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SNAP REACTORS

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CONTENTS

	Page
Acknowledgment	6
Abstract	7
I. Introduction	9
II. Preliminary Design Considerations for SNAP Reactor Safety	11
A. Operational Reactivity Requirements of SNAP Reactors	13
III. Techniques for Achieving Water Immersion Safety	15
A. Gadolinium Isotope Applications	15
1. Effect of Placing Gadolinium on Fuel Elements	17
2. Effect of Placing Gadolinium in Core/Reflector Interface Region	28
B. Effect of Core and Reflector Geometry Changes	31
C. Combined Effects of Geometry Changes and Gadolinium	34
IV. Effect of Intrinsic Subcriticality on Operational Capabilities	35
A. Penalties Associated with Use of Gadolinium	35
B. Penalties Associated with Core/Reflector Geometry Changes	36
1. Envelope-Change Weight Penalty	36
2. Pressure-Drop Weight Penalty	37
3. Performance Penalties	37
V. Conclusions	41
Appendices	
A. Influence of Intrinsic Subcriticality on SNAP Reactor Safety	43
B. Computation of Reactor-Shield System Weight	49
References	51

TABLES

	Page
1. Dilute Gadolinium Cross-Sections	16
2. Isotopic Abundance in Natural Gadolinium	17
3. Model for SNAP 8 Fuel Element Cell	18
4. Calculated K_{inf} for SNAP 8 Fuel Element Cells with Gadolinium-155	20
5. Calculated Worth of Gadolinium-155 on SNAP 8 Fuel Element Cells	20
6. Calculated K_{inf} for SNAP 8 Fuel Elements in Arrays with 10- and 30-mil Interelement Spacing	22
7. Worth of Gadolinium-155 in SNAP 8 Fuel Element Cell Arrays with 10- and 30-mil Spacing	22
8. Calculated K_{inf} for SNAP 8 Fuel Elements in 30-mil Interelement Spaced Arrays with 10- and 15-mil Cladding Thickness	23
9. Worth of Gadolinium-155 in 30-mil Spaced Fuel Element Cell Arrays with 10- and 15-mil Cladding Thickness	23
10. Calculated K_{eff} for 349-Element Reactor with Gadolinium-155 on Fuel Elements	25
11. Spectral Coefficient of Reactivity and Spectral Reactivity Defect for Fuel Temperature Change from 73.4°F to 1292.9°F	26
12. Effective Multiplication Factors for 211-Element Reactor with Gadolinium-155	27
13. Reactivity Worth of Black Gadolinium-155 in Core/Reflector Interface Region of 349-Element SNAP Reactor	29
14. Reactivity Worth of Black Gadolinium-155 in Core/Reflector Interface Region of 211-Element SNAP Reactor	30
A-1. Summary of Applicability of Intrinsic Subcriticality	46

FIGURES

	Page
1. Total Gadolinium-155 and -157 Cross-Section Times the Square Root of Energy vs Neutron Energy	18
2. SNAP Reactor and Water Neutron-Energy Spectrum (20°C)	18
3. Worth of Gadolinium-155 in SNAP 8 Fuel Element Cell Array	21
4. Variation in Effective One-Group Absorption Cross-Section with Gadolinium-155 Concentration	21
5. Worth of Gadolinium-155 on Fuel Elements in a 349-Element Reactor	26
6. Comparative Worth of Gadolinium-155 in 211- and 349-Element SNAP Reactors	28
7. SNAP 10A Type Reactor Isoreactivity Geometries for Operational and Intrinsically Subcritical Cores	32
8. SNAP 8 Type Reactor Isoreactivity Geometries for Operational and Intrinsically Subcritical Cores	33
9. SNAP 8 Reactor and Shield Weights for Operational and Intrinsically Subcritical Core Geometry Designs	36
10. Power/Lifetime Capability Limits for Reference SNAP 8 Reactor with Outlet Coolant Temperature = 1300°F	38
11. Power/Lifetime Capability Limits for Intrinsically Subcritical SNAP 8 Type Reactor with Outlet Coolant Temperature = 1300°F	38
A-1. SNAP 10A Reactor Shipping Sleeve	44
A-2. SNAP 10A Reflector Safety Devices	44
B-1. SNAP Reactor Shield Model	50

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ABSTRACT

Potential radiological hazards associated with the construction, launch, operation, and disposal of SNAP (Systems for Nuclear Auxiliary Power) have been studied. Accidental preorbital criticality and end-of-life disposal are the two most difficult safety problems which were identified. The prevention of accidental criticality is the subject of this report.

