TECHNOLOGY ISSUES FOR SHUTTLE MAIN ENGINE - STAGE INTEGRATION

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Introduction

The development goal of the Space Shuttle vehicle is to provide a flexible, high utility, low cost space transportation system. Achievement of the goal depends on early consideration of engine-stage capabilities in the imposed environments. Disciplines involved in integration considerations include structural design, thermal protection, materials, cryogenics, aerodynamics, launch support, maintenance and reliability. Discussions on propellant thermal conditioning, engine-stage dynamics and response, and base thermal environment will present an assessment of the existing technology base, illustrate potential problems and suggest technology tasks and approaches that may enhance the development of a main propulsion system.

- Propellant Thermal Conditioning
- Engine-Stage Dynamics And Response
- Base Thermal Environment

Propellant Thermal Conditioning

Feedline geyser suppression and propellant quality control are considerations critical to the engine-stage integration. A geyser results from the formation of a Taylor bubble in a line filled with boiling liquid. When the Taylor bubble fills a majority of the cross section of the line, it reduces the pressure on the fluid below, which feeds the Taylor bubble by flash boiling and "burps" fluid from the line. Geyser suppression is essential since the hydraulic forces produced during refill of long vertical LOX feedlines can greatly exceed the design loads. For example, S-IC LOX feedline geysers resulted in pump inlet pressures approaching 1400 psi.

Orbiter main-engine start requirements for propellant thermal conditioning are primarily to prevent vapor from forming in feed systems. The loss of accelerationhead pressure at booster cutoff will cause propellant "flashing" if the feed system propellants are superheated at tank pressures. Vapors would then have to be ingested by the engine pumps during the engine start. The more severe thermal conditioning requirements of the orbiter may dictate booster feedline designs due to the common engine concept.

The mechanics of geysering and the controlling geometric and environmental parameters have been established.[1] The geyser-nongeyser region correlation, presented on chart 3, can be used as preliminary design criteria for prelaunch conditioning of propellant feedlines. The existing geyser-nongeyser region correlation was developed for vertical feedlines, and modifications to the correlation may be required to establish utility for line configurations with significant horizontal runs or multiple branches. Propellant thermal conditioning systems used to suppress feedline geysers and control propellant quality are summarized on chart 4. These approaches may be applicable to the Shuttle vehicle if complex sequence schemes and single point failure modes are avoided.

