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Abstract

A general review of the technical merits of nuclear thermal rocket clustering is presented. A summary of previous analyses performed during the Rover program is presented and used to asses clustering in the context of projected Space Exploration Initiative missions. A number of technical issues are discussed including cluster reliability, engine-out operation, neutronic coupling, shutdown core power generation, shutdown reactivity requirements, reactor kinetics, and radiation shielding.

INTRODUCTION

Clustering of rocket engines refers to the parallel connection of two or more individual engines so that the performance of the propulsion system is superior to that of a single large engine. Chemical propulsion stages have employed clustering with great success for many years. Clustering of Nuclear Thermal Rocket (NTR) engines is of particular interest for those Space Exploration Initiative (SEI) missions which require high thrust (such as a piloted Mars Mission). Clustering is additionally advantageous as it may lead to 1) reduced single engine ground test facility size and cost, 2) the ability to meet a wider range of mission profiles through varying the number of engines in the cluster, 3) increased propulsion system reliability through redundancy, 4) lower engine development costs due to the reduced size of each engine and 5) reduced flight safety concerns through an engine-out operating capability. Figure 1 presents a sketch of a conceptual cluster configuration containing three engines. This figure identifies several important clustering issues: propellant heating, reactivity coupling, and payload dose due to scattering among the engines and off the nozzles. Control (startup and shutdown), engine-out performance, power tilting and stability are several other issues not depicted in this figure. Note that this concept utilizes engine/tank modules, as opposed to a single-tank configuration in which all engines share a common large tank. The modular approach was investigated in much detail during the Rover program under WANL's Project NE 1840 (Kim 1966). Key topics addressed by WANL included preliminary shield optimization, neutronics, kinetics, and control. A single tank configuration may be preferable because it minimizes tankage mass fraction and eliminates any streaming pathways from the engine cluster to the spacecraft payload.

FIGURE 1. Historical Cluster Configuration Employing Separate Engine/Tank Modules and Asymmetric Side Shields for Propellant Heating Minimization.

In addition to the work done by WANL, other studies performed by Aerojet General as part of Rover (Houghton 1965) and Douglas Aircraft Company through an internal R&D program (Woyski and Langley 1968) analyzed clustered NTRs. Nuclear interactions between coupled reactors was also investigated in detail at Los Alamos National Laboratory and a benchmark subcritical experiment was performed between two KIWI class reactors in September and October of 1964 (Chezum et al. 1967). The reference section contains a concise listing of relevant reports that came out of these efforts.

The departure point for this paper is an abbreviated argument for the use of a clustered NTR propulsion system. The probability of mission success rests heavily on the reliability of the spacecraft's propulsion system. A highly reliable clustered engine system is more easily attainable than a highly reliable single large engine because of the redundancy offered by the engine-out capability of a clustered propulsion system. This argument is calculated by

$$R=\sum_{k=0}^{n} \frac{N!}{(N-k)!k!} R_E^{N-k}\left[R_s\left(1-R_E\right)\right]^k, \tag{1}$$

where R is the overall propulsion system reliability, R_s is the engine-out safety (or shutdown cooling) subsystem reliability, R_E is the single engine reliability, N is the number of engines in the cluster, and n is the number of failed engines acceptable with mission success (Woyski and Langley 1968). Figure 2, shows the overall propulsion system reliability as a function of single engine reliability and the reliability of the engine-out safety subsystem (for a three engine cluster with a one engine-out capability). The safety system is needed in order to assure that the balance of the engines are not affected by any one failed engine. The advantage of a cluster system over that of a single engine system results from the ability of the cluster system to perform sufficiently when one of the engines fail. To emphasize this fact, Figure 2 shows the case where only a single large engine is employed (system reliability equals engine reliability). For an arbitrary system reliability goal of 0.991 and a 100% reliable safety subsystem, the reliability requirement for a cluster of three engines is 0.943 for any single engine in the cluster whereas a single large engine must be 0.991 reliable to attain the same 0.991 goal. Over 500 successful demonstrations of engine performance with one failure would be required to meet the 0.991 goal while less than 100 similar demonstrations would be needed to show 0.943 reliability (Woyski and Langley 1968). Consequently, the potential savings that a smaller testing program would result in makes clustering an attractive option worth pursuing. The disadvantage of clustering is a lower thrust/weight compared to a single large engine. Aerojet General estimated an overall mass penalty for clustering of around 30% but went on to identify a number of significant development challenges for the large NTR (Houghton 1965). The objective of this paper is to address the technical feasibility of clustering by grouping the majority of relevant issues into three areas: operational issues, reactor nuclear issues, and spacecraft shielding issues. The remaining sections address each of these areas by (where possible) summarizing past analyses and comparing them with present day technical, safety and performance requirements.

