

Upgrades to the NESS (Nuclear Engine System Simulation) Code

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In support of the President's Vision for Space Exploration, the Nuclear Thermal Rocket (NTR) concept is being evaluated as a potential propulsion technology for human expeditions to the moon and Mars. The need for exceptional propulsion system performance in these missions has been documented in numerous studies, and was the primary focus of a considerable effort undertaken during the 1960's and 1970's. The NASA Glenn Research Center is leveraging this past NTR investment in their vehicle concepts and mission analysis studies with the aid of the Nuclear Engine System Simulation (NESS) code. This paper presents the additional capabilities and upgrades made to this code in order to perform higher fidelity NTR propulsion system analysis and design.

Nomenclature

AR	=	Nozzle Area Ratio
BATH	=	Borated Aluminum Titanium Hydride
CERMET	=	Ceramic/Metallic Composite
h	=	Enthalpy
Isp	=	Specific Impulse
m	=	Mass
MCNP	=	Monte Carlo N-Particle transport code
N	=	Number of Items Indicated by Subscript
NERVA	=	Nuclear Engine for Rocket Vehicle Applications
NESS	=	Nuclear Engine System Simulation code
NFE	=	Number of Fuel Elements
NTR	=	Nuclear Thermal Rocket
P	=	Pressure
Q	=	Thermal Energy
SNRE	=	Small Nuclear Rocket Engine
T	=	Temperature
<i>Thrust</i>	=	Engine Thrust
TPA	=	Turbo-Pump Assembly
$\eta_{Contact}$	=	Non-Dimensional Contact Length
η_{TT}	=	Fraction of Heat Transferred to Tie Tube
ξ	=	Thermal Energy Deposition per Unit Mass

Subscripts

CE	=	Component of Fuel Element
Ch	=	Thrust Chamber
Chn	=	Fuel Element Propellant Channel
Core	=	Reactor Core
CT	=	Component Tie Tube
Exit	=	Fuel Element Exit
FE	=	Fuel Element
i	=	Axial Segment Index

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NE = Neighboring Fuel Element
 SE = Fuel Element Axial Segment
 ST = Tie Tube Axial Segment
 Tank = Propellant Tank
 TT = Tie Tube

I. Introduction

In order to fulfill the President's Vision for Space Exploration and conduct human exploration of the moon and Mars, many new technologies will be required. The propulsion system, in particular, is a technology that has an impact on practically every aspect of vehicle performance and mission design. Nuclear Thermal Rocket (NTR) technology can deliver specific impulse (Isp) values more than double that of any chemical based system by heating low molecular weight hydrogen to over 2600 K via thermal energy gained from a nuclear fission reactor, instead of a chemical reaction with an oxidizer, typically oxygen¹.

The requirement for exceptional propulsion system performance in order to successfully complete these future missions has been documented in numerous studies, and was the primary focus of the work done during the Nuclear Engine for Rocket Vehicle Applications (NERVA) program². The NASA Glenn Research Center (GRC) is leveraging this investment by applying this technology to their vehicle concepts and mission studies with the aid of the Nuclear Engine System Simulation (NESS) code. The primary focus of recent activities at NASA GRC has been on benchmarking and upgrading methods, models, and analysis tools against the Small Nuclear Rocket Engine (SNRE). Although never built, the SNRE has been the primary benchmark focus, primarily because of the maturity of the design and the available documentation regarding its preliminary design results. Two companion papers address both the neutronic analysis³ and integrated thermal-fluid-structural analysis⁴ of reactor core components conducted as part of this effort.

II. Nuclear Thermal Rocket (NTR) System Overview

A basic NERVA derived NTR propulsion system, as shown in Fig. 1, consists of a small nuclear fission reactor, turbopump assembly (TPA), nozzle, radiation shield, assorted lines, valves, pressure vessel, and the associated support hardware. Most NTR systems that have been designed and tested to date have been based on the expander cycle. This cycle utilizes thermal energy gained by the propellant, typically hydrogen, from active cooling of various engine subcomponents (nozzle, control drums, etc.) to drive the TPA, and thus power the cycle¹. As designs evolved during the early years of nuclear rockets, chamber pressure and engine size increased, thus additional energy was required to meet the increasing power requirements of the TPA. In response to this requirement, later designs began to extract additional thermal energy directly from the reactor core via tie tubes. This design's heritage dates back to the NERVA program⁵, and is the basis of NESS⁶. A simplified flow diagram of this type of expander cycle based NTR engine is shown in Fig. 2.

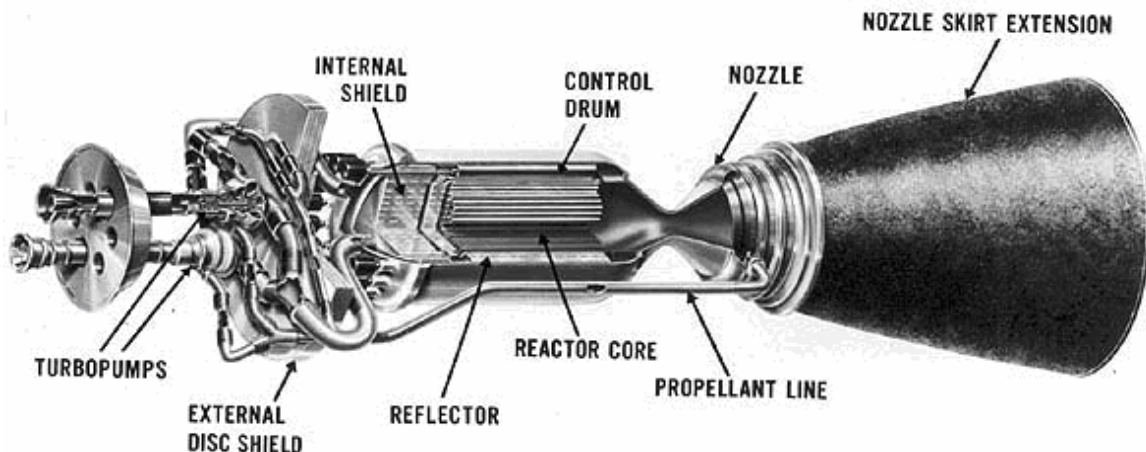


Figure 2. Typical NERVA Derived NTR Engine System.

