKES ADVANTAGE OF THE MAIN BOOST TANK AS AN ACCUMULATOR, A HEAT EXCHANGER, AND A SOURCE OF PROPELLANT. DEFINITION OF THE LOW PRESSURE SYSTEM SUITABLE FOR THE ORBITER AND BOOSTER IS THE SUBJECT OF CONTRACTED EFFORT BY MSC AND MSFC WITH MDAC-EAST AND TRW. IN ADDITION, THIS APS CONCEPT WILL BE CONSIDERED AS A TASK IN THE PHASE B VEHICLE DEFINITION PROGRAM.

PRESENTED ARE THE RESULTS OF ANALYSIS THAT HAVE BEEN CONDUCTED ON THE SUBSYSTEM DISCUSSING ALTERNATIVE METHODS OF OPERATION AND THE TECHNOLOGY REQUIREMENTS FOR SOME OF THE COMPONENTS AND ASSEMBLIES WHICH MAKE UP THE SUBSYSTEM.

THE BASIC LOW PRESSURE SYSTEM CONCEPT IS SHOWN IN THE ACCOMPANYING FIGURE. THE MAIN ENGINE TANKAGE IS THE CENTRAL ELEMENT SERVING AS AN ACCUMULATOR, HEAT EXCHANGER, AND SOURCE OF PROPELLANT. THE ADDITIONAL PROPELLANT IS SEPARATELY STORED. AS A FUNCTION OF THE APPLICATION OR MISSION THIS ADDITIONAL PROPELLANT MAY REQUIRE CONDITIONING TO THE PRESSURE AND TEMPERATURE LEVELS REQUIRED BY THE THRUSTER. THE THRUSTERS FEED DIRECTLY FROM THE MAIN ENGINE TANK.

THIS DISCUSSION DEALS PRIMARILY WITH THE CONDITIONING ASSEMBLY AND THE BEHAVIOR OF THE MAIN ENGINE TANKAGE AND THE THRUSTER. FIRST THE THRUSTER.

BASIC LOW PRESSURE APS CONCEPT



THE THRUSTER REQUIREMENTS ARE OF COURSE DEPENDENT ON THE VEHICLE CONFIGURATION, THE MISSION AND THE HANDLING QUALITIES REQUIRED BY AND DESIRED OF THE VEHICLE. TYPICAL THRUSTER REQUIREMENTS ARE SHOWN IN THE ACCOMPANYING FIGURE. THESE REQUIREMENTS ARE IN GENERAL AGREEMENT WITH THE LOW PRESSURE THRUSTER TECHNOLOGY PROGRAMS BEING FUNDED BY LeRC AND WERE USED THROUGHOUT THIS STUDY.

WHAT THIS THRUSTER DESIGN MEANS TO OVERALL SYSTEM IN TERMS OF SYSTEM REQUIREMENTS IS SHOWN BY THE NEXT FIGURE.

TYPICAL THRUSTER OPERATING REQUIREMENTS

- THRUST LEVEL ____ 1500 LB
- CHAMBER PRESSURE ____ 20 psia
- MIXTURE RATIO ____ 3:1 O/F
- INLET PRESSURE ____ 25 – 30 psia
- INLET TEMPERATURE ____ 300 – 600 $^{\circ}R$
- THRUSTER INLET LINE SIZE ____ ~3 IN DIA O_2 & H_2
- THRUSTER MAIN SUPPLY LINE SIZE ____ ~6 IN DIA O_2 & H_2
- MAIN ASCENT TANK PRESSURE ____ 35 – 45 psia

THE CHARACTERISTICS OF THE GAS-GAS THRUSTER WHEN COUPLED TO THE FEED SYSTEM HAVE BEEN ANALYZED. THESE DATA SHOW THAT THE MOST SIGNIFICANT EFFECT OF CHANGES IN INLET CONDITIONS IS IN THE MIXTURE RATIO SHIFT CAUSED BY VARIATIONS IN INLET PRESSURE AND TEMPERATURE. AS SHOWN, THE EFFECT OF INLET PRESSURE IS EXTREME, AN OPPOSING VARIATION OF 1 PSI IN OXIDIZER AND FUEL CAUSING 1 UNIT SHIFT IN MIXTURE RATIO. SHIFTS OF THIS NATURE HAVE LARGE IMPLICATIONS IN THRUSTER DESIGN. HOWEVER, EVEN IF THE THRUSTER COULD ACCOMMODATE THESE SHIFTS WITHOUT PERFORMANCE PENALTIES, THE PENALTIES ASSOCIATED WITH TANKING FOR THE MR UNCERTAINTY WOULD BE APPRECIABLE. THE SLOPE OF THE CURVE INDICATES CONTROL OF PRESSURE AS A REQUIREMENT. THE CURVE ALSO SUGGESTS THAT A CONTROL METHOD WHICH CONSTRAIN VARIATIONS IN INLET PRESSURE TO BE LIKE VARIATIONS WOULD BE DESIRABLE.