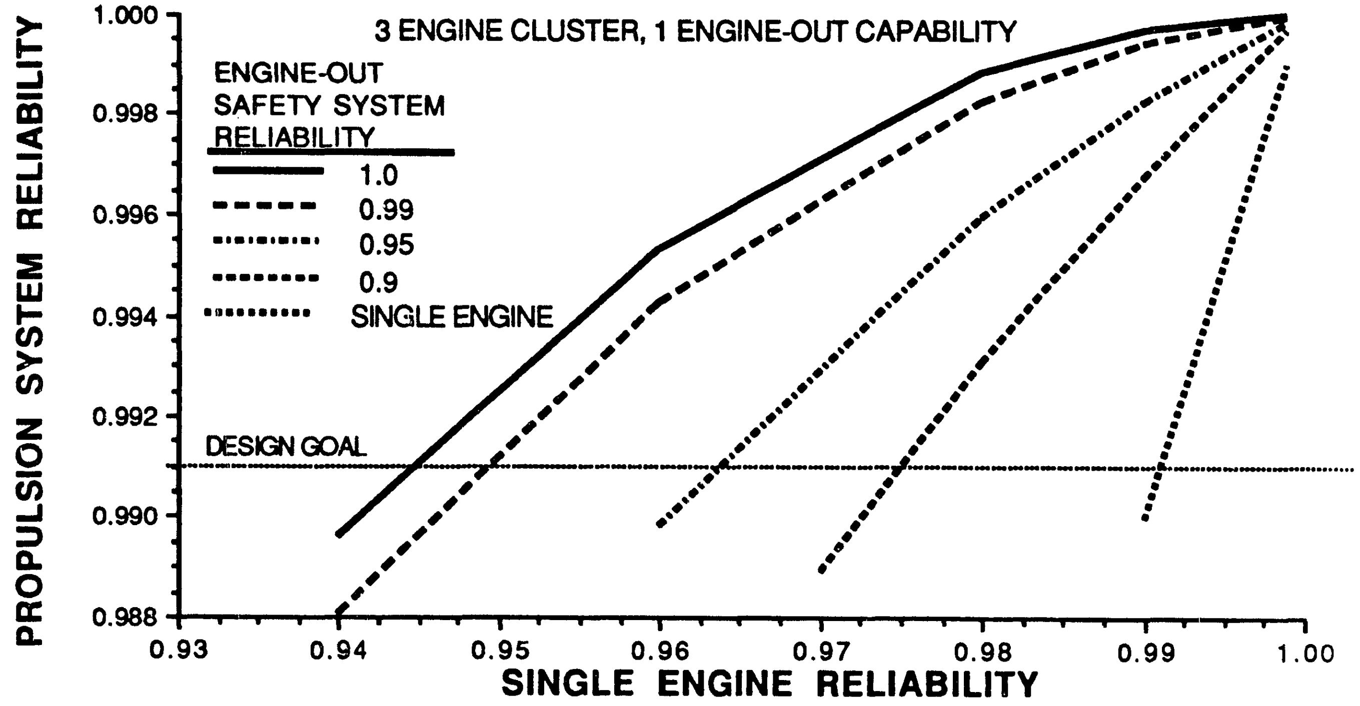

FIGURE 2. Propulsion System Reliability as a Function of Single Engine and Engine-out Safety System Reliabilities for a Three Engine Cluster.