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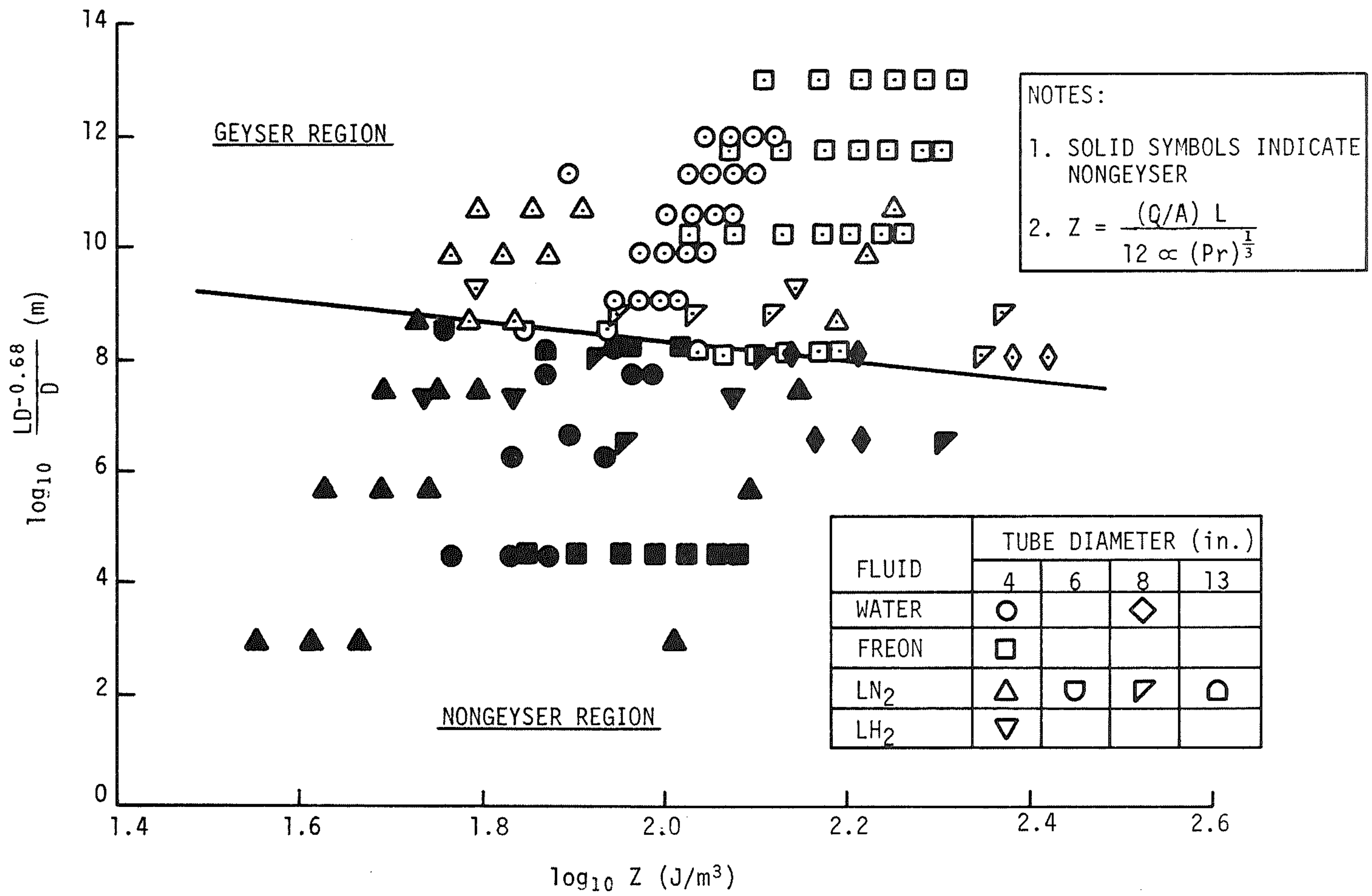
[1] Murphy, D. W., "Mechanics of Geysering of Cryogenics," Final Report NAS8-5418, June 1964.

Propellant Thermal Conditioning

- Requirement
    - Feedline Geyser Suppression - Prelaunch
    - Propellant Quality Control - Ignition
- Technology Status
    - Geyser-Nongeyser Criteria Established
    - Systems Available To Provide Subcooled Propellants