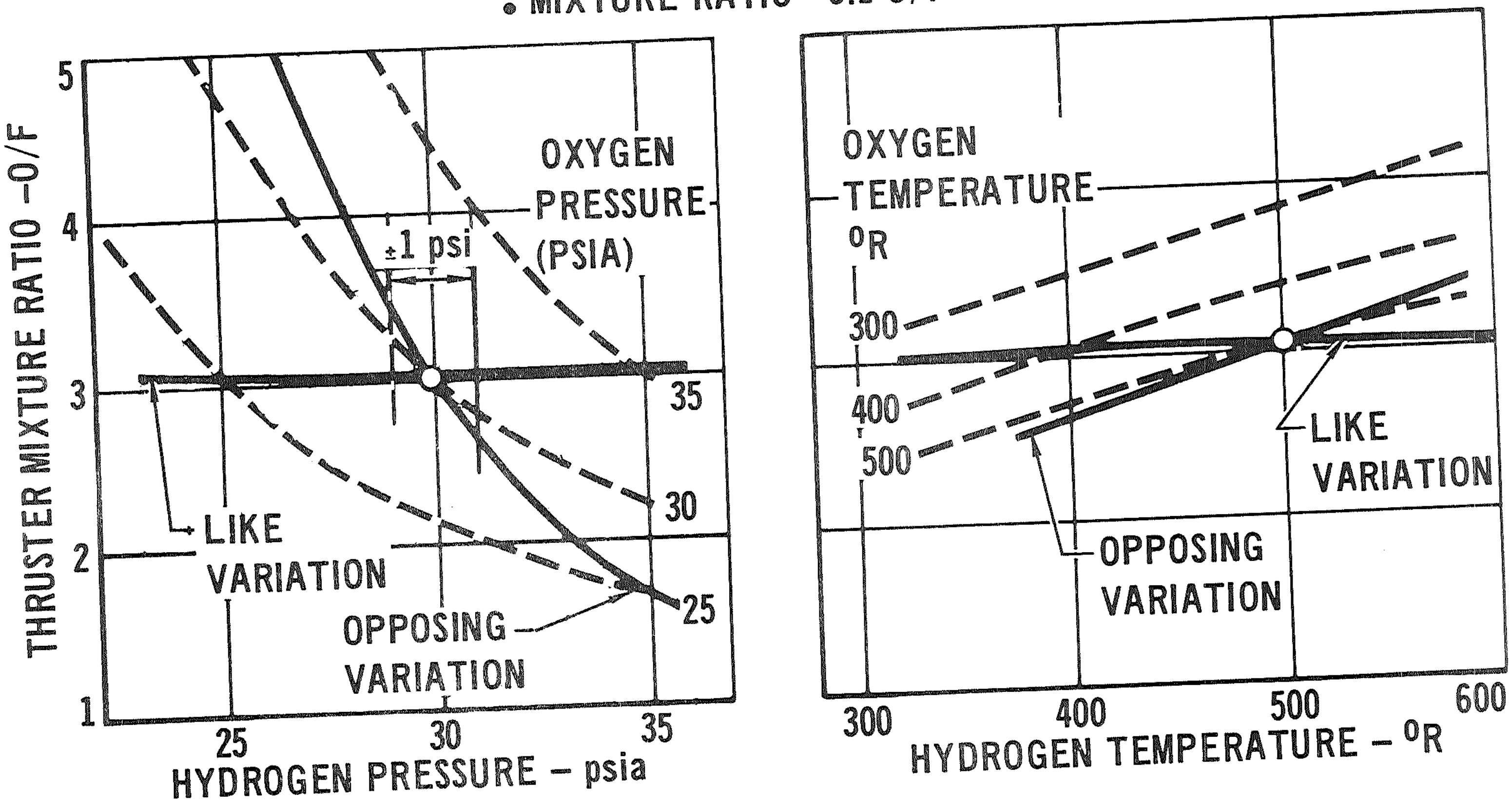
AS SHOWN IN THE FIGURE, THOUGH THE TREND WITH TEMPERATURE IS SIMILAR TO PRESSURE, THE CONSEQUENCE OF OPPOSING VARIATIONS IS SIGNIFICANTLY REDUCED. IT IS ANTICIPATED THAT THE TEMPERATURE VARIATION EXPERIENCED WILL APPROACH LIKE VARIATIONS DUE TO THE SIMILARITY OF THE BOOST TANK ENVIRONMENT. THE ABOVE STATEMENT ASSUMES THE CONDITIONING SYSTEM KEEPS BOTH PROPELLANTS AT THE SAME TEMPERATURE, 500°F, IN THE ILLUSTRATION. ANY VARIATIONS IN CONDITIONING SYSTEM PERFORMANCE WOULD BE REFLECTED AS AN OPPOSING VARIATION. THE SLOPE OF THE CURVE SUGGESTS A $\pm$50°R CONDITIONING SYSTEM TOLERANCE WOULD BE ACCEPTABLE.

RATHER PRECISE CONTROL OF THE OXIDIZER AND FUEL PRESSURES OR THE DIFFERENCE BETWEEN THEM IS REQUIRED. CONSIDERATION HAS BEEN GIVEN TO DOWNSTREAM REGULATION AND REGULATION BY MASS ADDITION.

THRUSTER MIXTURE RATIO SENSITIVITY

-AEROJET LIQUID ROCKET CO. DATA-

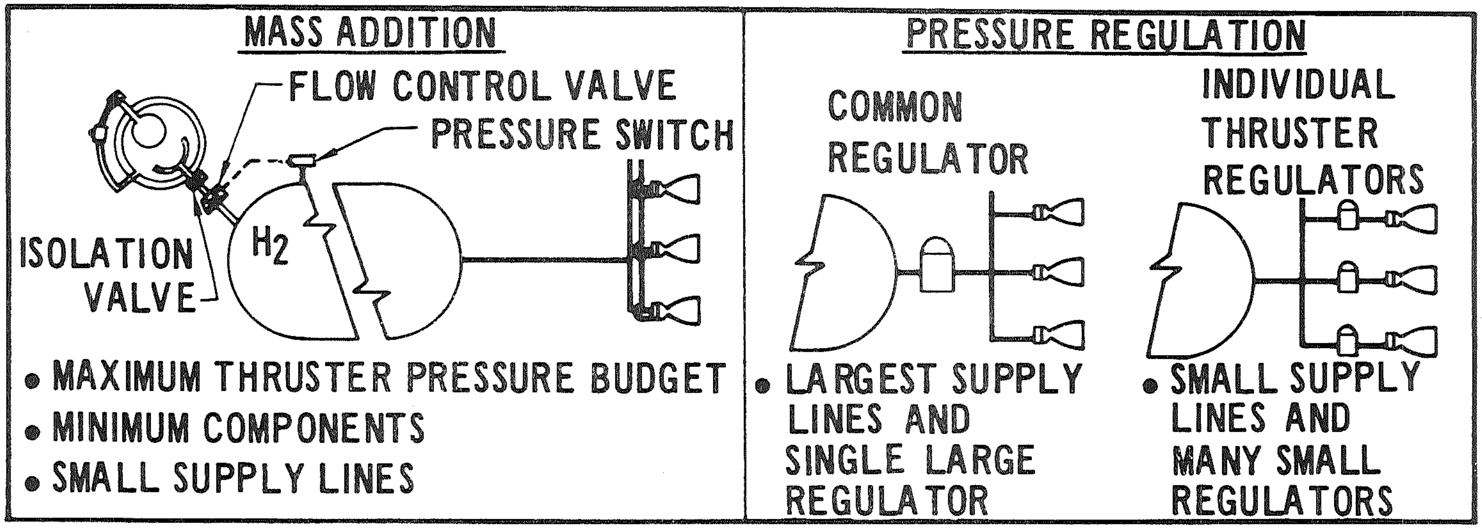
- THRUST – 1500 lb
- CHAMBER PRESSURE –20 psia
- MIXTURE RATIO –3:1 O/F



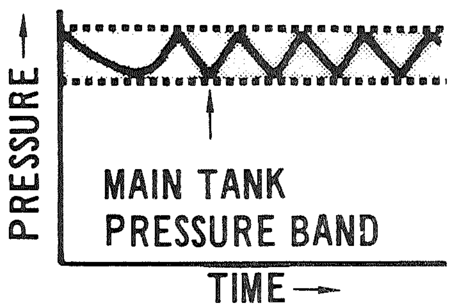
IN ALL CASES PRESSURE IN THE TANK IS CONTROLLED BY ADDING PROPELLANT TO THE TANK. THRUSTER INLET PRESSURE CAN THEN BE CONTROLLED EITHER BY REGULATION OF TANK PRESSURE WITHIN THE TIGHT BAND REQUIRED FOR MIXTURE RATIO CONTROL OR THE TANK PRESSURE BAND CAN BE WIDENED AND COMMON OR INDIVIDUAL THRUSTER REGULATORS ADDED DOWNSTREAM FOR CONTROL OF MIXTURE RATIO.