OPERATIONS

Perhaps the most important near term issue deals with the operation of the cluster and the philosophy by which an engine-out accident (EOA) will be handled. The EOA refers to any situation where an engine fails to rise to full power upon demand (irregardless of the cause of failure). In order to assist in this discussion, Table 1 was constructed which describes six possible operational schemes for a cluster system. The schemes use either 1) a pulsed cooling engine-out safety subsystem or 2) an engine-out jettison safety subsystem. A pulse cooling subsystem uses pulses of LH_2 propellant to cool a shutdown engine, removing any decay heat or coupling fission power generated in the core. The shutdown coupling power is present only if the adjacent reactors are still operating and is a consequence of the neutronic coupling between the cores. More will be said about steady state and shutdown neutronic coupling later. The jettison safety subsystem consists of some mechanism to rapidly disconnect the failed engine and eject it from the vicinity of the spacecraft. The need to either cool or jettison a failed engine is required in order to protect the remainder of the spacecraft from the possible consequences of reactor core melting. Furthermore, because trans-Mars injection may incorporate a triple perigee burn, jettison of a used engine before the third burn would entail jettison into Earth orbit. Even though the jettison system is essentially 100% reliable top level safety requirements may preclude the incorporation of a jettison system. Consequently, the three operational schemes in Table 1 which use a jettison system are not considered any further.

The concept of shutdown engine cooling by pulse cooling has been studied in fair detail (Retallick 1971) and was employed in many of the engine tests during Rover. Immediately after scram, full propellant flow is maintained until the decay power level is low enough to allow pulse cooling. Short bursts of propellant are then pumped through the reactor when core temperatures are sufficiently high. It was shown that propellant usage can be minimized if each pulse is long enough to sub-cool the core slightly. Three of the schemes in Table 1 use this technique to cool a shutdown engine. Of these, scheme 1 is undesirable because of the range of possible thrust/burn time combinations that result from not knowing when an engine will fail during the mission. Schemes 2 and 3 are attractive because they offer near constant propulsion system thrust/weight ratios in the event of an EOA. Scheme 3 offers a slightly higher reliability because the nominally operating engines are at a reduced thrust level (lower power, propellant flow rate, axial pressure drop, and axial stress). Note, however, that if the nominal thrust level is 75 klb (1500 MW) then the EOA (or design) thrust level is 112.5 klb (2250 MW) for a three engine propulsion system nominally rated at 225 klb thrust. A larger cluster of smaller engines will reduce the difference between the nominal and EOA power levels. Consequently, both schemes 2 and 3 should be investigated further. The selection of a final operational scheme should be made as early as possible so that consistent top level requirements can be specified .

TABLE 1. Descriptions of Possible Engine Clustering Schemes Including Engine-out Operation.

	ENGINE CLUSTERING SCHEMES		
ENGINE OUT FATE	1	2	3
PULSE SUB-COOLING	**A D E**	**B D F**	**C D F I**
JETTISON	**A E G H**	**B F G H**	**C F G H**

A- Nominal: all engines full thrust. Engine-out: remaining engines continue for longer burn.
B- Nominal: all engines full thrust, spare not run but cooled. Engine-out: spare engine stepped to full thrust.
C- Nominal: all engines at throttled thrust. Engine-out: remaining engines stepped to full thrust.
D- Propellant re-route if separate engine/tank modules are employed.
E- Optimal trajectory must envelope all possible combinations of nominal and engine-out thrust and burn time.
F- Near constant thrust/weight ratio maintained.
G- Safety concern related to jettison of used engine in Earth orbit.
H- Higher single engine reliability required to account for jettison system reliability.
I- Lower single engine reliability required due to reduced power during nominal operation.

NEUTRONICS/KINETICS

The primary difference between the behavior of an autonomous nuclear rocket engine and the behavior of an engine that is a member of a propulsion system cluster is the neutronic coupling that occurs between engines. This interaction can be described by the coupled reactor point kinetics equations:

$$\frac{dn_1(t)}{dt} = \frac{\left(\rho_1(t)-\overline{\beta}\right)}{l_1} n_1(t) + \sum_{g} \lambda_{g1} C_{g1}(t) + \sum_{i=2}^{m} a_{i\rightarrow 1}\left[\frac{n_i(t-\tau_{i\rightarrow 1})}{l_i}\right] \qquad (2)$$

and $$\frac{dC_{g1}(t)}{dt} = \beta_{g1}\frac{n_1(t)}{l_1} - \lambda_{g1} C_{g1}(t), \qquad (3)$$