GEYSER-NONGEYSER CORRELATION



Propellant Thermal Conditioning

- Technology Application

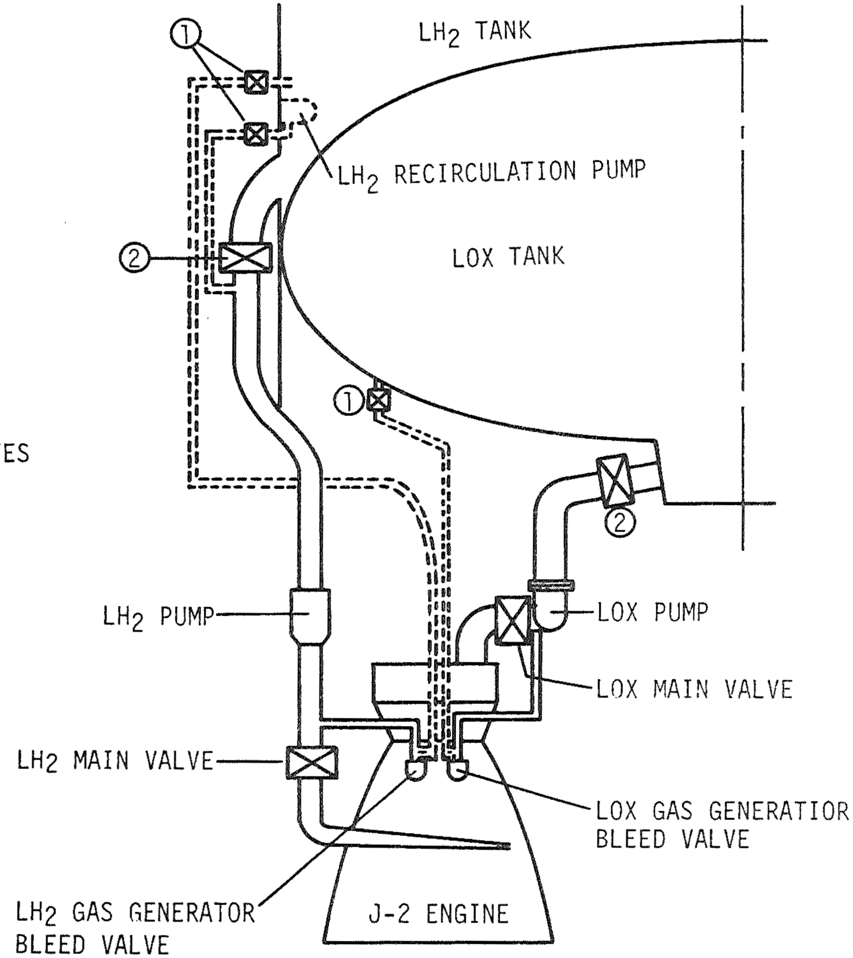
Method	Geyser Suppression	Quality Control	Shuttle Application
Subcool Replenish		Atlas (LO_2)	Constraint - Load/Facility
Recirculation - Natural	S-IC (LO_2)	S-II (LO_2) Atlas (LO_2)	Booster/Orbiter
- Forced		S-IVB (LO_2/LH_2) S-II (LH_2) Centaur	Orbiter
Evaporative Cooling	S-IB (LO_2)	S-IV (LO_2)	Limited Utility
Overboard Dump		S-IV (LH_2) Centaur	Impact - Payload/Abort

- Additional Geyser Suppression Schemes Are Being Investigated (NAS10-7258)

Propellant Thermal Conditioning

The Saturn S-II stage recirculation systems are typical. The thermal conditioning of the LO_2 feed system is accomplished by natural recirculation. Forced recirculation of the LH_2 feed system is provided by an electric motor driven pump. LH_2 flows through the prevalve by-pass line, feedline, pump, pump discharge line, and the tank return line. A few seconds prior to engine ignition, the LH_2 prevalve is open to flush any vapor trapped upstream of the prevalve into the tank.

PROPELLANT FEED SYSTEM



① RECIRCULATION VALVES
② PREVALVES

Propellant Thermal Conditioning

Propellant thermal conditioning considerations of engine-stage integration can impact the main engine technology program. Without propellant quality control, the propellant densities can vary over an order of magnitude. The technology required to develop mixture ratio control capability for these possibilities must be weighed against the degradation in vehicle reliability or maintainability resulting from implementing an optimum thermal conditioning system. "Flight-development" with the attendant failure risks may be required since the booster cutoff transient and the zero g environment cannot be simulated. Also, commonalty of booster and orbiter engines must be maintained. Past programs avoided these technology tasks and flight development risk by accepting the additional interfaces required to circulate bulk propellants through the feed system and back into the propellant tanks to effect continuous thermal conditioning.

Propellant Thermal Conditioning
Technology Issue

Conditioning System Reliability/Maintainability	Versus	Main Engine Development Cost
• Natural Recirculation - Stage/Engine Interface - Feedline Interconnects • Subcool Replenish (Booster Only) - Operational Constraint - Engine Interconnects • Forced Recirculation - Pump/Power/Controls - Stage/Engine Interface - Feedline Interconnects		• Mixture Ratio Control During Start - Fluid Dynamics - High Vapor Volume Pumping • Inherent Development Flight Risks - Limited 1g Simulation - Commonalty

Engine-Stage Dynamics and Response

Engine-stage integration studies to evaluate the dynamics and response characteristics of the propulsion system in the advanced development phase may preclude incompatibility of engine and stage designs and minimize potential for vehicle instability. A major redesign of the Saturn V booster (S-IC stage) resulted from the development of an engine control system that preceded and neglected stage considerations. The belated engine-stage integration analysis, indicated that the NPSH requirements would not be satisfied during the start transients. A portion of the LOX feedline was increased from 17 to 20 inches in diameter to successfully integrate the F-1 engine into the S-IC stage.