Water flooding and reflection, which results in increased neutron moderation in a SNAP reactor core, was found to be the most reactive situation which might be accidentally encountered. Two methods are described which assure that the water-flooded and -reflected reactor will be subcritical while retaining the desired excess reactivity when in the operational (NaK-cooled and beryllium-reflected) configuration. The two methods studied were:

- 1) Using highly spectrum-dependent thermal-resonance neutron absorbers on the fuel elements and in the core/reflector interface region; and
- 2) Changing of core and reflector geometry.

These methods were both effective.

It was concluded that the use of gadolinium as a spectrum-dependent thermal resonance neutron absorber should be further explored and that it should be incorporated in future SNAP reactor designs where subcriticality in water is required.

This study was conducted as one of the projects of the overall Aerospace Nuclear Safety Program.

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I. INTRODUCTION

Operation of SNAP (Systems for Nuclear Auxiliary Power) reactors at Atomics International's Santa Susana test site has amply demonstrated their ease of control and inherent stability during normal operation. Reactivity transients including the startup transients, are limited by the large negative fuel coefficient. In addition, the reactor control system is designed to prevent accidental insertion of large reactivity steps. Safety analysis has shown that radiological problems are unlikely to occur during normal operation of a SNAP reactor. The pre- and postoperational periods are those which have required extensive safety analysis.

Specific safety problems which have been identified and analyzed are those which occur during reactor assembly, prelaunch testing, transporting and handling, launch abort, and end-of-mission disposal. These problems are discussed briefly in the Appendix. As a result of these analyses, a number of nuclear safeguards (both procedural and mechanical devices) have been utilized to reduce the probability of a nuclear incident to a low level. For example, the two primary potential safety problems in the orbital operation of SNAP 10AFS-4 were recognized and dealt with early in the SNAPSHOT program.^{(1)*}

The first potential problem was that of accidental criticality from malfunctions during handling or launch operations, or premature reentry of the test vehicle. SNAP reactors are undermoderated so that the addition of water (or other good moderator) to the core results in an increase in reactivity. In addition, many materials other than beryllium can provide sufficient neutron reflection to result in criticality. The most reactive accident situation was determined to be water immersion and flooding of the reactor core.

The second potential problem was that of radioactive fission product dispersal upon reentry after operation. (Since a SNAP reactor is not operated until satisfactory orbit is achieved, this hazard does not exist until postoperational reentry.) The problem of postoperational radioactivity is discussed in References 1, 2, 3, and 4. The problem of preventing criticality when the

*Superscript numbers in parentheses are for References at the back of this report.

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reactor core becomes flooded with or immersed in water is the main subject of this report.

Two primary methods have been explored for preventing criticality of SNAP reactors upon immersion in water.

- 1) Using gadolinium on fuel elements and reactor vessel.
- 2) Changing reactor/reflector geometry.

The first method takes advantage of the unique neutron-absorption properties of the rare earth gadolinium. Gd-155 exhibits a 58,000-barn absorption resonance at an energy of 0.0268 ev. This energy coincides with the thermal neutron peak in the energy spectrum of neutrons in water. The neutron energy spectrum in an operating SNAP 8 reactor peaks at about 0.15 ev. It is shown in this report that the fraction of neutrons absorbed parasitically in Gd increases significantly when a SNAP reactor is water-flooded and -reflected. The reactivity change which results from increasing the Gd importance is sufficient to render a reactor subcritical in water while retaining normal operational capabilities with the Be reflector and NaK coolant.

The second method exploits the high neutron-leakage characteristic of SNAP reactors and the superior neutron-reflecting properties of Be relative to water. In general, the core geometry is changed to make a reactor configuration which is subcritical in water yet supercritical when Be-reflected.

It is shown in this report that the use of Gd isotopes involves a smaller reactivity penalty than core geometry changes to accomplish the goal of intrinsic subcriticality upon immersion in water. The reactivity penalty can also be expressed in terms of shortened operating lifetime, reduced power levels, increased shield weight, or a combination of these effects. These considerations and their inter-relationships are discussed in Sections III and IV of this report.

The important conclusion of this study and the study of end-of-life shutdown devices in References 5 and 6 is that SNAP reactors can be designed so that they are inherently safe from nuclear hazards for most conceivable missions.

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II. PRELIMINARY DESIGN CONSIDERATIONS FOR SNAP REACTOR SAFETY

SNAP reactors are compact, zirconium-hydride 10 wt % uranium fueled, liquid-metal cooled, beryllium-reflected reactors designed for reliable electrical power generation in space. Terrestrial, lunar, and marine applications are also feasible and are being explored. Description of a typical SNAP 10A reactor is given in Reference 2, a SNAP 8 reactor in Reference 7, and a higher-powered 349-element reactor in Reference 8.

