# ELES-1984: A THIRD GENERATION PRELIMINARY DESIGN TOOL

C. E. Taylor
Aerojet TechSystems Company
P.O. Box 13222
Sacramento, California 95813

## Abstract

The ELES-1984 computer code is a landmark development in the preliminary systems analysis of liquid rocket vehicles. It is capable of revealing subsystem interactions and design choice impacts on total vehicle performance. Its use enables very rapid determination of optimum vehicle designs.

## Overview

The liquid propulsion system models in ELES have been developed by Aerojet TechSystems Company under the auspices of AFRPL during the past few years (1980-1984) under contracts F04611-79-C-0054 and F04611-82-C-0062. The main purpose of ELES is to find optimum vehicle designs for specified mission requirements. Toward that end it is capable of evaluating the size, weight, and performance of system components over a range of design configurations, materials of construction, and operating points.

There are three main sections of the ELES computer code (see Fig. 1): a stage design section, a trajectory model, and a multivariable optimizer. The stage design section calculates the size, weight and engine performance of liquid or solid stages (see Fig. 2). The trajectory model uses a 2D round non-rotating earth, 1962 standard atmospheric data, Adams-Moulton/Runge-Kutta integration, and Kepler orbital mechanics. The optimizer provides optima for both stage design and vehicle guidance with design and guidance parameter sensitivites included. Mixed solid and liquid stage vehicles of up to 4 stages can be modeled by ELES.

The liquid engine feed system power cycles modeled by ELES are illustrated in Fig. 3. The list includes pressure fed engines and pump fed engines with the following turbopump power cycles: gas generator bleed, single preburner staged combustion, staged reaction, and