The POGO phenomena, a longitudinal vehicle stability problem induced and sustained by interaction of the structure, feedline and engine during flight, has been encountered on most liquid propellant launch vehicles. The Atlas, Titan and Saturn V (S-IC) oscillation amplitudes in the primary vehicle modes exceeded design limits for either payloads or crew. Saturn V (S-II stage) oscillations were experienced in stage modes that impacted performance and local structure. Multiple engine configurations, large range of operating parameters, and wide variations in payloads increase the potential for POGO. Therefore, the evaluation of the response characteristics of propulsion system should be a prime consideration in technology and advanced development planning.

Mathematical modeling techniques applicable to the physical elements of the propulsion system are adequate. A transient model of the propulsion system derived from engine and stage design data then updated and validated with component and subsystem data will support early engine-stage integration studies. These early studies will establish the sensitivity of mixture ratio control parameters to stage configurations and isolate engine control system concepts applicable to both booster and orbiter stages.

A comprehensive summary evaluation of vehicle stability technology, suggested stability criteria and recommended practices to achieve stability has been compiled.[2]

[2] Rubin, S., "Suppression of Structure-Propulsion Instability (POGO)," NASA Space Vehicle Design Criteria Program in Structure Contract NAS1-6024, May 1970.

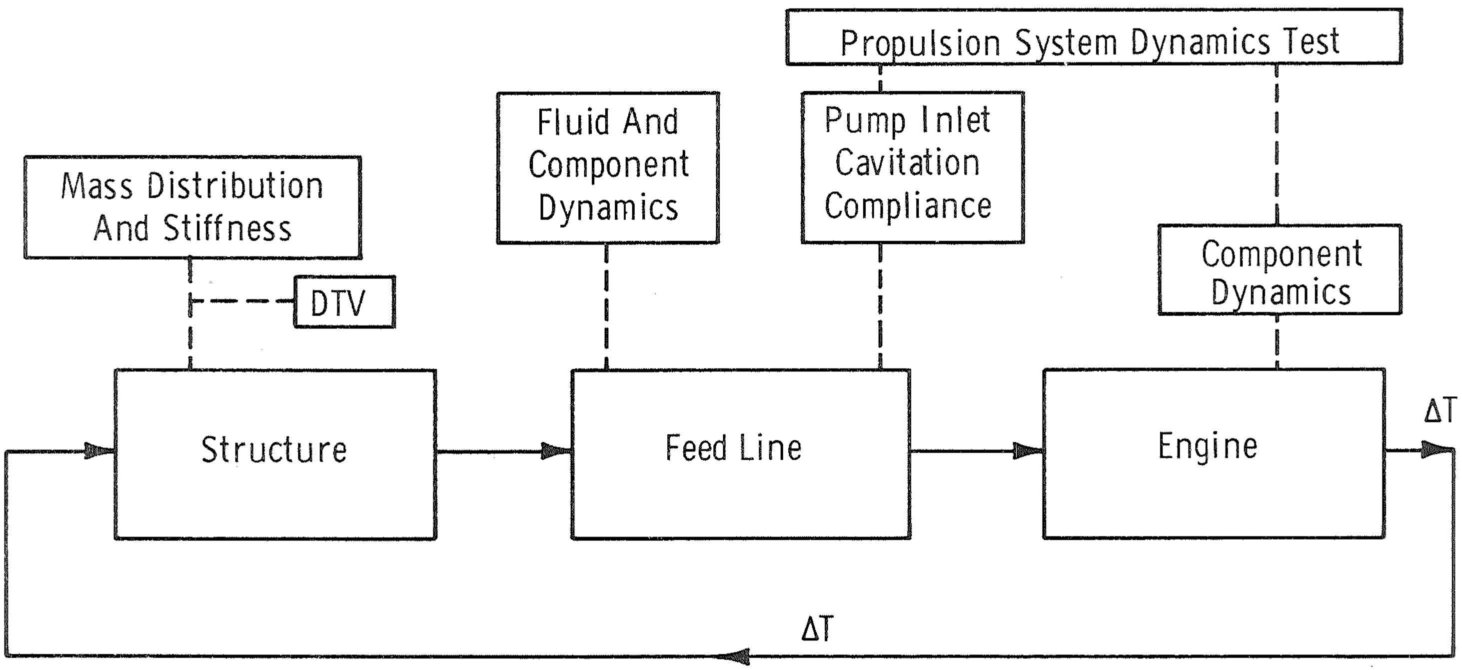
Engine-Stage Dynamics And Response

- Requirement
  - Engine/Stage Compatibility - Start, Cutoff, Throttling
  - Longitudinal Stability (POGO)
- Technology Status
  - Dynamic Modeling Techniques Available
  - POGO Stability Analytical Techniques And Criteria Established