These reactors have two principal characteristics which influence their normal performance and contribute to their response to water flooding and water reflection. These are a core having high neutron leakage and an under-moderated fuel. The compact high-neutron-leakage core design permits control of the operating reactor by use of movable reflector pieces called control drums. They rotate to vary the fraction of neutrons which leak from the system during operation. They are "opened" to increase neutron leakage, which shuts the reactor down. During normal operation, about 1/3 of the fission neutrons leak from the reactor.

The reactor is subcritical in air when the Be reflector is removed. Tests conducted in the Aerospace Safety Program have demonstrated that the SNAP 10A type Be reflector is invariably ejected upon, or before, impact on earth or water.⁽⁹⁾

The high neutron leakage which makes leakage control possible is also the primary contributor to the problem of accidental criticality. Analyses have indicated that neutron reflection by many materials other than Be might result in criticality. Several materials other than Be have been found to be quite effective neutron reflectors. Of these materials, water has been found to be the most probable reflector in an accident situation. Water is also the most reactive reflector material which might be encountered accidentally. The probability of accidental reflection by soil is lower than by water. In addition, soil is a less reactive neutron-reflector material than water, even when it is fully water-saturated. Therefore, only accidental water reflector has been analyzed in detail in this report.

Most of the leakage from a SNAP core (about 90%) is at energies in excess of 100 kev. The energy spectrum of the reflected flux (that returning to the core), depends upon the neutron-scattering properties of the reflecting material.

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Be is an excellent fast-neutron scattered with an $n, 2n$ reaction exhibited in the Mev range of energies and a very low absorption cross-section. It is the most reactive reflector material known. Water is also a good neutron scatterer, but is a better moderator than Be. That is, scattering is predominantly elastic with a large energy loss per event. The result is that neutrons are rapidly thermalized in water. Neutron decay and parasitic absorptions then significantly decrease the fraction of leaked neutrons which are returned to the SNAP core.

As an example of comparative nuclear worth of the reflecting materials; 2 to 2-1/2 in. of Be have been determined to be equal in worth to an infinite thickness of water reflector. The exact thickness depends on the reactor composition or, more specifically, the neutron-leakage spectrum and interface region macroscopic absorption cross-section.

The undermoderated fuel of SNAP reactors results in a reactivity increase when the core is water-flooded. The increased neutron moderation resulting from increasing the hydrogen/uranium ratio by adding water to the core results in a significant reactivity gain.

In this report, it has been assumed that the accident situation always results in (1) removal of the radial Be reflector, and (2) water flooding of the core region and infinite water reflection on all external surfaces of the core. The first assumption is based on data of Reference 9 which showed that the loosely connected Be reflector was readily separated from the reactor by a short drop onto soil or by reentry impact on soil or water. The second assumption is based on analysis which showed that water was the most reactive reflector material which might be encountered in an accident situation.

The concept of modifying the core in some way to render the bare (no Be reflector) core subcritical when water-flooded and -reflected has been termed "intrinsic subcriticality." The change in core neutron-energy spectrum which results from water-flooding of the core has been used in achieving intrinsic subcriticality through use of Gd on the fuel elements. This method is discussed in detail in Section III-A.

The high neutron leakage from the core has been used in two different ways to achieve intrinsic subcriticality. The application of Gd to the core/reflector interface region does not interfere with normal operation because the leakage and the reflected-neutron spectrum is fast. The energy lost per scattering event in Be is small.

When the Be reflector is replaced by water, however, the reflected spectrum is thermalized by elastic scattering in the water. The reflected flux

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(returning to the core) is significantly reduced by parasitic absorptions at the Gd thermal energy resonance.

The second method of using the high-leakage characteristic to achieve intrinsic subcriticality is to change the core geometry to increase core leakage. The core diameter may be decreased until the water-flooded and -reflected core is subcritical in water. The excess reactivity required for satisfactory system performance may be regained by using a thick Be reflector which is more reactive than the infinite water reflector.

SNAP reactors are designed for certain specific missions.⁽¹⁰⁾ The reactor design considers power and lifetime capabilities, reliability, system weight, and safety. Safety features are incorporated in the design to minimize the probability of an accident during handling and prelaunch operations, and to prevent accidental criticality in the event of launch abort over water. For example, a shipping sleeve of boron and void was designed for the SNAP 10A flight reactor to prevent criticality accidents during fueling, shipping,⁽¹¹⁾ and other pre-launch operations. Intrinsic subcriticality possesses the advantage of providing water immersion safety through nearly all phases of reactor operation until orbit is successfully achieved. The applicability of intrinsic subcriticality to each operational phase is summarized in the Appendix.