EACH CONCEPT HAS THE CHARACTERISTICS NOTED IN THE FIGURE AND EACH CONCEPT HAS LIMITATIONS AND PENALTIES ASSOCIATED WITH THOSE LIMITATIONS.

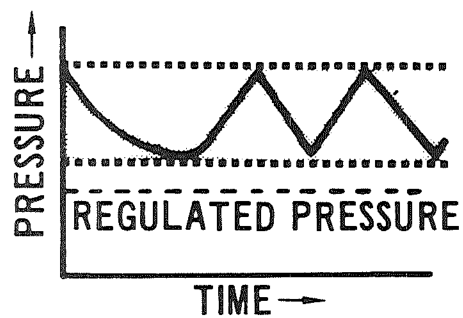
INJECTOR INLET PRESSURE CONTROL



TIGHT PRESSURE BAND



LARGE PRESSURE BAND

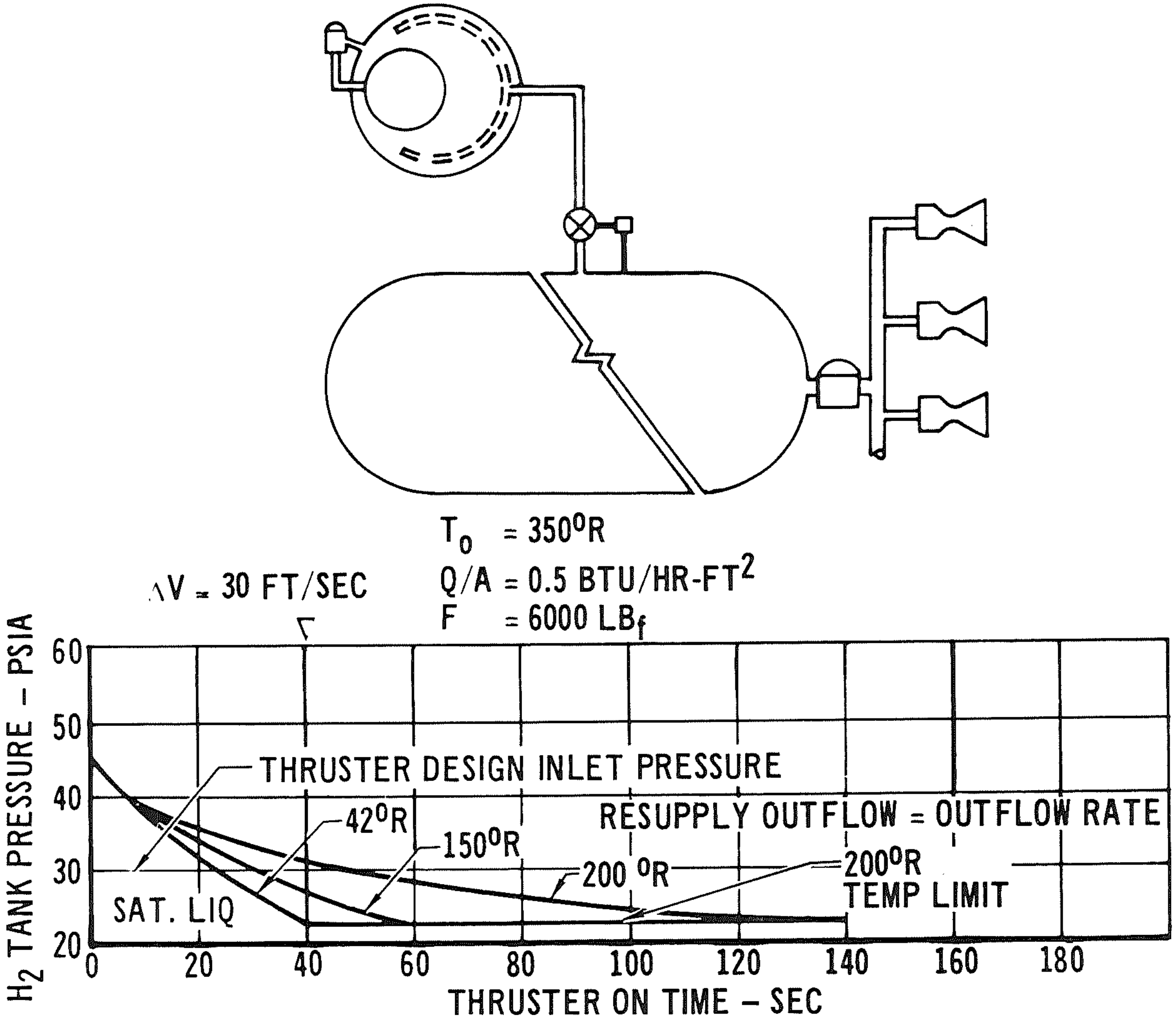


THE ADDITION OF PROPELLANT WITHOUT CONDITIONING, USING DOWNSTREAM REGULATION FOR CONTROL OF THRUSTER INLET PRESSURE AND MIXTURE RATIO, HAS THE INHERENT ADVANTAGE OF SYSTEM SIMPLICITY. HOWEVER, THIS SIMPLICITY IS GAINED AT THE COST OF LIMITING THE SINGLE BURN IMPULSE CAPABILITY OF THE SYSTEM. AS SHOWN IN THE FIGURE, INJECTING PROPELLANT AT SATURATION (HYDROGEN IN THE ILLUSTRATION) THE MAXIMUM SINGLE BURN IMPULSE THAT COULD BE OBTAINED IS 6000 LB THRUST OPERATING ABOUT 40 SECONDS, CORRESPONDING TO A ΔV OF APPROXIMATELY 30 FT/SEC FOR A TYPICAL ORBITER. THE DESIGN GOAL IS ABOUT 60 FT/SEC. THE MAXIMUM SINGLE BURN IMPULSE COULD BE EXTENDED TO THE LIMITS SHOWN ON THE CURVE BY PRECONDITIONING PROPELLANT.

PRACTICALLY THE LIMITATION ON SINGLE BURN IMPULSE IS SOMEWHAT SMALLER THAN QUOTED ABOVE. AT THE DESIGN POINT OF 30 PSIA MINIMUM THRUSTER INLET PRESSURE, THE LIMITATION WOULD BE EQUIVALENT TO A ΔV OF APPROXIMATELY 20 FT/SEC.

THE COST OF EXTENDING THE ΔV BY REDUCING THE NOMINAL THRUSTER CHAMBER PRESSURE OR INCREASING THE TANK PRESSURE TO ALLOW FOR A LARGER CHANGE IN TANK PRESSURE IS SHOWN ON THE NEXT FIGURE.