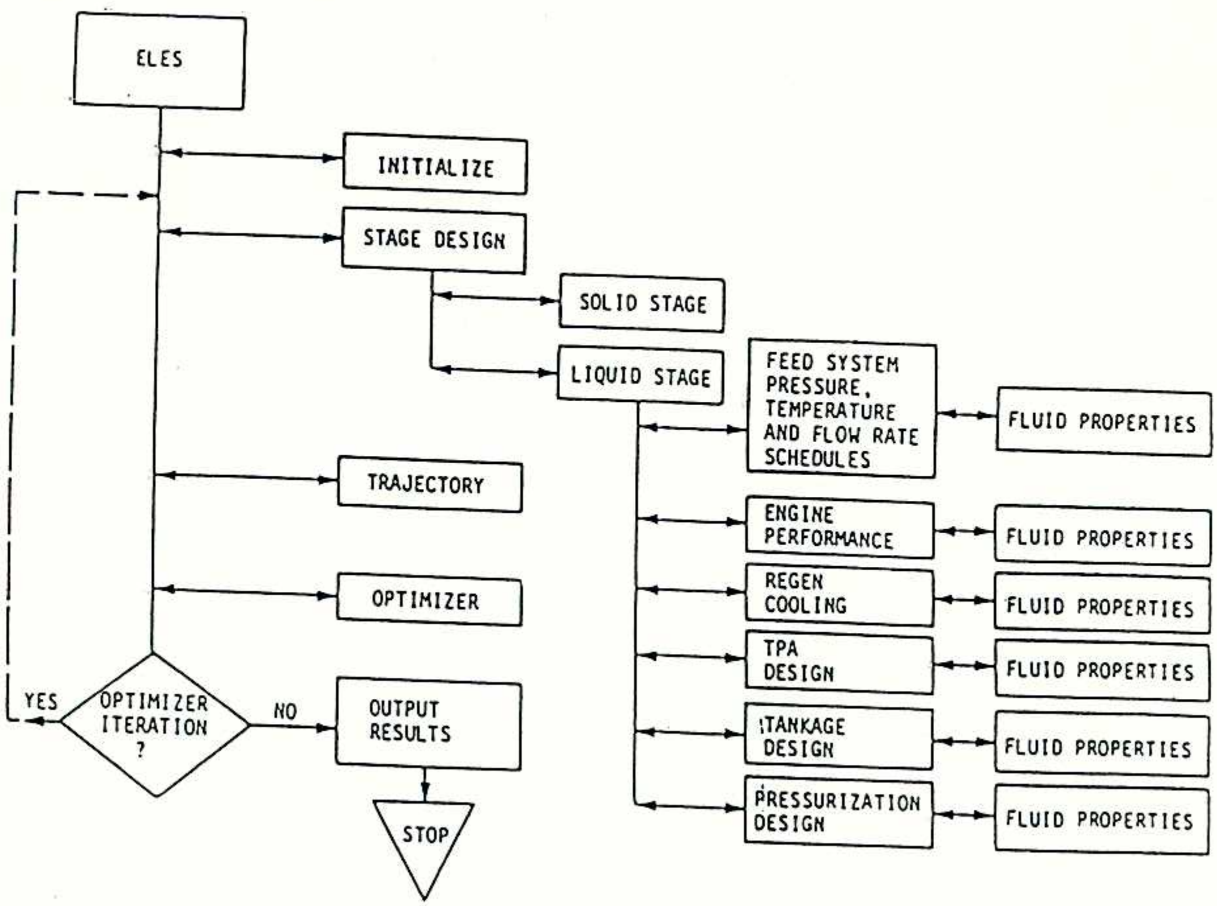


Fig. 1 ELES flow diagram

Propellant Tank Size/Weight

Pressurization Tank Size/Weight

Line Size/Weight

Positive Expulsion Size/Weight/Delta P

Engine Size/Weight/Performance (Nozzle, Valve, Injector, Chamber)

Thrust Mount Size/Weight

Gimbal System Size/Weight

Tank Residuals Weight

Tank Pressurization Requirements

Interstage Size/Weight

Delivered Specific Impulse (ideal one dimensional equilibrium performance degraded by kinetic, vaporization, boundary layer, mixing, two phase, divergence, and MR distribution losses)

Feed System Temperature/Pressure/Flowrate Schedules

Regenerative/Trans-Regen Cooling Requirements

Turbopump Assembly Size/Weight/Performance

Turbopump Design Parameter Breakdown

Regenerative Cooling Jacket Summary

Required Engine Barrier Mixture Ratio

Stage Tank Mixture Ratio

Fig. 2 Major Output Parameters of Liquid Stage Design Section

expander. The ELES engine analysis outputs engine size, weight, and performance, as well as turbopump assembly (TPA) size, weight and performance.

Engine performance is based on the standard JANNAF method. It begins with ideal one dimensional equilibrium (ODE) performance and degrades that ideal performance with loss multipliers. The calculation of these multipliers is performed by standard JANNAF procedures or by Aerojet derived methods. The analysis includes the effect of injector design, thrust chamber material, operating temperatures, propellant inlet temperatures, and thrust chamber geometry.

TPA design options are shown in Fig. 3 as gearbox, single shaft, and twin TPA. As required, the code will stage the pumps and turbines. The TPA is designed by considering system power requirements and drive fluid characteristics. Pump and turbine efficiencies are based on industry standards (Ref. NASA SP-8109, Fig. 6; AFRPL TR 72-45, Fig. 4).

The temperature and pressure drops across regenerative or trans-regenerative cooling jackets are calculated by creating a simplified thrust chamber geometry with slotted channels for coolant flow. Combustion gas and coolant heat transfer coefficients are calculated at discrete points along the chamber and are used to integrate the pressure drop necessary to maintain the chamber wall at nominal operating temperature. Transpiration cooled portions of the chamber are analyzed using techniques developed by Aerojet TechSystems for use with transpiration cooled re-entry vehicle nosetips.