Whether use of Gd or core/reflector geometry changes are selected to provide intrinsic subcriticality, it is possible that the design change will affect the operational performance in some way. For example, reducing the core diameter may limit the operational power level or lifetime. Use of Gd may result in some unburned poison remaining at the end-of-life thus tying up some reactivity which might have been used to extend operation or reduce the system size. Therefore, intrinsic subcriticality must be traded off against other design requirements to determine the cost in system capabilities or weight. Many missions (e.g. most terrestrial installations) do not require intrinsic subcriticality. Missions where launch abort is possible will usually require intrinsic subcriticality.

A. OPERATIONAL REACTIVITY REQUIREMENTS OF SNAP REACTORS

An approximate indicator of the potential operational capabilities (power/lifetime limitations) of a SNAP reactor is the amount of "cold clean" excess

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reactivity of the specific reactor design. The cold clean excess reactivity is that of the Be-reflected core with control drums fully inserted at 20°C with no fission products or burnable poisons in the core. Gd and end-of-life shutdown devices are also excluded in the cold clean case.

A sufficient amount of excess reactivity must be provided to compensate for the temperature and power defects, short-term reactivity losses (xenon buildup and hydrogen redistribution), samarium-149 accumulation, slow- and nonsaturating fission products, uranium fuel burnout, and hydrogen loss. In high-temperature SNAP reactors (1300°F outlet NaK temperature), the temperature defect and operational H₂ leakage are the two primary reactivity losses. For example, the temperature and power defect will be about \$2.15 and H₂ loss about \$3.75 for a typical 600-kw 211-element SNAP 8 design with $N_H = 6.05 \times 10^{22}$ at./cc.

Sm-149 fission product buildup may be compensated by preloading an equilibrium concentration of the isotope.

All other reactivity losses are compensated by control drum insertion or use of a burnable poison, or a combination of these mechanisms. Xe and H₂ redistribution for the above reactor will total about \$1.60 and the remaining fission products (excluding Xe and Sm) and fuel burnup will total about \$1.30. Thus, a total cold clean excess reactivity of about \$8.80 is required for this 1-yr operation case. The reactor meets this reactivity requirement with a Be reflector thickness of 3-1/4 in. The problem of intrinsic subcriticality is to provide an excess reactivity of less than \$0.00 when the reactor core is reflected by and filled with cold water, with a minimum performance penalty during normal operation. That is, the removal of the Be reflector and substitution of water, plus water-flooding of the core, must result in a reactivity reduction of $\geq \$8.80$ if intrinsic subcriticality is to be achieved in this specific example. Reactors designed for longer than 1-yr operation, or for operation at higher power or temperature, will generally have a higher cold clean excess reactivity.

The use of burnable poisons reduces the cold excess reactivity of the core by the reactivity worth of the poison. (The reactivity loss is potentially all restored during operation.) The reactivity change required to make the core subcritical when immersed in water is also reduced. This effect is discussed later.

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III. TECHNIQUES FOR ACHIEVING WATER IMMERSION SAFETY

In addition to the two methods listed previously for achieving intrinsic subcriticality, an additional one has been recognized but not fully explored. This involves changes in the core composition (e.g. decreased uranium content) so that the reactor becomes slightly overmoderated. The addition of water to the core would then further increase neutron moderation and lower the core reactivity. This method has not been examined in detail because the current undermoderated SNAP design was chosen for near-minimum reactor/reflector volume. An overmoderated core with the same power capabilities would be significantly larger in size and, hence, total system weight. In addition, changes in H_2 -to-U ratio might necessitate a new fuel development program to verify the manufacturing techniques and the reliability of the new fuel elements. The two methods for achieving intrinsic subcriticality which were chosen for study do not require the development of new fuel material.

The use of in-core burnable poisons has been considered throughout the SNAP reactor development program. In fact, every SNAP reactor operated to date (excepting the SNAP Experimental Reactor, SER) has contained Sm-149 as a prepoison to compensate for accumulation of fission product Sm-149, or to provide an operational reactivity gain in addition to the compensation. However, Sm-149 burns out quite rapidly at power levels above about 600 kw. Other burnable poisons have been studied in detail elsewhere.⁽¹²⁾

Both techniques for achieving intrinsic subcriticality which are presented in the following sections sometimes require use of a burnable poison to reduce the cold excess reactivity of the core. The cold (prepoisoned) excess reactivity of the core need only be sufficient to overcome the startup defects and short-term reactivity losses (plus a control contingency) if the burnable poison's burnout approximately matches the operational reactivity losses. This design approach is illustrated in examples in the following sections.

A. GADOLINIUM ISOTOPE APPLICATIONS

Gadolinium is a rare earth which has only recently become available in separated isotopic form. Two of the isotopes, Gd-155 and -157, exhibit very large absorption resonances in the thermal-neutron energy range. Accurate

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measurements of the Gd resonances were made in 1960, as reported in Reference 13. A 26-energy-group set of absorption cross-sections was recently prepared at Atomics International for both Gd-155 and -157. The pointwise cross-sections were weighted over a SNAP reactor neutron spectrum for use in reactor calculations. The prepared cross-section sets are shown in Table 1. The small cross-section changes shown in the table result from spectrum changes within each individual energy group. These intra-group spectrum changes cause small, but significant (up to 5%), changes in the effective group cross-section. Inter-group spectrum changes are adequately calculated by the ANISN neutron transport theory computer code.