PRESSURE PROFILES WITH MASS ADDITION



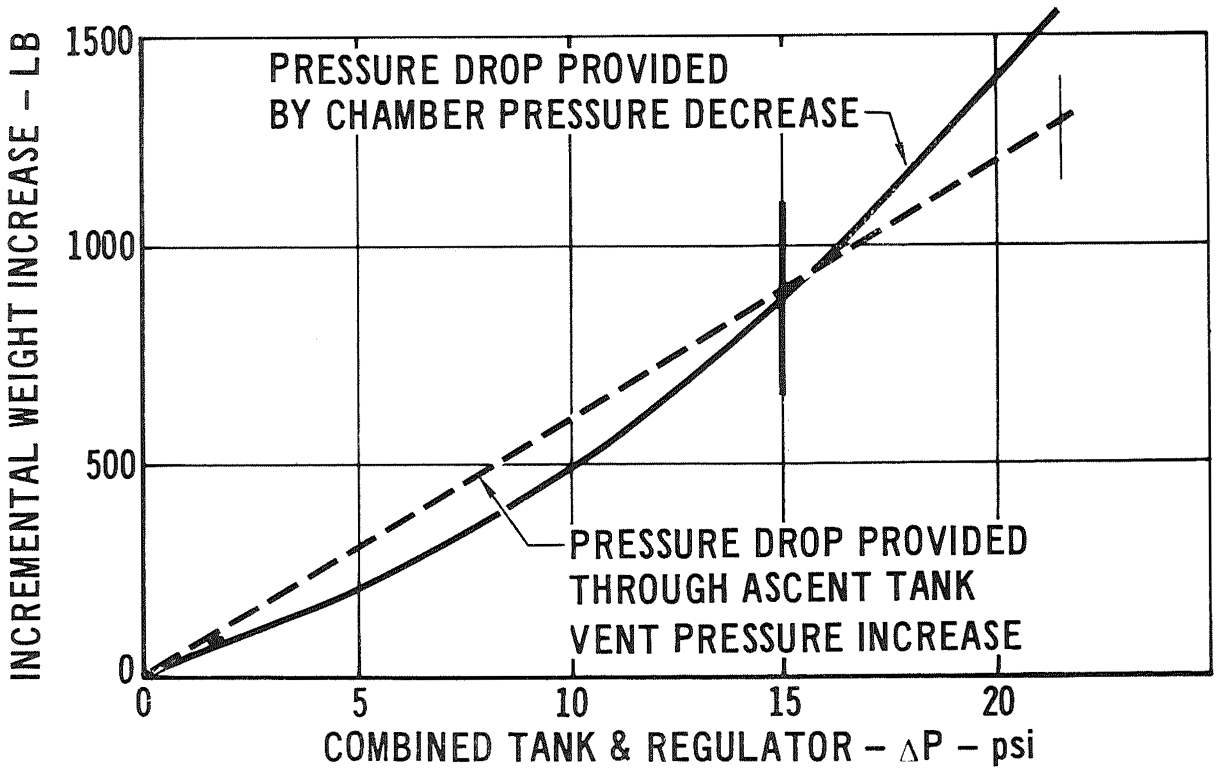
ILLUSTRATED IS THE WEIGHT PENALTY RESULTING FROM INCREASING THE ALLOWABLE PRESSURE DROP BUDGETED FOR TANK PRESSURE CHANGE PLUS REGULATOR PRESSURE DROP FOR A TYPICAL ORBITER. FROM THE DESIGN POINT DISCUSSED ON THE PREVIOUS CHART, THE SINGLE BURN ΔV COULD BE INCREASED FROM 20 FT/SEC TO 30 FT/SEC BY INCREASING THE TANK AND REGULATOR PRESSURE DROP FROM 15 PSI TO 22 PSI. THE WEIGHT PENALTY ASSOCIATED WITH THIS CHANGE WOULD BE 400-700 LBS INERT WEIGHT DEPENDING ON THE METHOD.

BASED ON THE MISSION TIME LINE OF THE VEHICLE DESCRIPTION DOCUMENT BEING USED FOR THE APS DEFINITION CONTRACTS, THE LOW PRESSURE APS WITHOUT CONDITIONING COULD ACCOMPLISH ALL OF THE ATTITUDE CONTROL AND STATION KEEPING FUNCTIONS FROM LAUNCH UNTIL REENTRY AT THE EXPENSE OF A MODERATE INCREASE IN SYSTEM INERT WEIGHT AND THE NECESSITY OF DEVELOPING PRECISE PRESSURE REGULATORS WITH LIFE CAPABILITIES EQUAL TO THE LIFE CAPABILITIES OF THE THRUSTER.

HOWEVER, FOR THE REENTRY PORTION OF THE MISSION, CURRENTLY STATED AS A ΔV OF 60 FT/SEC PRECONDITIONING OF THE PROPELLANT PRIOR TO INJECTION INTO THE ASCENT TANKS IS REQUIRED.