Engine-Stage Dynamics and Response

The POGO block diagram represents the important elements of the linear closed loop stability model and the source of essential input data. The structural model, developed from mass distribution and stiffness data, is validated by results from a dynamic test vehicle (DTV). The feedline and engine models are developed from component design or performance data. The pump inlet cavitation compliance dominates the feedline frequency but cannot be analytically described. Therefore, numerical evaluation of the pump compliance is accomplished by flow perturbation tests (pulsing) on engine or pump facilities that duplicate or dynamically simulate the stage feedlines.

POGO Block Diagram



Engine-Stage Dynamics and Response

Engine-stage integration studies initiated in the technology or advanced development programs should define engine characteristics applicable to booster and orbiter configurations. Engine development facilities that dynamically simulate stage feedlines could minimize previous integration problems.

Stability analyses conducted in the development phase will be supported by immature data. However, judicious application of the present technology base can indicate stability trends in the primary vehicle modes and the capability of engine and stage components to suppress oscillations. Since analytical evaluation of pump cavitation compliance for a new pump is not presently possible, Saturn data is being used to develop analytical or semi-emperical relationships between component and fluid parameters and the cavitation compliance (NAS8-26266). Also, an alternate approach to flow perturbation (pulsing tests) to experimentally define the response characteristics of a new propulsion system can be applied. This alternate approach utilizes the low level random oscillations from engine development test to isolate the system characteristics. A comparison of the feedline frequencies obtained from pump inlet measurements on non-pulsing and pulsing tests for Saturn propulsion systems is presented in chart 10. Characteristics adequate for preliminary engine/stage integration studies may be obtained from Shuttle main engine development tests by close-coupled instrumentation and accurate data acquisition and reduction.

Engine technology programs should include feasibility studies of active controllers that cancel or suppress flow perturbations within the engine system. The prime advantages of a wide range active controller is to negate the requirement for early isolation of the unstable vehicle mode. A secondary advantage is simultaneous development with the engine, thus, benefiting from extensive engine testing. The disadvantage is that the amplitude of an instability must increase to a finite level in order for the controller to function.