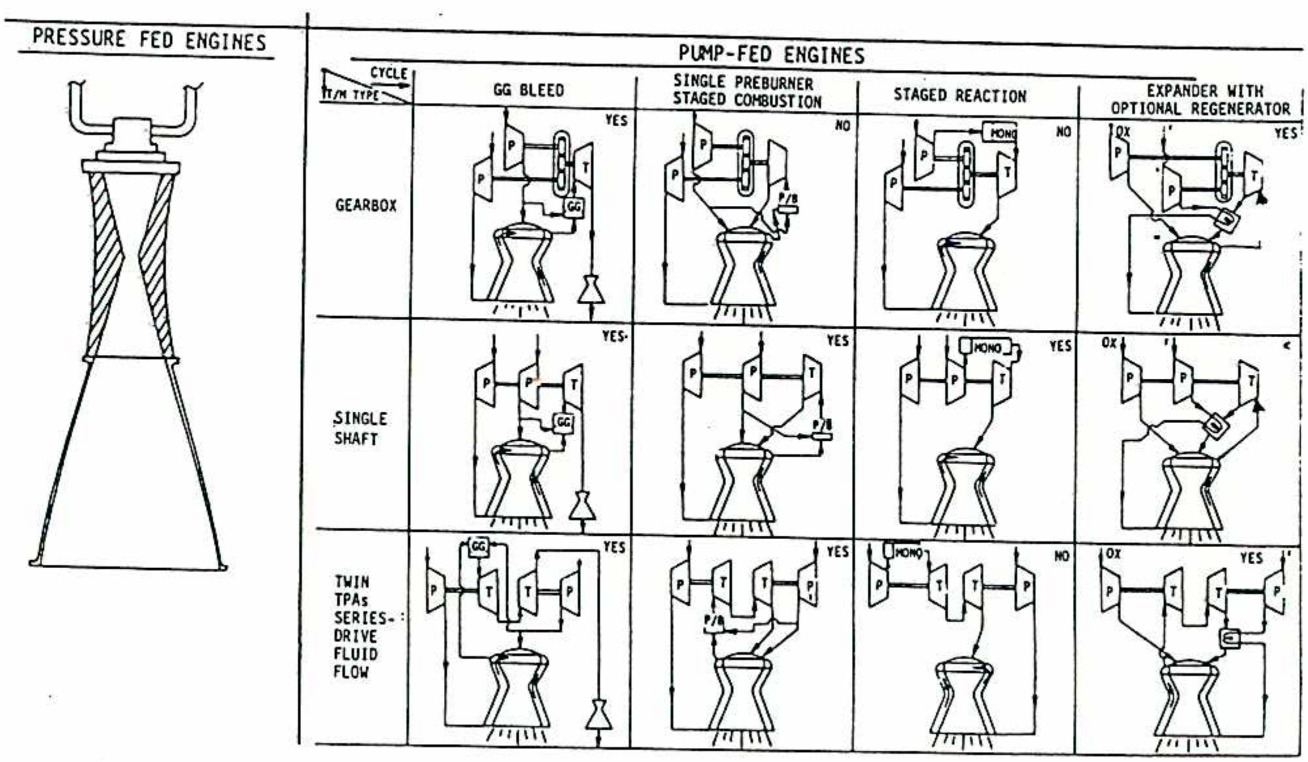


Fig. 3 Representative ELES engine cycles

A wide variety of tankage designs are available (see Fig. 4). Tandem tanks are designed by choosing tank head orientation, common or separate tank heads, suspended or monocoque construction, and pressurant tank location. The tanks may or may not contain a positive expulsion bladder or surface tension acquisition device. Non-conventional tankage is designed by choosing the number and type of propellant and pressurization tanks as well as propellant acquisition design. Each tank is individually specified to be toroidal, spherical, or cylindrical with elliptical heads. Tanks are located based on general location input and physical interference between the tanks and envelope.

Propellant tank pressurization options in ELES include cold gas, solid gas generator, and autogenous. With cryogenic propellants, the pressurant collapse is calculated with the Epstein* correlation. Pressurization requirements are affected by the vehicle operating temperature regime, and external heating loads.