The isotopic abundance of each isotope in natural Gd is shown in Table 2. The absorption cross-section of Gd-157 is so large that most (~80%) of the absorptions which occur in natural Gd can be attributed to this isotope. It is useful as a burnable poison only in the SNAP 10A power level range (40 to 60 kw).⁽¹²⁾

TABLE 1
DILUTE GADOLINIUM CROSS-SECTIONS

Group	Lower Energy		Gadolinium-155			Gadolinium-157		
			Spectrum Weighting			Spectrum Weighting		
			SNAP Reactor		Water	SNAP Reactor		Water
			73°F	1293°F	73°F	73°F	1293°F	73°F
1	3.0	Mev	0.076			0.021		
2	1.4	Mev	0.166			0.050		
3	0.9	Mev	0.260			0.086		
4	0.4	Mev	0.394			0.146		
5	0.1	Mev	0.717			0.314		
6	17.	kev	1.648	Same as at 73°F	Same as SNAP Reactor	0.781	Same as SNAP Reactor	Same as SNAP Reactor
7	3	kev	4.756			3.332		
8	550	ev	13.049			16.932		
9	100	ev	33.235			82.310		
10	30	ev	70.568			283.414		
11	10	ev	128.600			716.260		
12	3	ev	203.098			16.947		
13	1	ev	706.122			2,309.500		
14	0.675	ev	73.553	74.588	75.158	207.621	212.455	215.113
15	0.55	ev	130.454	130.145	130.158	458.384	457.058	457.113
16	0.405	ev	232.545	235.234	236.135	891.049	902.426	906.235
17	0.27	ev	556.354	570.490	586.620	2,269.74	2,330.13	2,399.17
18	0.2075	ev	1,284.64	1,293.43	1,332.90	5,413.52	5,451.76	5,623.79
19	0.135	ev	3,368.31	3,198.08	3,587.56	14,619	13,859.1	15,595.3
20	0.1055	ev	7,295.46	7,211.17	7,455.02	32,288	31,905	33,008.7
21	0.0775	ev	13,764.5	13,752.9	14,344.5	61,816	61,764	64,362.6
22	0.0475	ev	27,256.3	27,262.9	28,591.0	121,475	121,506	127,328
23	0.024	ev	49,409.6	49,233.2	50,386.1	211,257	210,600	214,880
24	0.012	ev	70,486.0	70,336.2	70,734.4	287,281	286,740	288,178
25	0.004	ev	100,464	100,160	100,553	408,413	407,023	408,819
26	0.	ev	337,581	337,581	337,581	1,360,730	1,360,730	1,360,730

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TABLE 2
ISOTOPIC ABUNDANCE IN NATURAL
GADOLINIUM

Isotope	Natural Abundance (%)
Gadolinium-154	2.15
-155	14.78
-156	20.59
-157	15.71
-158	24.78
-160	21.90

Gd-155 is a useful burnable poison in SNAP reactors with power levels in the 250-kw to 1-Mw range. All other Gd isotopes exhibit very small absorption cross-sections.

The peaks of the Gd-155 and -157 thermal absorption resonances occur at 0.0268 and 0.0314 ev, respectively. These resonances are shown in Figure 1. A typical SNAP reactor spectrum, for comparison, peaks at about 0.11 ev as shown in Figure 2. The neutron energy distribution in water peaks at 0.026 ev as shown in Figure 2. The fact that the H₂O spectrum is softer than the ZrH spectrum makes possible the use of Gd in designing an intrinsically subcritical SNAP reactor.

1. Effect of Placing Gadolinium on Fuel Elements

The reactivity effect of applying Gd-155 to SNAP 8 diameter fuel rods has been calculated using the ANISN computer code.⁽¹⁴⁾ The outside diameter of these fuel elements is 0.560 in. A 5-region model was constructed for a fuel element with water or NaK coolant, as shown in Table 3. Cell calculations were performed for an infinite array of elements with Gd concentrations in the 2.5-mil-thick ceramic hydrogen-barrier region varied from 0.0 to 0.126×10^{22} at./cc. Gd was placed in the ceramic region only. Atomics International has developed ceramics containing another rare earth (samarium), and these ceramics are expected to retain their desirable properties when Gd is used to replace Sm. The coolant region was an "equivalent annular" region which

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Figure 1. Total Gadolinium-155 and -157 Cross-Section Times the Square Root of Energy vs Neutron Energy

Figure 2. SNAP Reactor and Water Neutron-Energy Spectrum (20°C)

TABLE 3

MODEL FOR SNAP 8 FUEL ELEMENT CELL

Region Number	Material in Region	Region Outer Radius (cm)
1	Fuel rod	0.673
2	Void	0.680
3	Ceramic	0.686
4	Hastelloy-N	0.7115
5	Coolant, Nak or water	0.7615

contains a coolant volume equal to the coolant associated with the elements in a triangular array with 10-mil interelement spacing.