HARDWARE WEIGHT PENALTIES FOR REGULATION

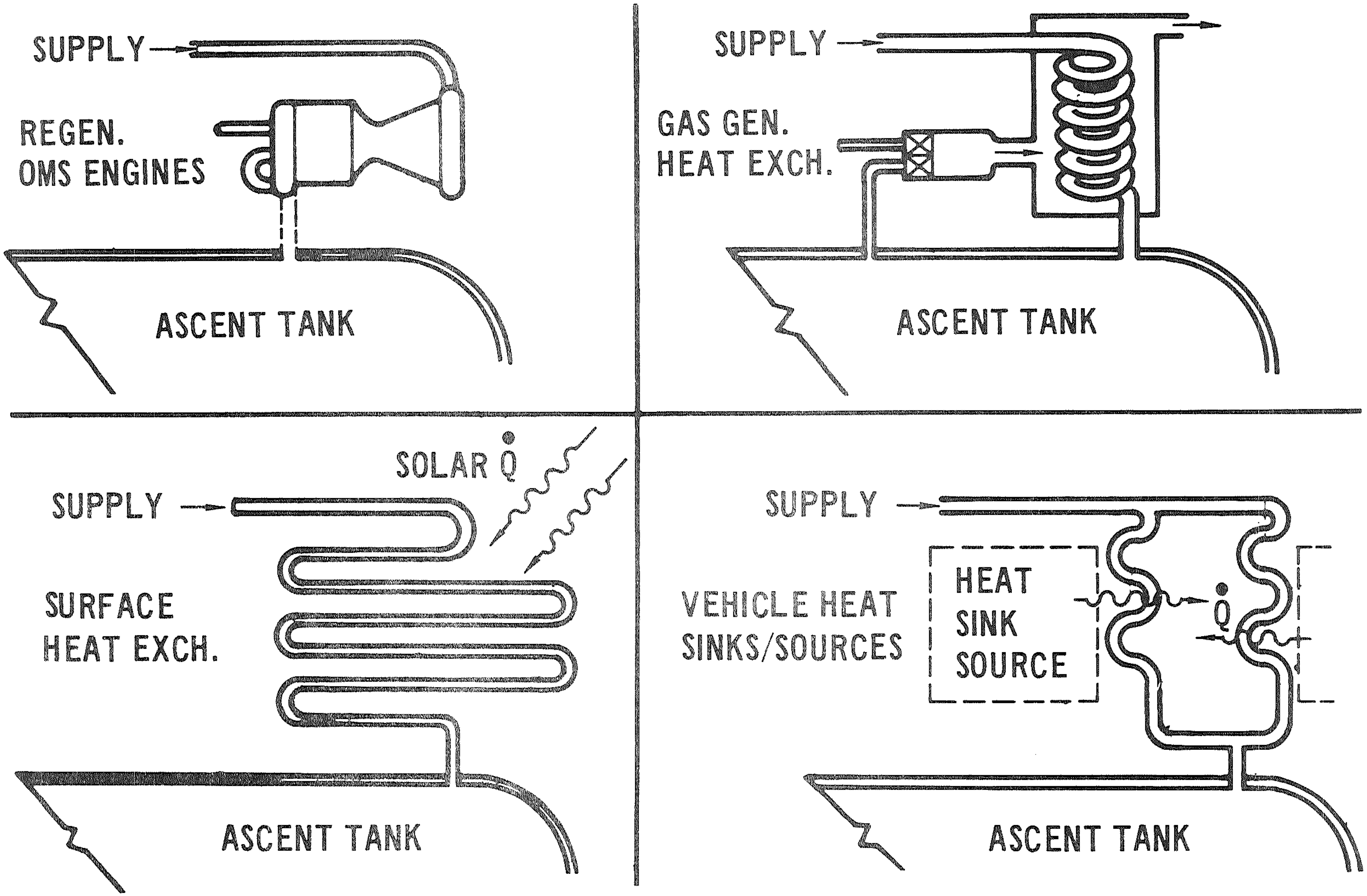
-COMMON REGULATOR CONCEPT-



PASSIVE AND ACTIVE CONDITIONING ASSEMBLY CONCEPTS ARE BEING ANALYZED. PASSIVE SYSTEMS INCLUDE SURFACE HEAT EXCHANGERS USING SOLAR ENERGY AND HEAT SINK TYPE HEAT EXCHANGERS USING THE VEHICLE STRUCTURE INCLUDING THE ASCENT TANK AS AN ENERGY SOURCE.

ACTIVE SYSTEMS BEING CONSIDERED ARE SHOWN IN THE UPPER HALF OF THE CHART. THEY RANGE FROM THE HIGHLY INTEGRATED REGENERATIVE SYSTEM WHERE THE ENGINES FOR +X AXIS MANEUVERS ARE USED AS HEAT EXCHANGERS TO PRECONDITION THE PROPELLANT FOR STORAGE IN THE MAIN TANK TO THE RELATIVELY STRAIGHT FORWARD SYSTEM WHERE A SEPARATE LOW PRESSURE GAS GENERATOR CONDITIONS THE PROPELLANT BEFORE STORAGE IN THE MAIN TANK.