Throughout the liquid stage design portion of the code there is a need for propellant properties data over an extremely wide range of temperature and pressure. This data is stored in tables for hydrogen and helium. The properties for all other propellants are calculated by the method of corresponding states. This allows analysis to occur in regimes where propellant data may not exist and for propellants which have very little experimental data.

## Liquid Stage Design Procedure

The general procedure used for calculating the size/weight/performance of liquid stages is described in Fig. 5. It begins with the initialization of propellant feed circuit parameters (temperature, pressure, flowrate). The remainder of the procedure refines those initial estimates.

Refinements to the feed schedules include calculating the engine's barrier mixture ratio, engine performance, regenerative cooling jacket properties, turbopump assembly (TPA) design, propellant tank pressurization requirements, and tankage heat transfer. Iterative procedures are used for some of the parameters.

When the propellant feed schedules are finalized, the calculations of size, weight, and performance of the TPA, engine, and tankage can take place. A stage summary of those parameters and related parameters can then be made.

*Epstein, M. and Anderson, R, "An Equation for the Prediction of Cryogenic Pressurant Requirements for Axisymmetric Propellant Tanks," Advances in Cryogenic Engineering, Volume 13, New York (1968), Page 207.

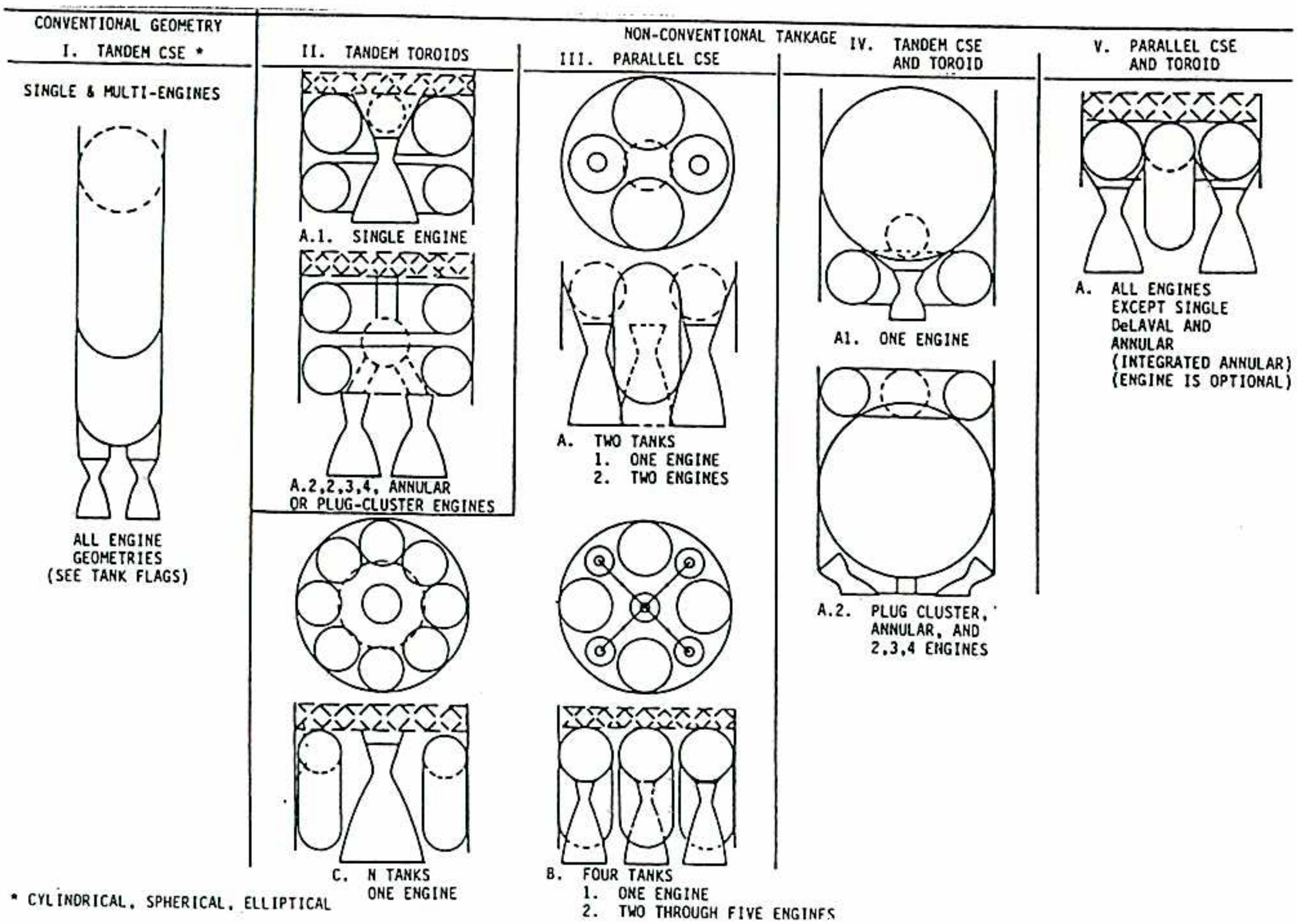


Fig. 4 Representative ELES tankage options.

1) Initialize temperature schedule

2) Calculate engine barrier mixture ratio

3) Initialize flowrate schedule (using some rough estimates)

   3.1) Estimate tank sizes

      3.1.1) Estimate tank heat transfer

      3.1.2) Estimate pressurization requirements

4) Calculate feed system pressure schedule

   4.1) Calculate engine performance

   4.2) Perform regen cooling analysis (if required)

5) Perform non-conventional nozzle modifications

6) Calculate flowrate schedule (using improved estimates)

   6.1) Calculate tank sizes

      6.1.1) Calculate tank heat transfer

      6.1.2) Calculate pressurization requirements

7) Design TPA (if required) (iterate, if not power balanced)