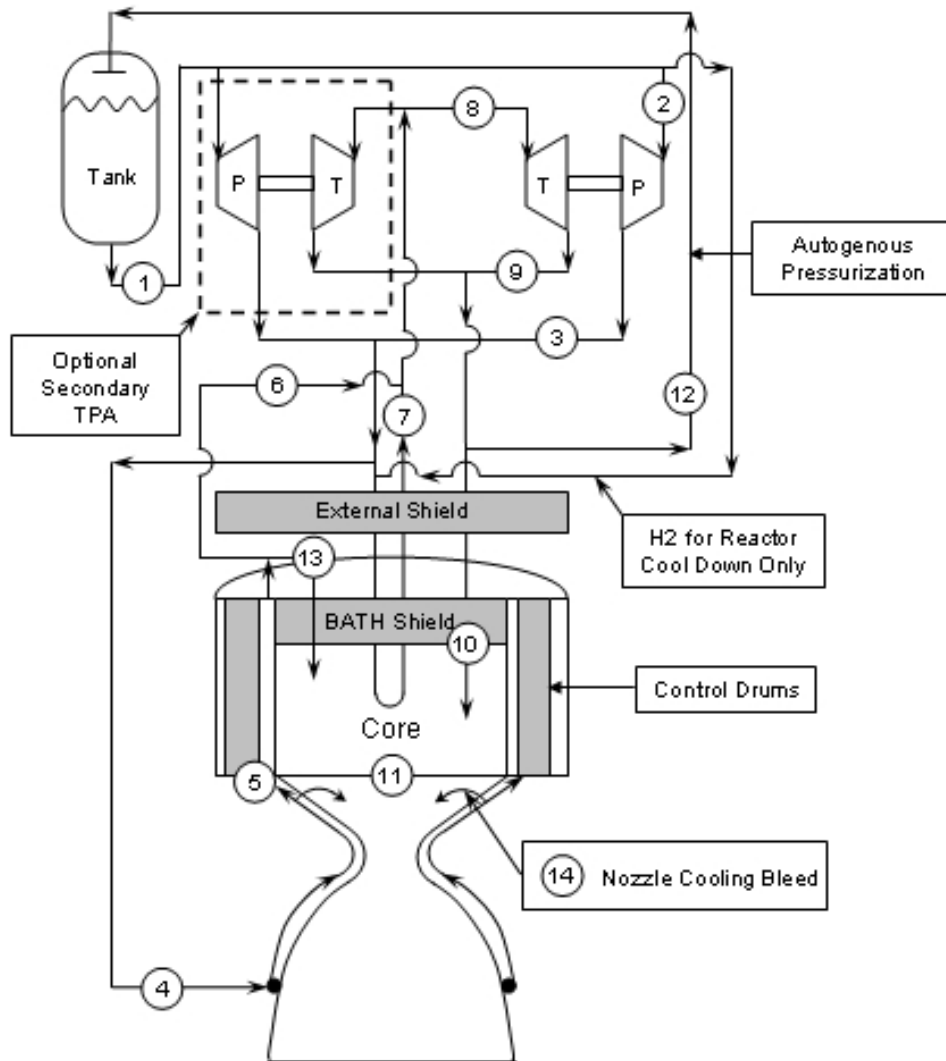


Figure 2. Typical Expander Cycle NTR Flow Diagram.

A. Reactor Assembly

In a NERVA derived NTR system, tie tubes and fuel elements are assembled to create the reactor core. In this assembly, the ratio of fuel elements to tie tubes is adjustable. A typical arrangement is shown in Fig. 3, where each tie tube is surrounded by six fuel elements, and each fuel element is in contact with three tie tubes. The fuel elements around the perimeter of the core, however may contact fewer tie tubes². The ratio of fuel elements to tie tubes is also an input variable for the NESS Code^{6,7}.

The assembled reactor core is surrounded by additional and partial hexagonal beryllium filler elements, which are used to complete a cylindrical core. This completed assembly is placed inside a beryllium barrel, which is itself surrounded by control drums. The control drums consist of a neutron moderator-reflector on one side and a neutron absorber on the other. Thus, the reactor reactivity can be adjusted by rotating the control drums. The control drums are the same length as the tie tubes and the fuel elements. This entire assembly is then placed inside a vessel⁷. A cross section of a NERVA derived reactor assembly is shown in Fig. 3.