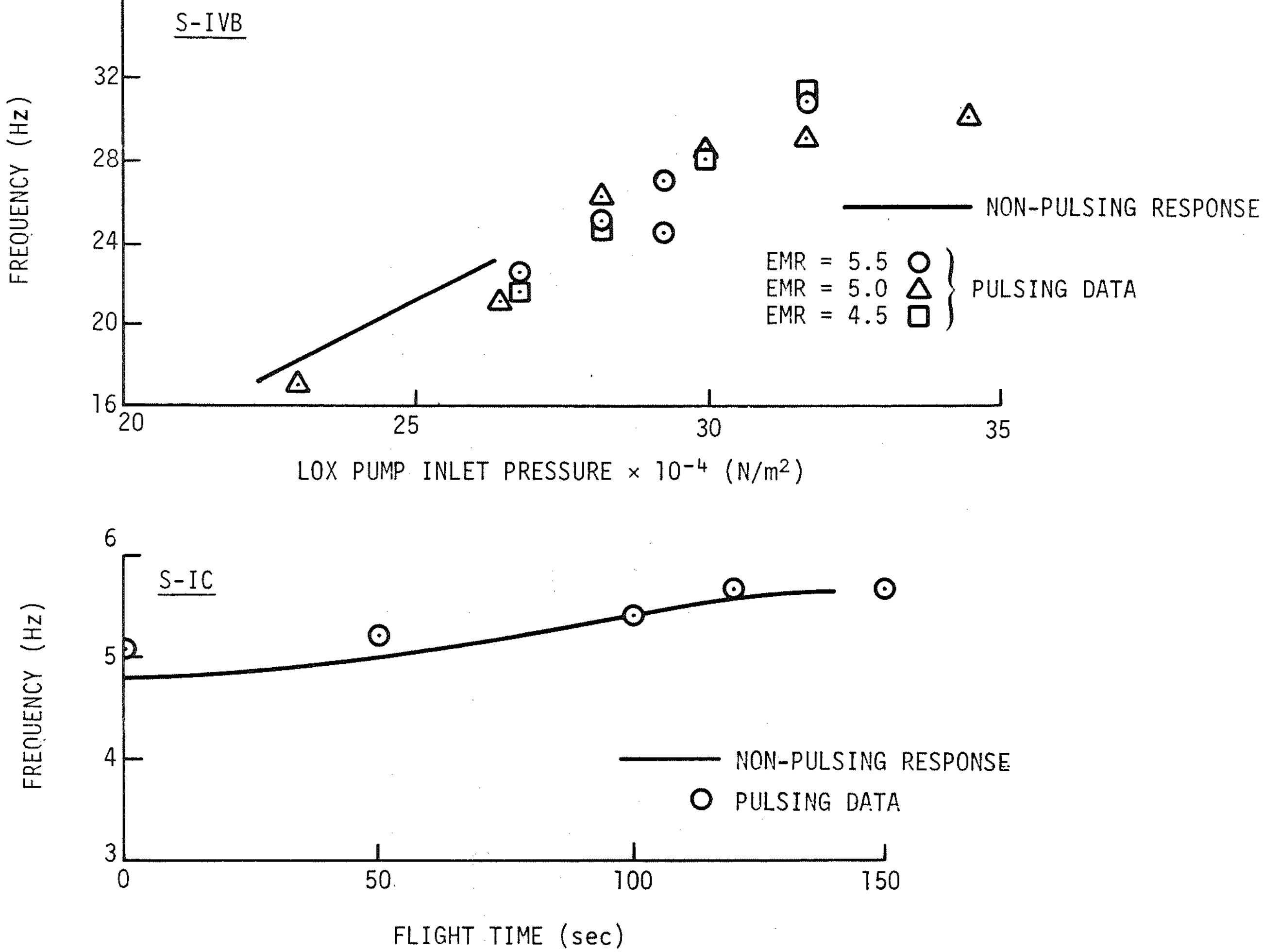
Stage technology programs should provide for accumulators in the feedline. The accumulators should be located near the pump inlet, lower the feedline resonant frequency below the significant structural modes and not degrade engine performance.

It is improbable that active controllers or feedline accumulators can preclude all oscillations. Therefore, the allowable amplitude/frequency relationship for the Shuttle crew and passengers must be established.

Engine-Stage Dynamics And Response
Development Approach

- Early Engine-Stage Integration
    - Define Engine Controls And Common Usage
    - Dynamically Simulate Vehicle At Engine Development Facility
- Pump Cavitation Modeling
    - Develop Correlation Based On Previous Data (NAS8-26266)
    - Evaluate Dynamic Response From Development Tests
- Engine Dynamic Flow Controller (Feasibility Studies)
- Baseline Provisions For Stage Accumulator
- Establish Oscillation Limits For Crew/Passengers

LOX Feedline Resonant Frequency



Base Thermal Environment

The base thermal environment is dictated by vehicle configuration, engine arrangement, engine gimbaling characteristics and booster-orbit attachment. The major areas impacted by base heating or vehicle-plume interaction are presented on chart 12. The booster thermal design criteria for components and the reusable base thermal protection system will be dictated by ascent convective heating. Impingement heating of stage surfaces during separation, one consideration in selection of a vehicle thermal protection concept, will not be discussed in detail. Aerodynamic heating of the orbiter base region during reentry will be significant.

The prime considerations for the Shuttle base thermal protection system are reusability, maintainability and minimum weight. However, the present technology is based on the concept of low utility. The operation/reliability of control surfaces subsequent to repeated impingement heating, accessibility to protected components and unsymmetrical heating due to canted heat shield are unique Shuttle considerations not emphasized in previous programs.