The cell outer boundary condition was specified to provide isotropic reflection of all neutrons. This boundary condition simulates an infinite array of elements.

NAA-SR-11361

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Cross-sections used in analysis of the fuel element cell arrays were from the "new 26-group" library.⁽¹⁵⁾ Gd-155 and -157 absorption cross-sections were generated from the data of Moller, et al.⁽¹³⁾

These cross-sections were weighted over the spectrum of interest and are shown in Table 1. Spectra were calculated with the 100-GT code (an unpublished AI computer code).⁽¹⁶⁾ Scattering in the Gd was neglected as the calculated effect was negligible (about +15¢ reactivity worth in a 211-element reactor).

The infinite multiplication factors which were calculated for the cells with 10-mil interelement spacing are shown in Table 4. Worths were calculated using $\beta = 0.008$. The reactivity worth of Gd-155 in the infinite cell array is shown in Table 5.

The small reactivity effect due to water flooding (\$1.15) was largely due to the close element spacing which restricts the coolant volume. Calculations for a 30-mil-spaced cell array are described below.

The cold operational cell array was \$1.71 more reactive than the "hot-operational" (1293°F zirconium-hydride spectrum, NaK-cooled) cell array. This result was anticipated because thermal spectral hardening shifts neutrons to higher energies.

Table 5 shows that the Gd-155 worth increased about 20% when the cold cell became water-flooded, and decreased about 18% when the cold spectrum was changed to a 1293°F spectrum. These results are shown in Figure 3 for the cell calculations with 10-mil interelement spacing. A 2200-m/sec cross-section of 60,000 barns and region thickness (t) of 0.006 cm were used to evaluate $\Sigma_a t$ for each concentration.

Figure 4 shows how the effective one-group absorption cross-section varies with concentration of Gd for the three neutron-energy spectra which were studied. This figure shows that the effective Gd-155 absorption cross-section in the operational fuel element array (with $\Sigma_a t$ of 0.28) is only about one-half the effective cross-section calculated with a dilute concentration. As the Gd burns out, the effective cross-section of the remainder increases. This effect, and the effect of spatial variation in burnout, has not yet been examined in detail.

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TABLE 4
CALCULATED K_{inf} FOR SNAP 8 FUEL ELEMENT CELLS
WITH GADOLINIUM-155

Σ_{at} of Gadolinium-155 on Fuel Elements	K_{inf} for Cells		
	73°F Spectrum		1293°F Spectrum
	NaK Coolant	Water Coolant	NaK Coolant
0.0	1.6837	1.7101	1.6709
0.073	1.5932	1.6019	1.5971
0.146	1.5316	1.5258	1.5464
0.292	1.4488	1.4275	1.4700
0.438	1.3924	1.3630	1.4163

TABLE 5
CALCULATED WORTH OF GADOLINIUM-155 ON SNAP 8
FUEL ELEMENT CELLS

Σ_{at} of Gadolinium-155 on Fuel Elements	Worth in Cell (\$)		
	73°F Spectrum		1293°F Spectrum
	NaK Coolant	Water Coolant	NaK Coolant
0.0	Reference	Reference*	Reference†
0.073	-4.22	-4.94	-3.46
0.146	-7.37	-8.83	-6.02
0.292	-12.04	-14.47	-10.22
0.438	-15.53	-18.61	-13.45

*Water coolant with no gadolinium was worth +\$1.15 more than the reference NaK-cooled case.

†The 1293°F spectrum cell array with no gadolinium was -\$1.71 less reactive than the 73°F spectrum cell array with NaK.