where n is reactor power, l is average neutron lifetime, ρ is reactivity, β is the total delayed neutron fraction, λ_g is the gth group precursor decay constant, C_g is the gth group precursor concentration, $\alpha_{i\rightarrow 1}$ is the coupling reactivity at reactor 1 due to reactor i, and $\tau_{i\rightarrow 1}$ is the transfer time delay of neutrons leaving reactor i and reaching reactor 1. If all reactors in the cluster are identical, at the same steady state power level, and $\tau_{i\rightarrow 1}$ is neglected, the last term of Equation (2) becomes a total reactivity coupling coefficient at reactor 1 due to all other reactors in the cluster (Woyski and Langley 1968, Chezem et al. 1967, and Mowery and Romesburg 1965). Simplistically, the coupling coefficient is the amount of reactivity that must be added to reactor 1 in order to restore its criticality when the ith reactor is removed from the cluster. Mathematically, the coupling reactivity between engine 1 and the ith engine is the product of three factors: a leakage factor for the ith engine, a geometric attenuation factor between the two reactors, and an effectiveness or reactivity factor for engine 1. Individual coupling reactivities can be superimposed to get the last term of Equation (2) for clusters of greater than two engines.

Several methods have been developed to estimate these three factors for a cluster of NTRs. WANL employed multigroup transport calculations to estimate the driver core leakage and driven core effectiveness factors. Douglas developed a simple method for estimating the geometric attenuation tor but did not consider the angular importance of incident neutrons at the driven core boundary. WANL and Douglas later made adjustments to account for this deficiency. WANL predictions of t pling reactivity between two identical cores at criticality are presented in Figure 3 along with tl rimental results of the KIWI-PARKA experiment at Los Alamos. As expected, the coupling re y between cores is small and is inversely proportional to separation distance and to core size. It is important to realize that coupling is relative; it makes sense only when talking about the coupling at one reactor due to another. This idea is graphically depicted in Figure 1 which shows the six coupling coefficients involved in a three engine cluster. In the nominal operating case all of the coefficients are equal and coupling is straight forward. Only in the EOA case are there more than one coefficient. For example, in the case where engine #3 is out: $\alpha_{1\rightarrow 2} = \alpha_{2\rightarrow 1}$ = several cents, $\alpha_{3\rightarrow 1} = \alpha_{3\rightarrow 2}$ = zero , and $\alpha_{1\rightarrow 3} = \alpha_{2\rightarrow 3}$ = engine #3 shutdown margin, which is typically minus several dollars. The fact that coupling is not reversible between the out engine and any operating engine is of little consequence except for the shutdown engine's power tilting which is discussed later.

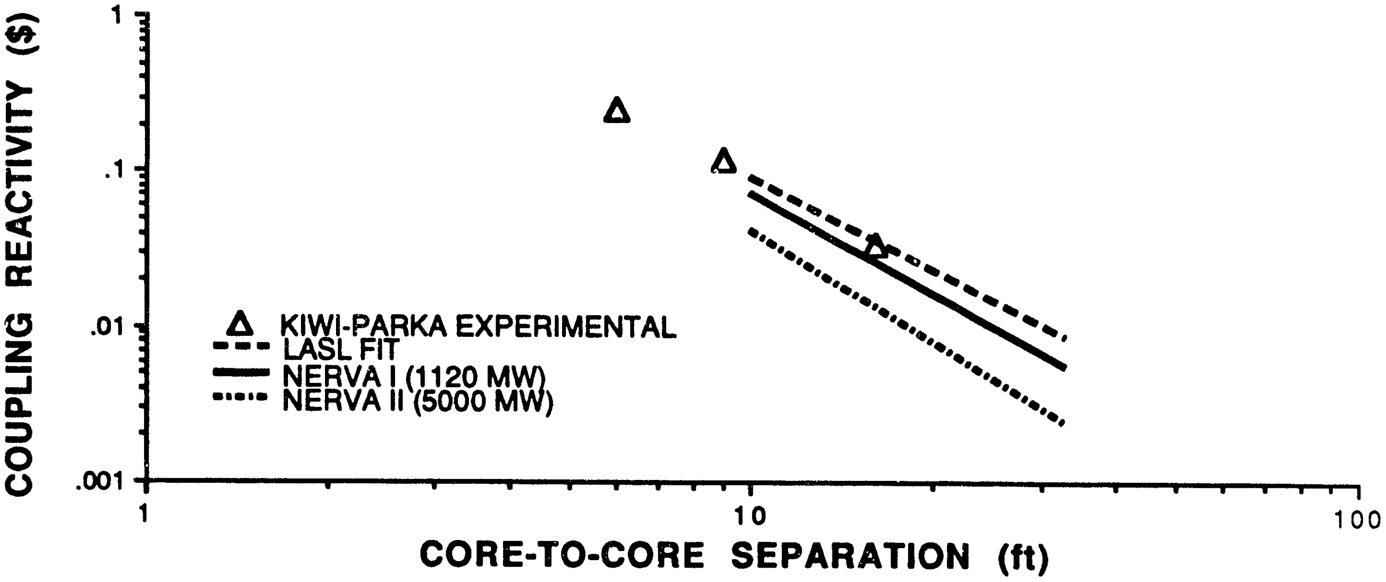

FIGURE 3. Experimental and Past Analytical Predictions of Coupling Reactivity as a Function of Core Separation.(from Kim 1966).