The base thermal environment cannot be accurately defined by analytical techniques. Therefore, empirical extrapolation of pertinent data from previous programs is used to develop models that establish preliminary heating profiles. The estimates of the relative temperature of the base region presented on chart 13 were derived from Saturn flight data. The maximum booster environment occurs during ascent with equilibrium temperatures approximately 80% of the Saturn S-IC level. The orbiter ascent levels are equivalent to the Saturn S-II level, however, reentry heating is a more severe condition due to the extended exposure period.

Analytical and experimental studies are necessary to provide an accurate model of the base thermal environment. The assessment of the base region flow fields, engine arrangement and vehicle aerodynamics should provide design criteria for the engine or vehicle components. Well conceived and carefully conducted model test programs are required to complement the analytical studies. An alternative to developing an accurate model of the base thermal environment is to use over-conservative designs and upgrade the design criteria with flight development tests.

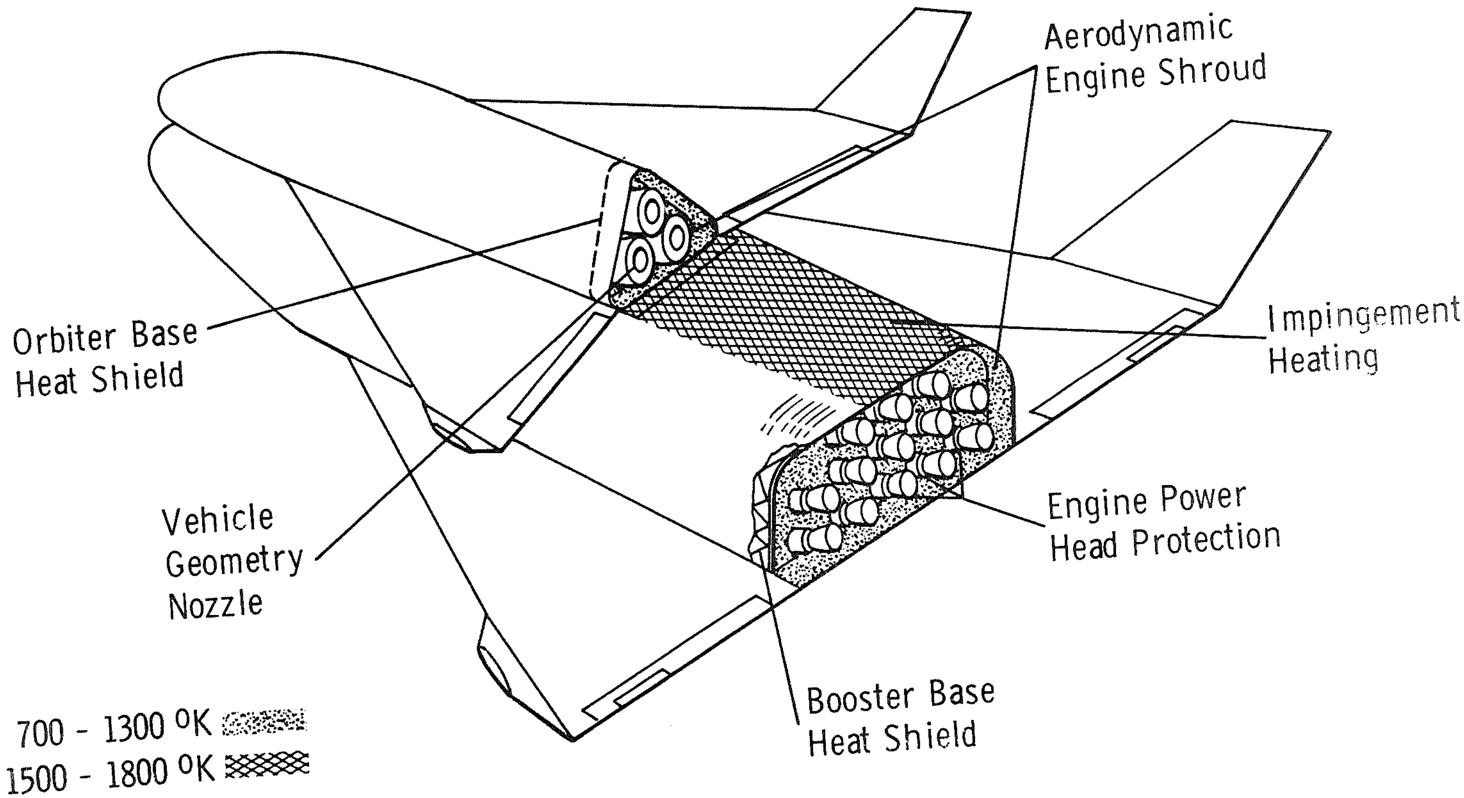
Base Thermal Environment

- Requirements
  - Identify Areas Impacted By Exhaust Plume/Vehicle Interactions
  - Establish Thermal Environment For Engine And Vehicle Components