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Figure 3. Worth of Gadolinium-155 in SNAP 8 Fuel Element Cell Array

Figure 4. Variation in Effective One-Group Absorption Cross-Section with Gadolinium-155 Concentration

The effects of varying the fuel element pitch (interelement spacing, since the element size was assumed constant) were also briefly studied. Cell calculations were performed with the outer radius of the cell set equal to 0.8615 cm (30-mil spacing). The results of these calculations are tabulated in Table 6. A comparison of Gd-155 worth to that calculated for the 0.7615-cm-radius cell (10-mil spacing) is shown in Tables 6 and 7. The incremental negative reactivity worth of Gd-155 was essentially unaffected by the pitch change in the cold operational cell configurations. The negative worth of Gd-155 in the H₂O-flooded cases, however, was greatly increased in the larger-spaced element array. This results because increased neutron moderation increases the importance of parasitic absorption in Gd. H₂O flooding increases the negative Gd-155 worth by 50% in the 30-mil spaced array, compared to a 20% worth increase in the 10-mil spaced array. The increased negative Gd-155 worth therefore readily compensates for the increase in positive H₂O worth in the larger array if large Gd concentrations are used. H₂O flooding of the larger-spaced array is worth +\$2.19, with no Gd, compared to +\$1.15 for the 0.025-cm-spaced element array. This result is in agreement with the predicted effects of increasing the H₂ content of the fuel element array.

NAA-SR-11361

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TABLE 6
CALCULATED K_{inf} FOR SNAP 8 FUEL ELEMENTS IN ARRAYS
WITH 10- AND 30-mil INTERELEMENT SPACING

Σ_{at} of Gadolinium-155 (2200 m/sec)	K_{inf}			
	NaK		Water	
	10-mil Spacing	30-mil Spacing	10-mil Spacing	30-mil Spacing
0.0	1.6837	1.6656	1.7101	1.7157
0.073	1.5932	1.5781	1.6019	1.5799
0.146	1.5316	1.5178	1.5258	1.4905
0.292	1.4488	1.4370	1.4275	1.3720
0.438	1.3924	-	1.3630	-

TABLE 7
WORTH OF GADOLINIUM-155 IN SNAP 8 FUEL ELEMENT CELL ARRAYS
WITH 10- AND 30-mil SPACING

Σ_{at} of Gadolinium-155 (2200 m/sec)	Worth (\$)			
	NaK		Water	
	10-mil Spacing	30-mil Spacing	10-mil Spacing	30-mil Spacing
0.000	Reference	Reference	Reference*	Reference†
0.073	-4.22	-4.16	-4.94	-6.26
0.146	-7.37	-7.31	-8.83	-11.01
0.292	-12.04	-11.94	-14.47	-18.25
0.438	-15.53	-	-18.61	-

*The water-cooled 10-mil-spaced array was \$1.15 more reactive than the NaK-cooled 10-mil-spaced array.

†The water-cooled 30-mil-spaced array was \$2.19 more reactive than the NaK-cooled 30-mil-spaced array.

The effects of increasing the element cladding thickness were also studied briefly. An interelement spacing of 30 mils was assumed, and both 10- and 15-mil clad thicknesses were analyzed. (The element pitch increased by 10 mils in the thicker clad cases.) The results of these cases are shown in Tables 8 and 9. Table 9 shows the negative reactivity worth of Gd-155 for the

NAA-SR-11361

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TABLE 8
CALCULATED K_{inf} FOR SNAP 8 FUEL ELEMENTS IN 30-mil
INTERELEMENT SPACED ARRAYS WITH 10- AND
15-mil CLADDING THICKNESS

Σ_{at} of Gadolinium-155 (2200 m/sec)	K_{inf}			
	NaK		Water	
	10-mil Clad	15-mil Clad	10-mil Clad	15-mil Clad
0.0	1.6656	1.6157	1.7157	1.6817
0.146	1.5178	1.4715	1.4905	1.4640

TABLE 9
WORTH OF GADOLINIUM-155 IN 30-mil SPACED FUEL ELEMENT
CELL ARRAYS WITH 10- AND 15-mil CLADDING THICKNESS

Σ_{at} of Gadolinium-155 (2200 m/sec)	Worth (\$)			
	NaK		Water	
	10-mil Clad	15-mil Clad	10-mil Clad	15-mil Clad
0.0	Reference	Reference	Reference*	Reference†
0.146	-7.31	-7.58	-11.01	-11.05

*The water-cooled 30-mil-spaced 10-mil-clad cell array was +\$2.19 more reactive than the comparable NaK-cooled array.

†The water-cooled 30-mil-spaced 15-mil-clad cell array was +3.04 more reactive than the comparable NaK-cooled array.

two clad thicknesses studied. Changing the cladding thickness does not result in any significant* change in the Gd-155 worth in either the operational or H_2O -flooded cells.

The foregoing cell calculations indicated that the increased worth of Gd-155 when H_2O -flooded might permit design of an intrinsically subcritical SNAP reactor. Increasing the interelement spacing from 10 to 30 mils significantly

*Uncertainty in calculated worths due to computer code convergence is $\pm 25\%$.

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enhanced the Gd worth upon H_2O -flooding. Increasing the cladding thickness while retaining constant interelement spacing did not significantly affect the worth.