One unwanted consequence of neutronic coupling is the subcritical fission power generated in an out engine during an EOA. Recall that the coupling coefficient is the product of leakage, geometric attenuation and incident neutron fission effectiveness factors. Between a shutdown engine core and an operational core the leakage and geometry factors are constant from nominal to EOA conditions. Relative to the shutdown engine, however, the effectiveness factor scales linearly with the subcritical multiplication factor which in turn scales linearly with the shutdown margin of the shutdown core. Even though the shutdown reactor is far from critical, the nearby operating engines act as a significant source of neutrons which can undergo multiplication and produce power. Furthermore, the leakage term scales linearly with the power level of the driver core and the geometric term varies little for constant core separation distances (because of small changes in the view factors between reactors). WANL calculated the shutdown power level as a function of coupling coefficient for both the NERVA I (1120 MW) and the NERVA II (5000 MW) engines. Table 2 presents several shutdown power levels calculated by WANL along with other scaled estimates for several shutdown margins and for a 1500 MW nominal power level. Also shown in this Table are the 2% decay power levels (following scram) for comparison. Note that even for minimal shutdown margins, pulse cooling systems designed for decay power levels should be more than adequate to remove EOA coupling powers (assuming the original failure mechanism does not propagate to the shutdown safety subsystem).

Table 2. Cluster Shutdown Engine Heat Generation Rates due to Decay Power and Neutronic Coupling to Adjacent Operating Engines.

Nominal Engine Power Level (MW)	Maximum Decay Power Level (MW)	Power Level in Single Shutdown Coupled Core[1] Shutdown[2]= $2	$4	$25
1100	44	31[3]	15[3]	2.5
1500	60	41	21	3.3
5000	200	110[3]	60[3]	8.8

[1] Multiply by number of active engines in cluster to get total heating in shutdown engine

[2] β=0.007

[3] From Mowery and Romesburg 1965.

The subcritical fission power generated in the shutdown reactor is not, however, evenly distributed throughout the core. During nominal operation, power tilting is very small. Both LASL and WANL calculated nominal core power tilting levels of less than 1% and the KIWI-PARKA experiment demonstrated the same (Kim 1966, Chezum et al. 1967). During an EOA, however, power tilting is proportional to shutdown margin and peak-to-average heating rates on the order of 4 or 5 at the shutdown core interface with an adjacent operating reactor will be experienced. Although not presented here, WANL clearly showed this effect as a function of radial position and shutdown margin (Mowery 1965). LASL experimentally showed these behaviors and more recently, we have used MCNP to show this effect and results are presented in a companion paper. Note that as the shutdown margin increases in magnitude, the total amount of fission power generated in the shutdown core decreases but preferentially peaks at the peripheral interface of the core. Table 2 indicates that the peak heating rate due to coupling power is much less than the decay power level right after shutdown. In fact, the 4% decay power level shown corresponds to the heating rate immediately after scram and drops off with a stable period of 80 seconds soon afterwards. This decay power level is determined by the prompt drop approximation:

$$\frac{P}{P_0} = \frac{\beta}{\rho_s + \beta} \qquad (4)$$

where P is the power level, β is the total delayed neutron fraction and ρ_s is the shutdown reactivity.

Consequently, during an EOA ρ_s influences the integrated energy generated in the scrammed reactor, the amount of coupling between reactors in a cluster, and the power tilting in the shutdown core. The $25 margin indicated in Table 2 is used to estimate the maximum decay power level and is an estimate based on preliminary water immersion criticality calculations using a detailed MCNP model. This large shutdown margin will substantially reduce shutdown core coupling power but will strongly perturbate the power generation towards the adjacent reactor interfaces. Once all engines in the core are shutdown, the coupling power level goes to zero and the shutdown cooling system need only remove decay heat which drops to about 0.1% of the nominal power level in about one hour.