8) Update propellant temperature schedule (iterate on temperature schedule, if required)

9) Calculate TPA size/weight (if required)

10) Calculate engine size/weight

11) Calculate tankage size/weight

12) Calculate stage summary size/weight/performance

Fig. 5 Liquid Stage Design Procedure

## ELES Input

ELES-1984 operates in a "batch" type mode which means that during program execution there is no interaction between the user and the code. After normal program termination ELES will have created output files which can be examined by the user.

The main form of interaction between the user and ELES takes place prior to program execution when the user creates an input file. This input file is submitted to ELES at run time. The input file (named "ELESINP") contains up to 34 NAMELIST blocks which contain the input variables. Although all 34 blocks are not always read by ELES, it is recommended that all namelist blocks be included in ELESINP in their proper order. This precaution can prevent a whole class of termination errors.

Using the liquid stage models in ELES to their fullest potential involves the use of hundreds of inputs. In order to organize the input procedures for those variables, an input worksheet has been developed. The first portion of that worksheet is presented in the ELES New Users Guide, pages 29 through 41. The remainder is presented in the ELES Advanced Users Guide, Pages 4 through 52.

The new users worksheet is concerned with a general overview of basic ELES options; that worksheet is the best place to begin. There are two major types of input in the advanced users worksheet; 1) recurrent input which must always be considered and 2) contingent input which need only be considered if prior choices dictate.

The recurrent input includes general inputs, injector related inputs, thrust chamber inputs, and tankage inputs. These should be considered every time ELES is run.

The contingent input worksheet relates to tandem tanks, non-conventional tanks, cold gas pressurization, solid gas generator pressurization, turbopump assemblies, regen/trans-regen cooling, tankage heat transfer, positive expulsion bladders, user defined propellants, throttling trajectories, and short nozzle designs. Each category need only be considered if it is a part of the design in question.