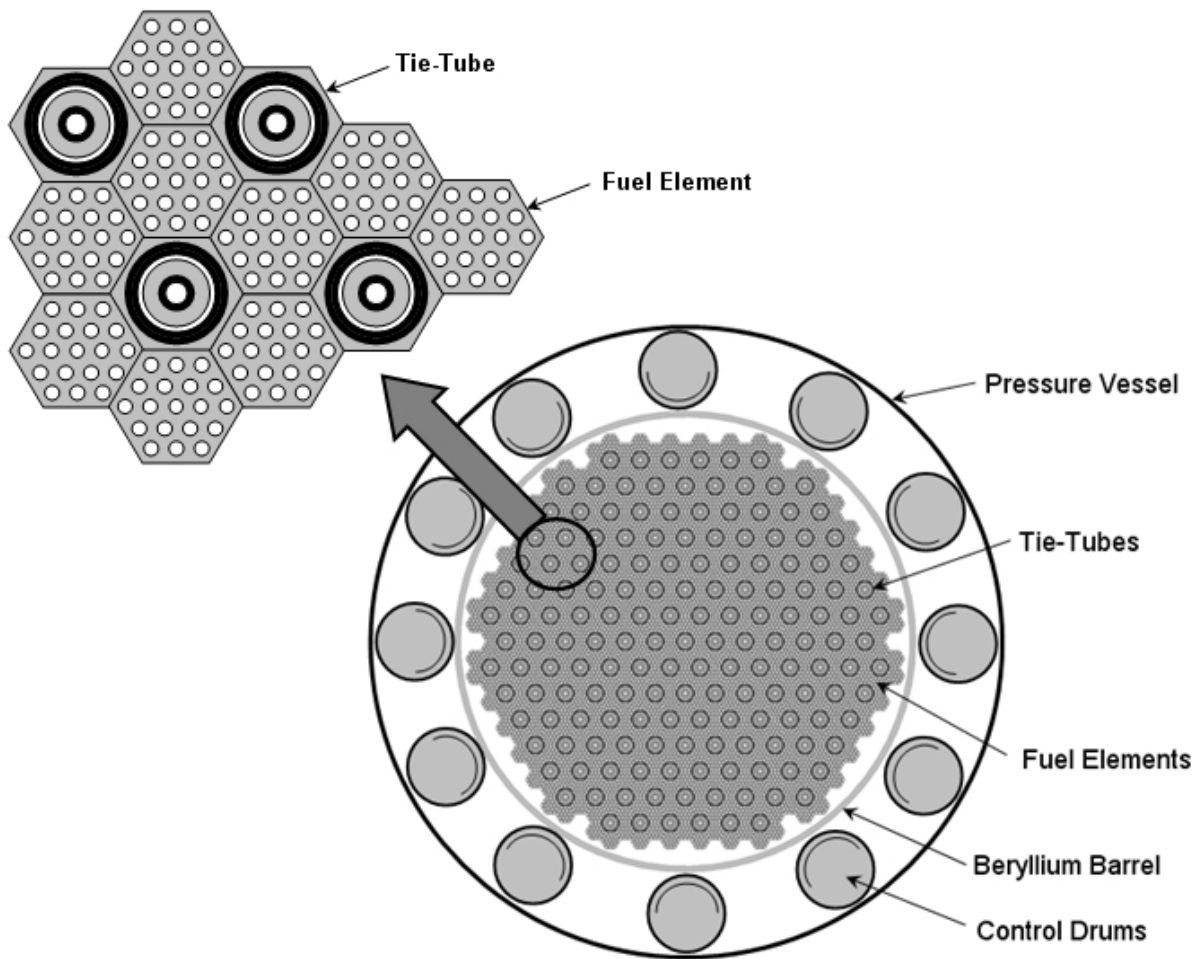
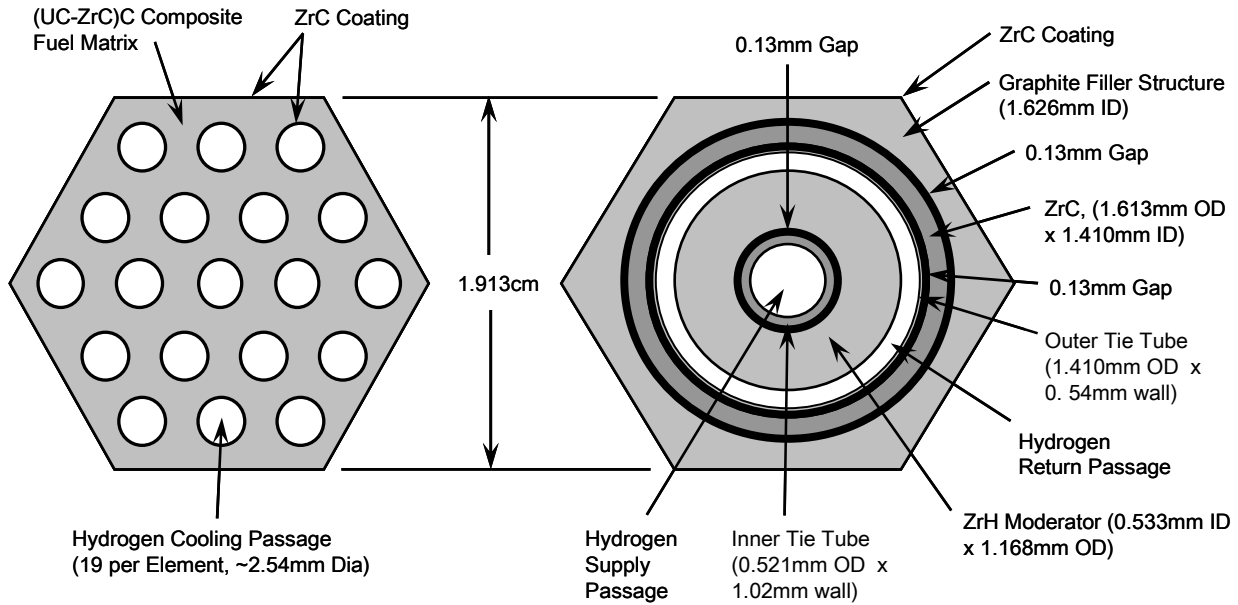


Figure 3. Typical NERVA Derived Reactor Cross Section.