Several other issues are relevant to any technical discussion of clustered NTRs but, unfortunately, are beyond the scope of this paper. In particular stability, control, and detector positioning have been identified as points requiring further analysis. Both WANL and Douglas derived the transfer function for a cluster of nuclear rockets and found that no inherent instabilities exist. In fact, open loop stability was found to be higher for the cluster than for a single engine because of the neutronic coupling loops. LASL experimentally determined the zero power transfer function of the KIWI-PARKA system using an oscillating rod technique and similar conclusions were drawn. Both WANL and Douglas predicted that sequential startup of the cluster poses no obvious problems. Douglas did, however, show that simultaneous startup, or for that fact any common mode transient, would lead to power density spikes due to inherent feedback reactivity exacerbated by neutronic coupling. Staggered startup tends to smooth the rise of all engines and should be considered (Kim 1966, Chezum et al. 1967 and Woyski and Langley 1968). In order to facilitate a rapid and smooth simultaneous startup, a reactivity based controller should be considered in order to close the control loop. In this case, detector location may play a role in the effectiveness of the control system especially if in-line or nonsymmetric engine configurations are employed.

SHIELDING

The technical challenge of shielding a cluster of NTRs is only marginally more difficult than of shielding a single large engine. Of particular concern is the shielding mass penalty associated with using a cluster instead of a single large engine. The discussion here is general in nature as a more detailed discussion is presented in a companion paper (Houts and Buksa 1991). Shielding may be needed to shield one reactor from another or the spacecraft from the cluster as a whole. For example, shielding requirement for spacecraft components (such as turbopumps, valves, propellant tanks, or electronic equipment) is significantly different from those for shielding a crew from reactor generated radiation. In both cases it is important to account for both primary (originating from the reactor) and secondary (from primary collisions) radiations. Figure 1 depicted two of the most important secondary sources: the (N,γ) reaction in liquid H_2 and nozzle scattering. Neutron scattering rates from the nozzle will be small because the nozzle contains very little mass. Gammas scattered back towards the payload will have low energies and can be attenuated by residual propellant or by spot shielding of the crew. Primary neutrons and gammas can best be shielded at the reactor where the shield cross sectional area is the smallest. A single tank configuration will offer additional shielding from the reactors and nozzles because its diameter would shadow shield the entire propulsion system. From a crew dose standpoint, an internal neutron/gamma shield may not be required because of the good attenuation of hydrogen propellant and the presence of a reconfigurable crew storm shelter. An internal shield may, however, be required to reduce tank propellant heating, the radiation dose to components located near the engine inlet, and to reduce the time that the crew has to spend in the storm shelter following the final burn if the engines are not jettisoned then (not necessarily in Earth Orbit). A preliminary internal shield design was attempted by WANL in order to arrive at an optimum shield design (Kim 1966). Throughout these analyses, the top level requirement was to minimize propellant heating through the use of internal shields and included rough estimates of the propellant heating due to the energetic (N,γ) reaction which has a large thermal neutron cross section. WANL looked at using a top shadow shield, top shield extensions, and side shields and concluded that sufficient attenuation is possible through the use of a top shadow shield with small vertical extensions. Side shields were only minimally effective and complicated the thermal-hydraulic design of the core periphery. As indicated earlier, the reactivity coupling between operating engines is very small and no neutron shielding between reactors will be needed for the sake of neutronic isolation.

CONCLUSIONS

As a consequence of their increased reliability, economy, and flexibility, clustered NTR propulsion systems should be considered for SEI missions requiring high thrust levels. As a first step an engine-out accident operational scheme should be identified as soon as possible and should take into consideration top level safety requirements and engineering practicalities. The neutronic interaction between reactors in a cluster does not impact the performance of the cluster during nominal operation. During an engine-out accident, however, the coupling is manifested as a power source in the shutdown engine (in addition to decay heat) and is preferentially located at the interface with the adjacent engine. Clustered NTRs are inherently stable, can be sequentially started, and (with small internal shields only) do not require large amounts of additional shielding in order to limit dose rates to engine components, propellant, or the crew. Several areas have been identified where further research and development may be required, including simultaneous startup, reactivity based control, detector positioning, shutdown heat removal system design and the design of a (possibly in core) large reactivity shutdown system. Contemporary computational techniques need to be developed to verify cluster neutronic, kinetic, and thermal hydraulic behaviors, particularly for the engine-out accident case which involves reactors at unequal power levels.

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