It is highly recommended that the user photocopy all applicable worksheets and fill them out prior to program execution.

## ELES Output

The output from ELES consists of detailed stage summary pages as well as an overall vehicle summary. For each liquid stage, there is an output page for warning messages, tankage summary, stage graphical schematic, engine summary, propellant summary, regenerative cooling jacket summary, turbopump assembly (TPA) summary, feed system temperature and pressure schedules, and an overall stage weight breakdown.

The purpose of the warning page is to alert the user to potential design flaws or program problems. Examples of warning messages include injector orifices diameters below a typical minimum, tank wall thicknesses design criteria (buckling, minimum gauge, hoop stress, etc.), or unusual termination of an iteration loop. It is the users responsibility to ignore or respond to warning messages.

The tankage summary gives a tank-by-tank description of the stage. Output includes tank contents, pressurization method, thicknesses, dimensions, materials of construction, safety factors, residual propellant weights, pressurant weight, line weights, propellant acquisition system weight, and tank weights.

The stage graphical schematic is drawn to scale on the line printer with actual tank head ellipse ratios. The size of the schematic is automatically adjusted to fill the page. Because some line printers do not use the standard number of characters per inch in the horizontal and vertical dimensions, that information may be input by the user. All graphics are performed by pseudo-Tektronix routines in ELES which mimic standard Tektronix commands. It is therefore relatively easy to convert ELES to create high resolution Tektronix schematics.

The engine summary begins with basic engine design information (power cycle, cooling method, propellant combination) and then proceeds to more detailed engine descriptions. The left side of the engine summary page is devoted to size and weight information. The right side is devoted to performance-related engine parameters including a breakdown of individual loss mechanisms to engine performance. References to "core" and "barrier" are due to the core and barrier stream tube model used in the performance calculations.

The propellant summary page applies over the operating temperature range of the on-board propellants. For storable propellants this corresponds to the operating temperature range of the vehicle. The first line of the propellant summary declares whether the propellant combination is a user defined propellant combination or a library propellant combination. ELES allows for easy simulation of non-library propellants using propellant property inputs. Using the method of corresponding states, ELES predicts propellant properties over a very wide range of temperature and pressure. These calculations are used to design tanks, pumps, regenerative cooling jackets, etc.

The propellant properties displayed are primarily tank design parameters. The density of each propellant at its maximum temperature is used to calculate the tank volume requirements. The vapor pressure is used in determining tank pressure requirements.

The regenerative cooling summary describes the heat transfer characteristics of the combustion chamber at various points along the gas side wall. The heat transfer coefficient and heat flux is indicated at each point as well as liquid coolant bulk temperature and pressure. Simplified one dimensional heat transfer and fluid hydraulics are used to estimate the overall temperature rise and pressure drop across the regen jacket.

The TPA summary gives detailed descriptions of the pumps and turbines in the power cycle. Speeds, dimensions, efficiencies, flowrates, number of stages, weights, horsepowers, and admission fractions are included for pumps, boost pumps, and turbines.

The pressure and temperature schedules show the pressure and temperature at various key points in the propellant feed system as well as pressure and temperature changes across key sections of the feed system. A flowrate schedule is also included which shows flowrates through the major components of the feed system.

The overall stage weight summary is a list of all items in the stage which contribute to its weight. Inert weights are presented separately from propellant or pressurant weights.

The final page of output is the vehicle summary which gives an overview of all vehicle stages. The stage masses, mass fractions, dimensions, and performances are overviewed.

## Concluding Remarks

Since its initial configuration in 1980, ELES has been of great benefit to its creaters in analyzing propulsion system concepts in a timely, cost-effective manner. As its use spreads it is establishing itself as a standard in the field of preliminary propulsion system design. To the authors knowledge there is no comparable method by which propulsion system design parameters can be optimized with nearly the speed or accuracy which ELES offers.