B. Tie Tubes and Fuel Elements

A typical expander cycle chemical rocket engine, such as the RL-10, derives the energy required to drive its TPA by means of regenerative nozzle and thrust chamber cooling. The quantity of thermal energy obtained via nozzle and control drum cooling in an NTR system, however, is usually inadequate. Tie tubes provide a means to extract additional thermal energy from the reactor core to drive the TPA, while also providing necessary axial support to the reactor core. Tie tubes can also be used to help cool the engine during shutdown, and to potentially drive a closed-loop Brayton cycle based electrical power generation system during the coast phase of the mission⁸. This bimodal use of an NTR system (providing both propulsion and electrical power) is a unique capability deserving of further analysis.

A tie tube is a hexagonal support element which serves as a dual pass heat exchanger through the reactor. Cold working fluid, typically hydrogen, is forced down the center of the tie tube, and then returns via an outer coaxial annular flow path. Tie tubes are the same size (typically 1.905 cm) as a reactor fuel element. NERVA derived uranium and graphite based fuel elements are also hexagonal in cross-section, but incorporate 19 equally spaced holes that are ~2.54 mm in diameter. These 19 holes are the flow path for the propellant to pass through the reactor and into the thrust chamber located at the bottom of the reactor^{1,5}. A typical NERVA derived tie tube and fuel element, which are represented in NESS, are shown in cross section in Fig. 4.



a) Typical NERVA Derived Fuel Element

b) Typical NERVA Derived Tie Tube

Figure 4. Tie Tube and Fuel Element Cross Sections.

C. NTR Fuels

There are several NTR fuel candidates available that cover a wide range of operational temperatures. These fuels range from the well understood coated UC_2 in graphite, shown in Fig. 5, to the more exotic tricarbide⁹. A comparison of the various fuel candidates is shown in Fig. 6, where the specific impulse curves are representative of hydrogen¹ at a chamber pressure of 6894.75 kPa and nozzle area ratios of 100:1, 300:1, and 500:1.

The NESS baseline fuel is (U,Zr)C-Graphite composite³, also shown in Fig. 5, which was tested during the NERVA program in the nuclear furnace⁹. Due to this testing, and its higher operational temperature relative to the coated UC_2 in graphite, it is the most likely fuel candidate in the near term. Although there has been substantial work done on the ceramic and metal matrix (CERMET) class of fuels, they have not yet matured to the point that it can be considered a viable NTR fuel class in the near term without substantial research and testing. NESS, however, can easily accept new few types as they become available. All that is needed is density and thermal property data, with the density data being unnecessary if data from the Monte Carlo N-Particle (MCNP) transport code is used instead of the traditional NESS input dataset.

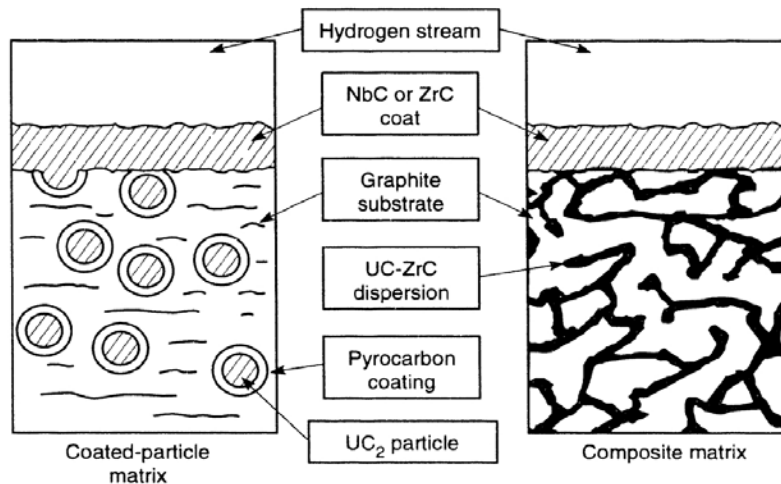


Figure 5. NTR Fuel Comparison.

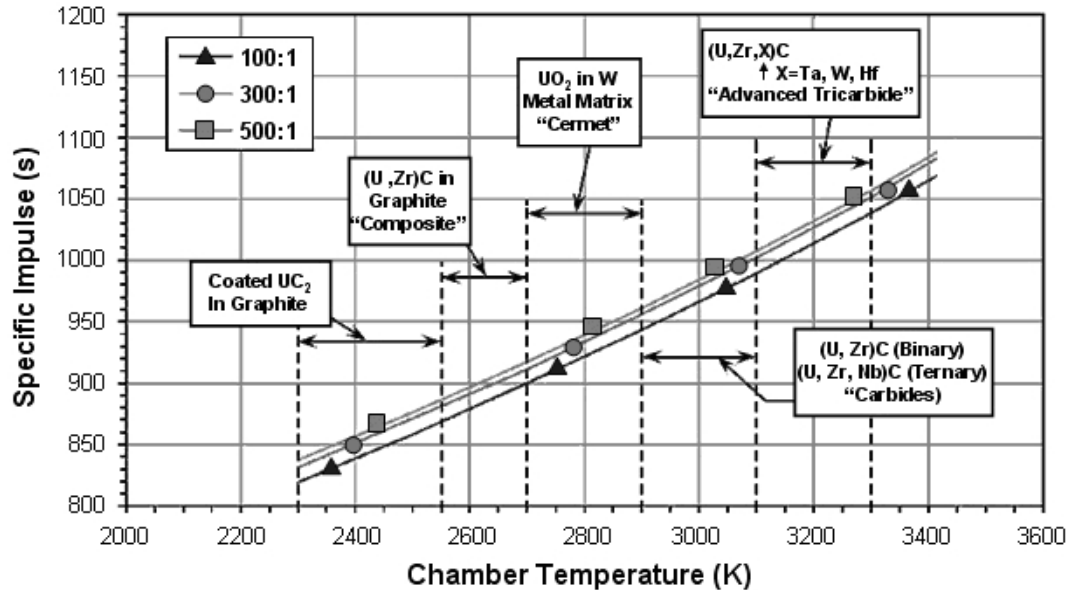


Figure 6. NTR Fuel Comparison. *Isp* curves represent hydrogen propellant.