  - Define Criteria For Reusable Base Thermal Protection System

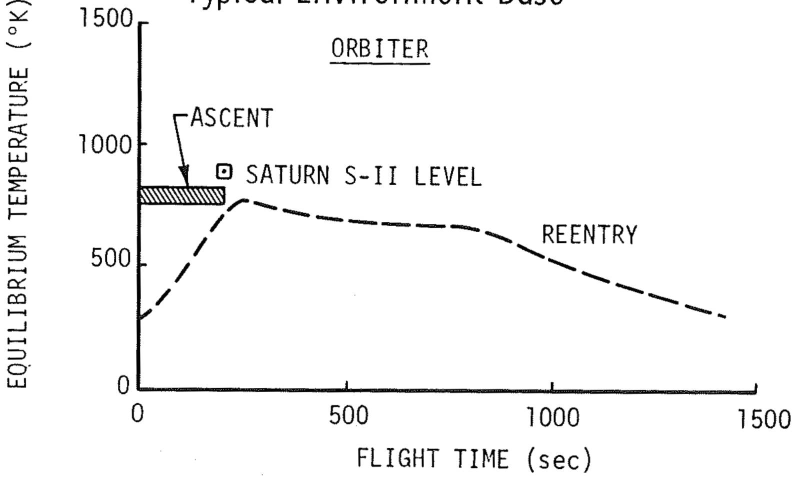
- Technology Status
  - Analytical Technology Inadequate
  - Preliminary Heating Environment Established
  - Some Problem Areas And Design Interactions Identified

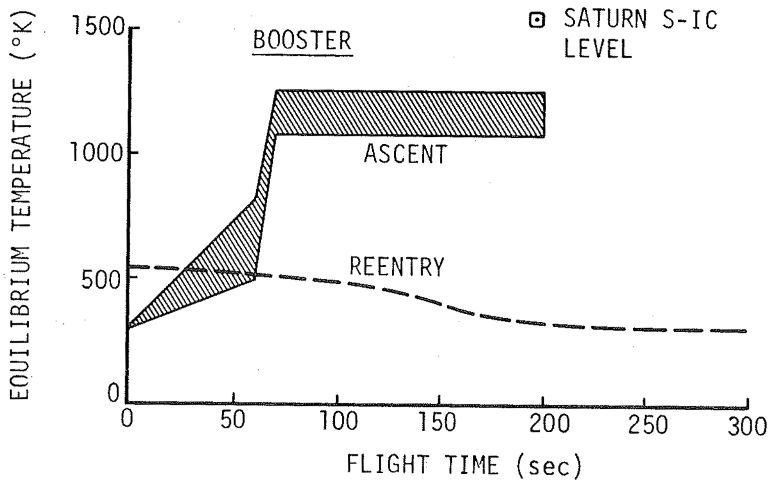
- Development Approach
  - Improve Analytical Models
  - Define Criteria For Base And Engine Components
  - Conduct Model And Component Tests

Vehicle-Plume Interaction Areas



Typical Environment Base





SUMMARY

The high performance objectives and cost effective development goals of the Shuttle main engine are enhanced by early consideration of engine-stage integration requirements. The propellant thermal conditioning required to suppress feedline geysers can also provide orbiter propellant quality control at booster-orbiter staging. This capability could reduce engine development cost. Early analytical and experimental consideration of the engine-feedline transient response will preclude incompatibility of the engine control system and the vehicle feedlines and will minimize the potential for longitudinal vehicle instability (POGO). The application of existing base heating data to the Shuttle is limited. Therefore, technology tasks are required to develop adequate models of the base thermal environment and to establish design criteria for engine and stage components.