CONDITIONING ASSEMBLY CONCEPTS

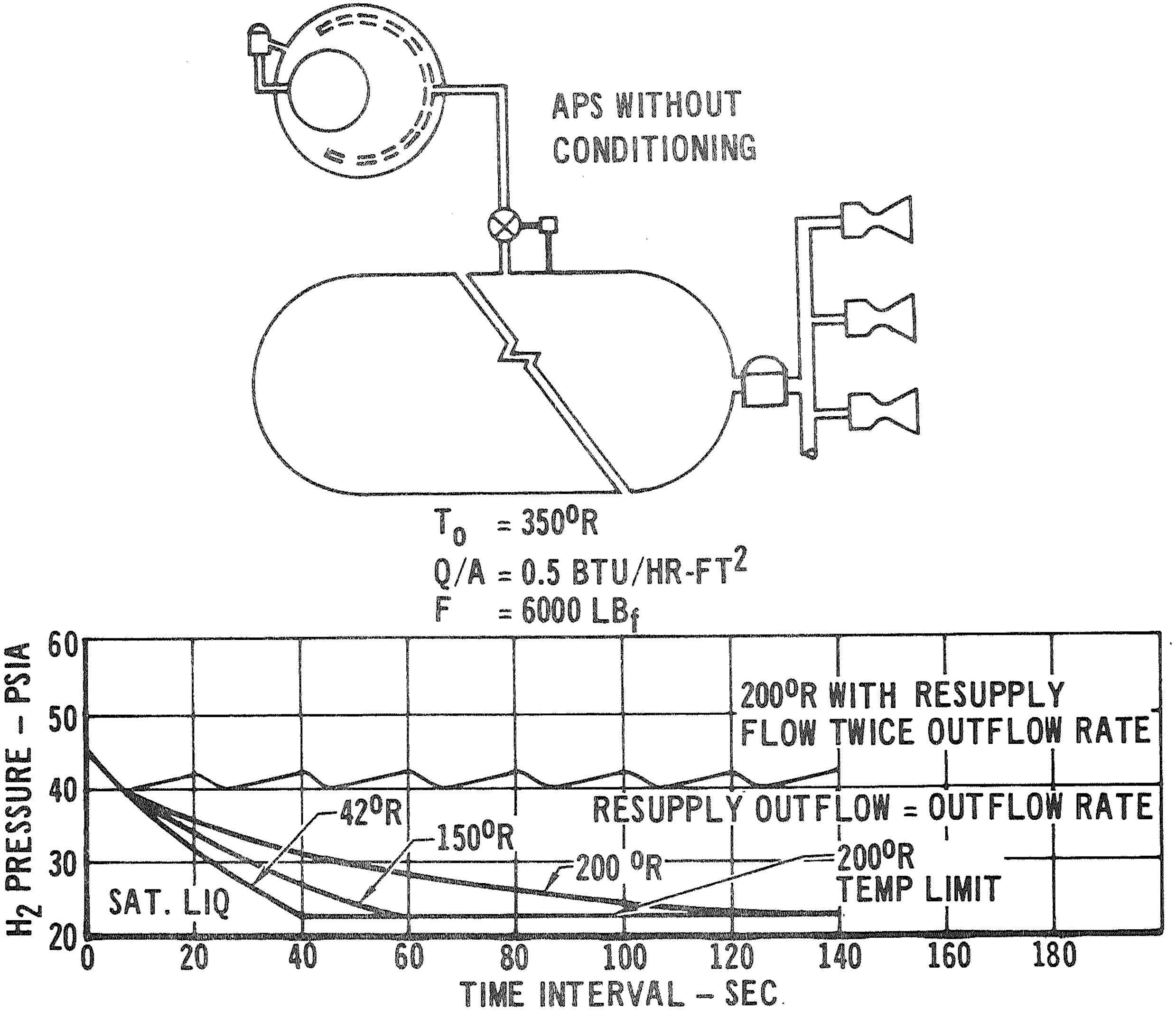


WHAT THE CONDITIONING SYSTEM IS REQUIRED TO DO IS TO EXTEND THE SINGLE BURN IMPULSE CAPABILITY OF THE SYSTEM. THIS CAN BE ACCOMPLISHED BY PARTIALLY CONDITIONING THE PROPELLANT ALONG THE 150°R AND 200°R LINES SHOWN ON THE FIGURE. HOWEVER, IN THIS CASE, AS PREVIOUSLY DISCUSSED, A DOWNSTREAM REGULATOR IS REQUIRED FOR MR CONTROL AND THE RESULTING SUBSYSTEM HAS THE COMPLICATIONS OF BOTH GAS PRESSURE REGULATION AND CONDITIONING.

AN ALTERNATIVE IS TO CONDITION THE PROPELLANT WITHIN THE PRESSURE LIMITS REQUIRED FOR MIXTURE RATIO CONTROL WITHOUT DOWNSTREAM REGULATORS.

APPROACHES TO THIS ALTERNATIVE ARE DISCUSSED ON THE FOLLOWING TWO CHARTS.

PRESSURE PROFILES WITH MASS ADDITION



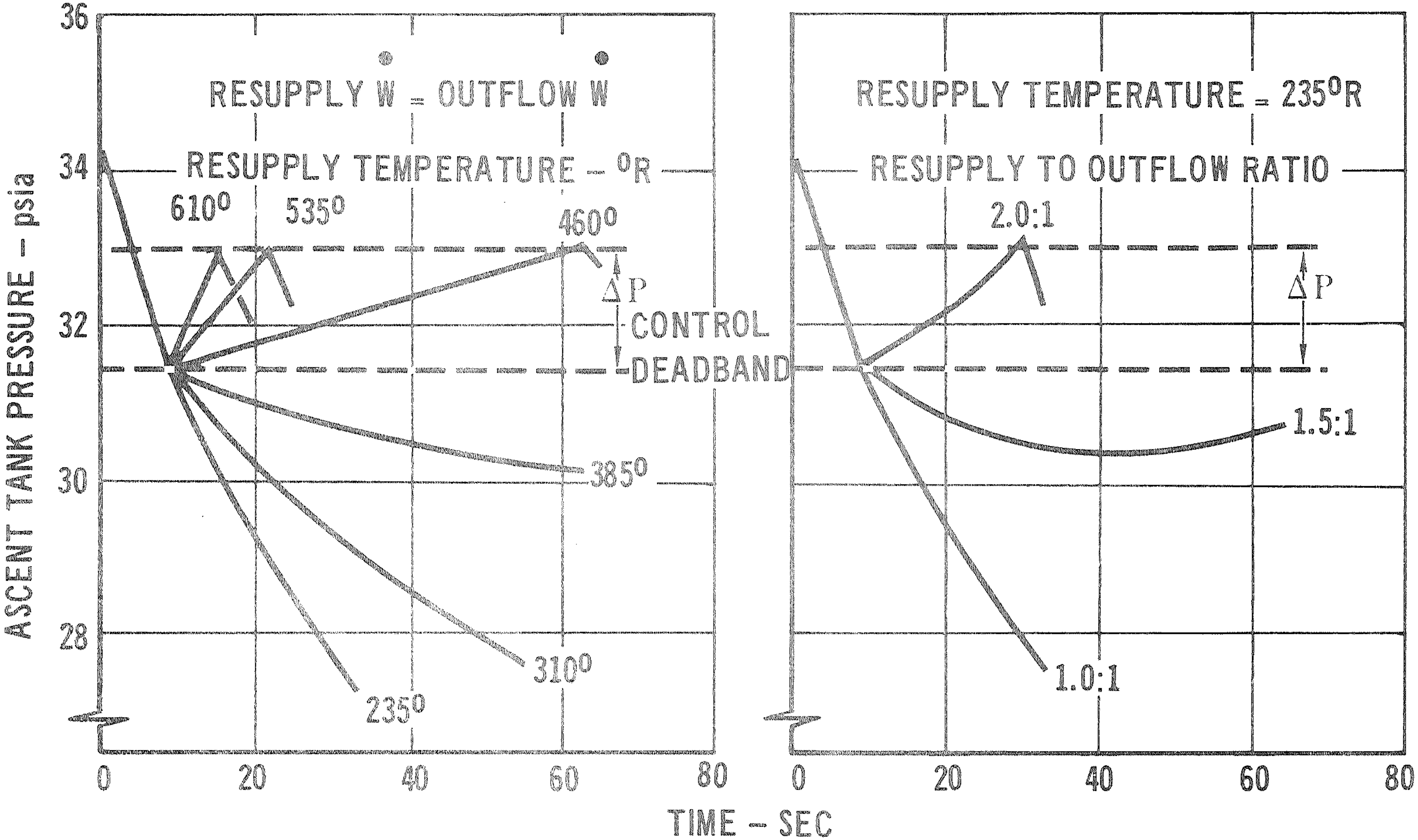
THE RESUPPLY CAN BE AT A RATE EQUAL TO THE OUTFLOW AND THE TEMPERATURE ADJUSTED TO MAINTAIN PRESSURE WITHIN THE PRESCRIBED LIMITS OR, AT A FIXED CONDITIONING TEMPERATURE, THE RESUPPLY FLOW RATE CAN BE ADJUSTED TO MAINTAIN TANK PRESSURE. THE ALTERNATIVES ARE SHOWN IN THE CURVES OF THE CHART.

FOR THE CASE OF RESUPPLY FLOW EQUAL TO OUTFLOW, A CONDITIONING TEMPERATURE OF APPROXIMATELY 460°R IS REQUIRED TO MAINTAIN TANK PRESSURE WITHIN THE CONTROL DEAD BAND. LOWER TEMPERATURES CAUSE PRESSURE DECAYS AS A RESULT OF REDUCING GAS TEMPERATURE. HIGHER TEMPERATURE CAUSES REPEATED CYCLING OF THE CONDITIONING SYSTEM.

FOR EVERY TEMPERATURE LINE THERE IS A RATIO OF INFLOW/OUTFLOW THAT CAN BE USED TO MAINTAIN TANK PRESSURE WITHIN THE REQUIRED LIMITS. FOR THE CASE OF 235°R RESUPPLY TEMPERATURE, THE INFLOW IS TWO TIMES THE OUTFLOW. THE PENALTY OF THIS SYSTEM WOULD BE VENTING OF EXCESS PROPELLANT DURING WARM-UP FOLLOWING SHUTDOWN.