III. NESS Program

The NESS program was developed for rapid preliminary design and analysis of NERVA derived NTR propulsion systems. It is derived from the Expanded Liquid Engine Simulation program, which was modified to include Westinghouse Electric Corporation's near-term solid-core reactor design models Enabler-I and Enabler-II⁶. NESS can perform preliminary design and estimate the weight, performance, size, and operating characteristics of NTR propulsion system components, including the reactor. Code outputs also include engine cycle parameters including pressures, temperatures, and mass flows. NESS can model expander, gas generator, and bleed cycles, with all cycles using hydrogen as the propellant, and the gas generator cycle using oxygen as needed. All of these engine cycles can be driven by either a single or dual TPA configuration, with the TPA being either a common shaft or geared type^{1,6}.

Regardless of the engine cycle selected, each TPA is based on either an axial or centrifugal pump with an optional inducer stage. While performing TPA design calculations, NESS checks for the need to stage the pump or turbine, and allows up to four stages for centrifugal pumps, twenty stages for axial pumps, and two stages for turbines. To avoid unrealistic designs, NESS checks the maximum allowable tip speeds (1500 ft/s for hydrogen), forces the inducer and the pump to have the same RPM, and designs a partial admission turbine if the blade height falls below 0.3 in. The axial pump performance calculations are essentially the same as for the centrifugal pumps, with one exception being the specific speed at which NESS will stage the pump (~3200 for axial and ~800 for centrifugal)^{6,10}.

NESS also has the ability to design a dual TPA NTR system around a pump out condition. NESS begins by sizing a single TPA to provide a prescribed pump-out thrust level. Then it analyzes the same system using two of these pumps working in parallel, but each are operating at reduced speed and flowrate^{1,6}. This second analysis run operates the pumps at an off design condition, but either pump would operate at its design point in the event of a TPA failure. Due to the dependency of a NTR engine on the TPA, redundant and robust TPA systems will be necessary for both manned lunar and Mars missions.

IV. NESS Upgrades

A. Hydrogen Properties

Recently it was discovered that the algorithm used by NESS to calculate hydrogen fluid properties often gave incorrect results for inputs near the saturated liquid line. Upon further investigation, it was found that the data tables used for interpolation were not spaced equally in temperature, thus causing the interpolator used in NESS to often have difficulties interpolating in temperature between the two data sets. This problem was solved by modifying NESS to use the NASA GRC thermodynamic properties program GASPLUS¹¹ for the determination of para-hydrogen thermodynamic properties if temperature is at, or below, 2700 R.

B. MCNP Reactor Inputs

The original NESS reactor sizing algorithm begins by taking the user prescribed chamber temperature, pressure, and area ratio, and calculating engine Isp^6 . Using Isp and the required thrust level, the required propellant mass flow rate is obtained, and in turn, is used to determine the number of fuel elements via Eq. (1).

$$NFE = \frac{Isp(AR, P_{Ch}, T_{Ch})}{Thrust} \left(\frac{h_{Ch} - h_{Tank}}{\dot{Q}_{FE}} \right) \quad (1)$$

Although this approach is useful for initial reactor sizing, it is inadequate as more detailed reactor information becomes available for a given design, as it assumes equal (average) thermal energy release from each fuel element. NESS does, however, employ a hot element peaking factor for pressure drop calculations, thus simulating a thermal energy generation rate distribution in the reactor. This factor is not needed if multi-element MCNP data are used; being that the complete reactor thermal energy generation distribution is represented. It is still needed, however, if data for only one averaged fuel element are present in the input.

The NESS reactor sizing has been updated to allow the user to input the analysis results from a reactor design via an output file from the MCNP code. The new algorithm accepts all the fuel elements and tie tubes of a MCNP analyzed reactor design as a collection of components, which are typically segmented in the axial direction, with each segment of each component having both mass and energy deposition information. Unlike the original NESS reactor algorithm, where the number of fuel elements was calculated, with the use of MCNP output, the number of fuel elements is known, and the total reactor thermal power output is calculated by Eq. (2).

$$\dot{Q}_{Core} = \sum_{FE=1}^{N_{FE}} \sum_{SE=1}^{N_{SE}} \sum_{CE=1}^{N_{CE}} m_{CE} \dot{\xi}_{CE} + \sum_{TT=1}^{N_{TT}} \sum_{ST=1}^{N_{ST}} \sum_{CT=1}^{N_{CT}} m_{CT} \dot{\xi}_{CT} \quad (2)$$

It should be noted that the data NESS receives from a MCNP model can be of very high detail. A fuel element model can include the fuel, fuel element cladding, and both the propellant channel cladding and hydrogen propellant in all of the propellant channels. The tie tube model can also comprise all of the various tie tube components, including the hydrogen in the inner and outer flow passages, expansion gaps, tube walls, moderator, insulator, graphite hex, and the outer cladding⁵.

NESS can accept MCNP data for either an entire fuel element and tie tube or axially segmented ones. If there is only one axial segment given per fuel element in the MCNP output, the original NESS axial thermal power distribution, shown in Fig. 7, is then used for each fuel element in conjunction with its respective total thermal power output. If axially segmented data are available, then no profile is applied, since the appropriate power distribution is already present in the segmented data. The difference in the NESS axial thermal power profile and one obtained from an explicit MNCP model of the SNRE is shown in Fig. 8.

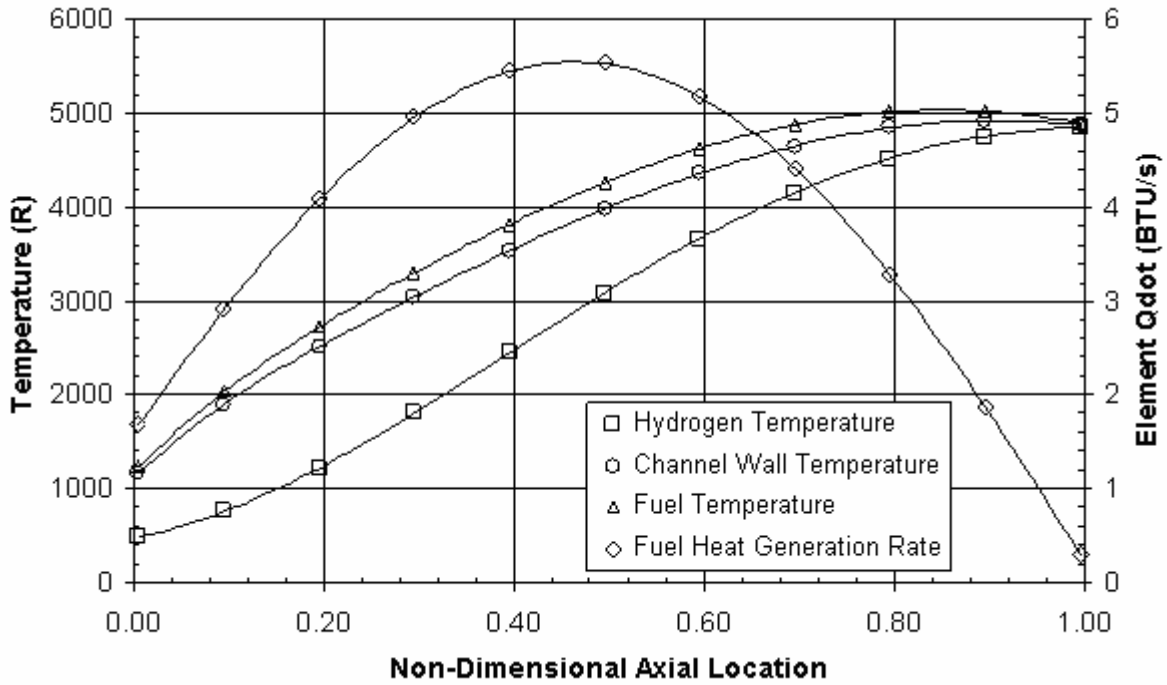


Figure 7. Typical NERVA Derived Fuel Element Temperature and Heat Generation Profiles. Data from a NESS model of SNRE utilizing NESS thermal power generation profile and SNRE nominal operating conditions. Non-dimensional axial location of zero indicates the propellant entrance, and one indicates the propellant exit.

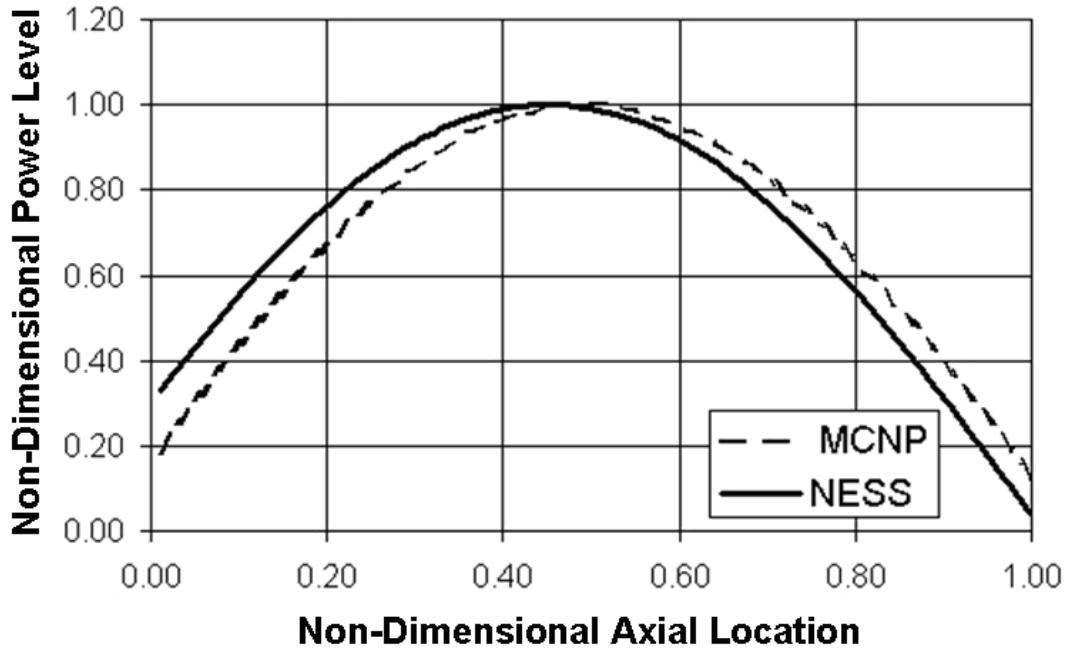


Figure 8. NESS and MCNP Non-Dimensional Axial Power Profile Comparison. MCNP analysis is based on uniform fissile loading of a SNRE class reactor. Zero indicates the propellant entrance, and one indicates the propellant exit.