THE TRADE BETWEEN VENT PROPELLANT AND CONDITIONING PROPELLANT REQUIRED IS SHOWN IN THE NEXT FIGURE.

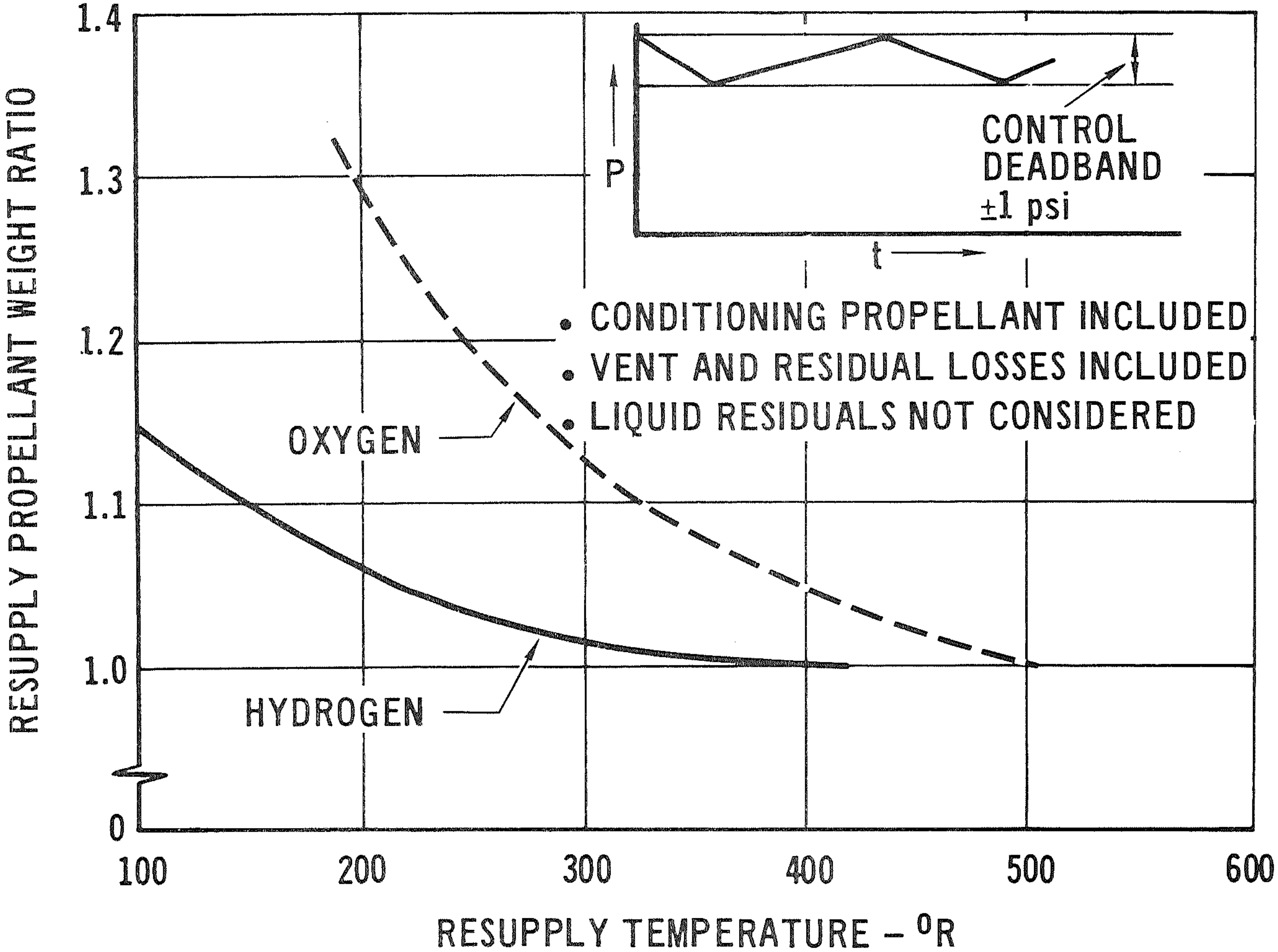
EFFECT OF RESUPPLY CONDITIONS ON OPERATION
ASCENT SYSTEM O_2 TANK



THE TRADE OF PROPELLANT REQUIRED FOR CONDITIONING OF THE IMPULSIVE PROPELLANT VS THE VENT LOSSES AND INCREASED GAS RESIDUALS LEADS TO THE CONCLUSION THAT FOR MANEUVERS APPROACHING 50 FT/SEC A CONDITIONING TEMPERATURE APPROACHING AMBIENT TEMPERATURE IS MOST DESIRABLE. THIS TREND IS ILLUSTRATED BY THE CURVE OF CHART. THE POINT AT 500°R IS AN ARBITRARY REFERENCE POINT.

EFFECT OF CONDITIONING TEMPERATURES ON RESUPPLY

-ORBITER - ≤ 50 FPS MANEUVERS-



THE EFFECT OF ASCENT TANK HEATING RATE ON SYSTEM PERFORMANCE HAS BEEN EXAMINED TO DETERMINE THE EFFECT ON SYSTEM OPERATION AND PERFORMANCE. AS ILLUSTRATED BY THE CURVES, DURING THE THRUSTER FIRING AN ORDER OF MAGNITUDE CHANGE IN HEAT FLUX HAS LITTLE IMPACT ON THE AMOUNT OF TOTAL IMPULSE AVAILABLE WITHOUT PROPELLANT CONDITIONING.

DURING NONUSE HOWEVER, AN ORDER OF MAGNITUDE CHANGE IN HEAT FLUX WOULD EFFECT THE TIME TO VENT BY AN ORDER OF MAGNITUDE. IN THE PRACTICAL SENSE THE PROPELLANT IN THE TANK WILL COME TO EQUILIBRIUM WITH THE ENVIRONMENT THUS THE VENT LOSSES WILL ALWAYS OCCUR IF THE PROPELLANT IS CONDITIONED TO A TEMPERATURE LESS THAN THE TEMPERATURE OF THE ENVIRONMENT.

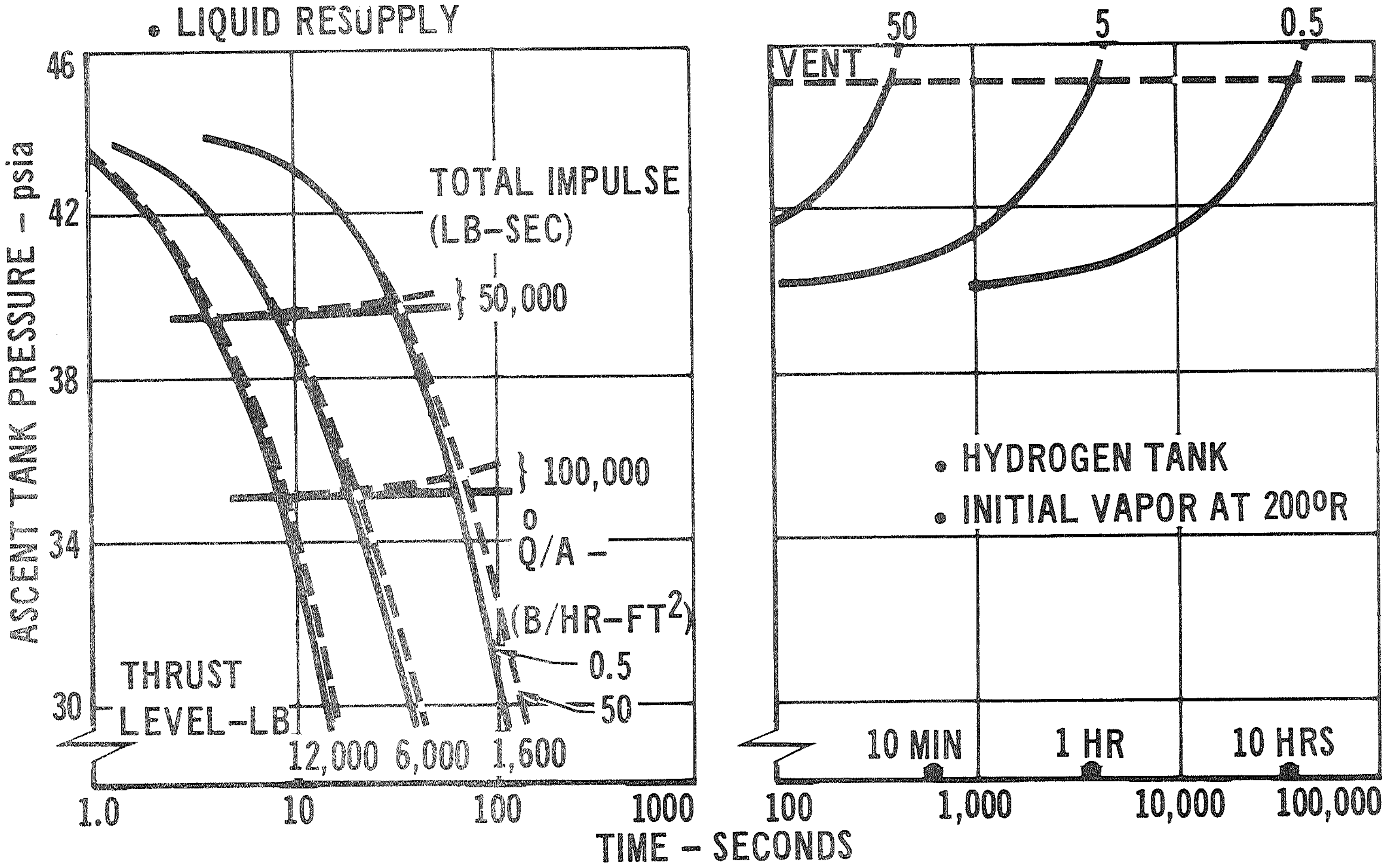
EFFECT OF ASCENT TANK HEATING RATE

DURING THRUSTER FIRING

- HYDROGEN TANK
- NO THERMAL CONDITIONING
- LIQUID RESUPPLY

DURING NON-USE PERIODS

$\dot{Q}/A$ -(B/HR-FT^2)



A CRITICAL ELEMENT IS THE REGULATION ASSEMBLY. THE PERFORMANCE REQUIREMENTS ARE GIVEN IN THE FIGURE. CRITICAL AND BEYOND THE STATE OF THE ART ARE THE ACCURACIES AND CYCLE LIFE REQUIREMENTS. THE ACCURACY REQUIREMENTS GIVEN ARE REQUIRED TO ATTAIN ABOUT A 2% PROPELLANT OUTAGE DUE TO MR UNCERTAINTIES. THE REQUIREMENTS ON LIFE VARY WITH THE SYSTEM CONCEPT. THE PROMISE OF LOWER CYCLE LIFE AND LINE SIZE ON THE LIQUID RESUPPLY REGULATION SYSTEM IS ATTRACTIVE. HOWEVER A PROPELLANT CONDITIONING SYSTEM WILL PROBABLY BE REQUIRED WITH THIS SYSTEM TO MINIMIZE VENT LOSSES AND, AS A FUNCTION OF THE APPLICATION, TO ATTAIN SUITABLE SINGLE BURN TOTAL IMPULSE CAPABILITY.

CONDITIONING SYSTEM REQUIREMENTS ARE GIVEN. SIGNIFICANT EXPERIMENTAL WORK WITH LOW PRESSURE HEAT EXCHANGERS OF THE REQUIRED CAPACITY HAS NOT BEEN ACCOMPLISHED.

PRESSURE CONTROL
- CONDITIONING ASSEMBLY SUMMARY
-LOW PRESSURE APS-

PRESSURE CONTROL REQUIREMENTS	SINGLE REGULATOR	THRUSTER REGULATORS	RESUPPLY REGULATOR
OPERATING PRESSURE	30–45 PSI	→	→
CONTROL ACCURACY	±0.5 PSI	→	→
FLOW RATE – OXYGEN	12 LB/SEC	3 LB/SEC	12 LB/SEC
– HYDROGEN	4 LB/SEC	1 LB/SEC	3 LB/SEC
TYPICAL LINE SIZE	6" DIA	3" DIA	1–2" DIA
*CYCLE LIFE	4	1	1/100
*RESPONSE	10–15 MS	10–15 MS	200–500 MS

CONDITIONING ASSEMBLY REQUIREMENTS	
FLOW RATE – OXYGEN	12 LB/SEC
– HYDROGEN	4 LB/SEC
OPERATING PRESSURE	30–45 PSI
OPERATING TEMPERATURES	300–600 ^oR
*CYCLE LIFE	1/100

*REFERENCED TO THRUSTER LIFE REQUIREMENT AND THRUSTER VALVE RESPONSE OF 10–15 MS.

CONCLUSIONS

1. REGARDLESS OF THE APPLICATION PRESSURE REGULATION IS REQUIRED.
2. THE PRESSURE REGULATION CONCEPT SHOULD CONSTRAIN OXIDIZER AND FUEL PRESSURE TO VARY IN SAME DIRECTION FOR BEST CONTROL OF OUTAGE.
3. CONDITIONING IS REQUIRED FOR MANEUVERS GREATER THAN 30 FT/SEC.
4. CONDITIONING TO AMBIENT TEMPERATURE MINIMIZES THE VEHICLE – SUBSYSTEM PERFORMANCE INTERFACE AND RESULTS IN MINIMUM SYSTEM WEIGHT.