C. Tie Tube and Fuel Element Heat Transfer

The thermal performance of the tie tubes is integral to the successful operation of a NTR expander cycle engine¹. The original NESS algorithm simply utilized an average pressure drop and enthalpy gain across the tie tubes⁶. These calculations have been updated to calculate an enthalpy gain for the hydrogen coolant based on the thermal energy generation of each surrounding fuel element, a predetermined ANSYS contact length, and the number of tie tubes that each of those fuel elements touches.

For every tie tube, the total thermal power output of each of its surrounding fuel elements' axial segment is multiplied by a percentage predetermined by a three dimensional ANSYS Multiphysics technique, which combines FLOTRAN for the fluid analysis, ANSYS thermal for the thermal analysis, and ANSYS structural for the stress analysis of a nominal fuel element and tie tube interface⁴. This thermal energy is then summed for each axial segment, if it is within the contact length. Once all the appropriate segments are summed, the mass averaged enthalpy gain across the tie tube is calculated by using Eq. (3).

$$\Delta \bar{h}_{TT} = \frac{1}{\dot{m}_{TT}} \left(\sum_{SE=N_{SE}}^{N_{SE}} \sum_{NE=1}^{N_{NE}} \eta_{TT} \sum_{CE=1}^{N_{CE}} m_{CE} \dot{\zeta}_{CE} \right) \quad (3)$$

Equation 3 also contains a contact length term, which is used to simulate the effects of thermal expansion of the engine components during operation. It allows conductive heat transfer to occur aft of a specified axial location, which is also predetermined by the before mentioned ANSYS analysis.

D. Reactor Energy Balance

The original NESS calculations performed an energy balance by creating a control volume around the entire engine, and thus the entire enthalpy gain of the propellant was due to thermal energy from the reactor. The energy gain obtained from cooling a particular engine subcomponent was simply calculated as a fraction of reactor thermal output. With the upgrade to accept an existing reactor design, however, the reactor energy balance has become more involved.

The data obtained from MCNP can be used to calculate thermal energy generation rates in all the reactor components that are contained in the output file. Thus, if various components weren't modeled, or not included in the output files, their thermal contribution to the engines' thermodynamic cycle must be estimated using the original NESS percentages. This is done by taking the appropriate energy fractions normalized to the cores', not the total, thermal energy output, and multiplying by the current reactor design core thermal energy deposition rate. This highlights the difference between the classical thermodynamic handling of NTR engine systems, and the reality of nuclear systems, where thermal energy deposition can occur in engine components due to their individual nuclear interactions.

E. Propellant Flow Rate Determination

In the original NESS algorithm, propellant flow rate was determined by the chamber conditions, thrust required, and the nozzle area ratio, all of which are inputs to the code and the reactor design process⁶. With the ability to accept MCNP calculated results of a reactor design as input, propellant flow rate, and thus thrust, are now calculated outputs. The primary driver in the propellant flow rate calculations is the peak fuel temperature. NESS now cycles through all the fuel elements to determine which has the highest thermal power output, once heat transfer to the tie tubes is taken into account, and performs a pressure drop analysis on a propellant channel in this particular fuel element. Because the transport properties of the propellant are functions of temperature and pressure, the fuel element with the highest heat generation requires the largest propellant mass flow rate to provide adequate cooling, and thus also have the highest pressure drop of any fuel element in the reactor. Therefore, it sets the minimum required reactor inlet manifold pressure as well as the minimum chamber pressure.

NESS has been upgraded to utilize the inlet manifold pressure calculated for the highest performing fuel element as a starting point to calculate the effective inlet pressure required by each fuel element to reduce the propellant mass flow rate to a level where by the maximum allowable fuel temperature is reached in each fuel element, thus maximizing fuel, and engine, performance. On the other hand, if all the fuel elements were subject to the same pressure drop, the propellant exit enthalpy and mass flow rates would vary across the reactor, thus reducing engine Isp. The importance of scheduling the propellant mass flow rate is illustrated in Fig. 9 for a NERVA derived fuel element operating at SNRE inlet and exit conditions, and shows how propellant mass flow rate and exit enthalpy vary as a function of available fuel element power.

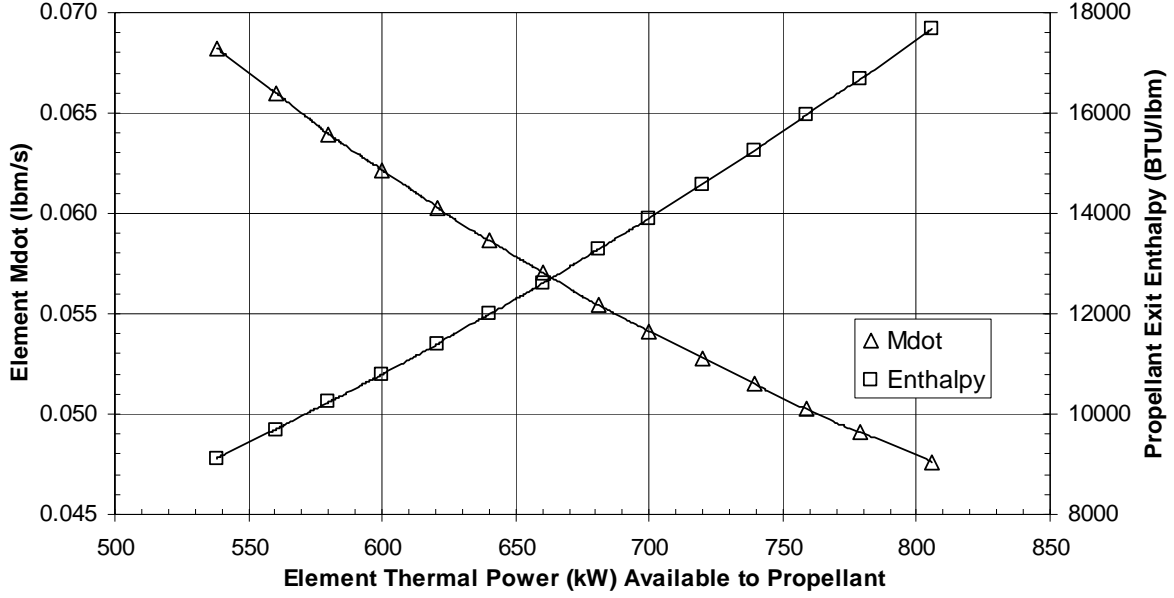


Figure 9. Fuel Element Propellant Mass Flow Rate and Exit Enthalpy vs. Fuel Element Available Power. *Hydrogen cooled NERVA derived fuel element operating at SNRE conditions.*

Due to the heat gained by the propellant while passing through various NTR components, in conjunction with the pressurization performed by the TPA, the hydrogen propellant is a supercritical gas when it reaches the reactor inlet. Thus, the heat transferred to the propellant by the fuel elements is determined by both the absolute pressure of the propellant and the pressure drop across the fuel element, since the propellant can not be considered incompressible. In addition, the propellant transport properties are functions of pressure and temperature, which vary along the length of the fuel element. This leads to an iterative solution where the equations for heat transfer and pressure drop are solved together for each axial segment along the contact length until the channel wall temperature converges for a steady state operating condition, so that Eq. (4) is satisfied.

$$\left(1 - \sum_{TT=1}^{N_{TT}} \eta_{TT}\right) \sum_{CE=1}^{N_{CE}} m_{CE} \dot{\zeta}_{CE} = \sum_{Chn} \dot{m}_{Chn} (h_{i+1} - h_i) \quad (4)$$

Once solved, these equations yield a unique inlet pressure, fuel element pressure drop, propellant exit properties, and a fuel element axial temperature profile for each fuel element.

F. Engine Performance

Now that NESS has calculated the conditions required at the reactor inlet manifold, it must iterate within the flow circuit, shown in Fig. 2, until a TPA power balance is achieved, maximum allowable fuel temperature is not exceeded, and the engine cycle closes. At this point, the mass averaged enthalpy at the thrust chamber is calculated via Eq. (5), and is used in conjunction with the calculated chamber pressure to yield the mass averaged thrust chamber temperature.

$$\bar{h}_{Ch} = \frac{1}{\dot{m}_{Total}} \sum_{FE=1}^{N_{FE}} \sum_{Chn} \dot{m}_{Chn} h_{Exit} \quad (5)$$

With the mass flow rate, chamber temperature, and chamber pressure now known, the nozzle area ration can be used to determine the engine's thrust and Isp. Engine component mass estimates can also be obtained from the MCNP data, if all the required component data are represented. Otherwise, the original NESS mass estimation algorithm is used.

G. Shield Model

NESS has both an external and internal shield model. The external shield model has been recently updated, and now provides the option of a three part user defined shield. The shield consists of two stacked disks encircled by a third annular shield which can be either cylindrical or tapered, as is shown in Fig. 10. The material density, radii, thicknesses, and void fractions (for propellant cooling passages) are input by the user. Although typical shield materials such as lead and borated aluminum titanium hydride (BATH) are the defaults in NESS⁶, the new shield model allows the user to use any materials they wish.

At the time of this writing, NESS does not yet perform any radiation reduction or mass based optimization calculations with this external shield model, or the default external shield model, but simply tracks the shield mass.

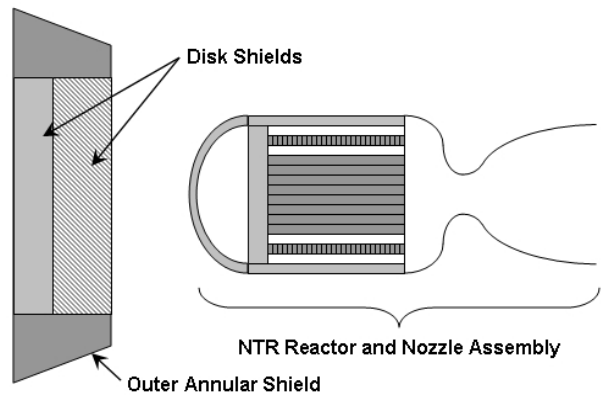


Figure 10. User Defined NESS External Shield. External shield is shown with its' relative placement to the reactor and nozzle assembly for illustration purposes only. Drawing is not to scale.

V. Conclusion

Due to the work accomplished during the NERVA program, and recent advances in computational techniques, system level design and analysis tools such as NESS are being updated to increase both their capability and flexibility. With the ability to utilize higher fidelity level inputs from other disciplines, NESS can accomplish more detailed system and component design and analysis, while maintaining its original capability and ease of use.

Acknowledgments

The author would like to thank Mr. Joseph A. Hemminger, Bruce Schnitzler, Dr. Stan Borowski of the NASA Glenn Research Center, as well as the Prometheus Power and Propulsion Project for their leadership and guidance throughout this work.

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