Reactor calculations were performed for two typical SNAP reactor designs to determine the synergistic effect of finite size (high leakage) on the worth of Gd-155 in the fuel elements. Analyses were performed for reactors with 211 and 349 fuel elements. The cladding thickness was 10 mils, as was interelement spacing, for both reactor calculations.

The 349-element reactor was studied in greater detail than the 211-element because the larger reactor (the limit of current core sizes) would be more difficult to design as an intrinsically subcritical core.

Cross-sections used in the reactor calculations were the "new 26-group" set. Core region macroscopic (flux and volume weighted) cross-sections were obtained from the cell calculations. Three-in.-thick Be reflectors were assumed for both reactors in the operational configuration. An infinite water reflector (6 in.) was used in the H_2O -flooded and -reflected cases. Fuel element length for all reactor calculations was 16.875 in. Calculations were iterated until radial and axial leakage from the reactor core stabilized (buckling iteration technique).

The ANISN neutron-transport theory computer code was used to calculate the effective multiplication factor (k_{eff}) for the 349-element core in three configurations:

- 1) 73.4°F SNAP reactor spectrum, NaK coolant, 3-in. Be reflector
- 2) 1292.9°F SNAP reactor spectrum, NaK coolant, 3-in. Be reflector
- 3) 73.4°F SNAP reactor with H_2O spectrum, H_2O coolant, 6-in. H_2O reflector.

The Σ_a of Gd-155 on the fuel elements was varied from 0.0 to 0.438. Gd-155 was also introduced into the core/reflector interface region with a Σ_a of 0.0 or 5.0. The results of the interface poison calculations will be presented in Section III-A-2 of this report.

The calculated k_{eff} for various concentrations of Gd-155 on fuel elements in the three configurations listed above are shown in Table 10. The calculated

TABLE 10
CALCULATED K_{eff} FOR 349-ELEMENT REACTOR WITH
GADOLINIUM-155 ON FUEL ELEMENTS

Σ_{at} (2200 m/sec) of Gadolinium-155		Reactor Configuration		
On Fuel Elements	Core/Reflector Interface Region	Cold Operational	Hot-Spectrum Operational	Cold Water Flooded and Reflected
0.0	0.0	1.202	1.186	1.200
0.0	5.0	1.173	1.160	1.159
0.073	5.0	1.113	1.114	1.086
0.146	0.0	1.093	1.099	1.072
0.146	5.0	1.073	1.079	1.038
0.292	5.0	1.018	-	0.974

Gd reactivity worth is shown in Figure 5. This figure illustrates that the worth of Gd-155 on SNAP 8 fuel elements in a 349-element reactor increases about 26% upon H_2O -flooding and -reflection (this compares to a 20% worth increase upon H_2O -flooding the infinite cell array). A \$15.00 loading of Gd-155 thus becomes worth \$18.90 upon H_2O -flooding.

The worth of Gd-155 in the "hot-spectrum" cases is shown to be somewhat less than in the cold-spectrum cases in Figure 5. This difference is due to spectral hardening with temperature as observed in the cell calculations.

The spectral component of the temperature coefficient of reactivity may be obtained from the hot and cold spectrum reactor calculations. The calculated spectral defect and spectral coefficient of reactivity are shown in Table 11. These results indicate that the spectral component of the temperature coefficient of reactivity becomes positive for Gd-155 loadings with Σ_a of about 0.07. Since the spectral coefficient appears to converge to about $+0.08\%$ /°F for large Gd-155 loadings, the overall reactivity coefficient remains negative. The total isothermal temperature coefficient for a typical SNAP 8 reactor is about -0.2% /°F.

Figure 5. Worth of Gadolinium-155 on Fuel Elements in a 349-Element Reactor

TABLE 11

SPECTRAL COEFFICIENT OF REACTIVITY AND
SPECTRAL REACTIVITY DEFECT FOR
FUEL TEMPERATURE CHANGE
FROM 73.4°F TO 1292.9°F

Σ _a t of Gadolinium-155 on Fuel Elements	Σ _a t of Gadolinium-155 in Interface			
	Spectral Defect (\$)		Spectral Coefficient (¢/°F)	
	0.0	5.0	0.0	5.0
0.0	-1.40	-1.20	-0.115	-0.098
0.073	-	+0.10	-	+0.008
0.146	+0.62	+0.64	+0.051	+0.052

Only two 211-element reactor configurations were calculated for various Gd-155 concentrations:

- 1) 73.4°F SNAP reactor spectrum, NaK coolant, 3-in. Be reflector
- 2) 73.4°F SNAP reactor with H₂O spectrum, H₂O coolant, 6-in. H₂O reflector.

The k_{eff} calculated for these configurations is shown in Table 12. The worth of Gd-155 in the 211-element core is compared to the worth in the 349-element core in Figure 6. This figure illustrates that the Gd-155 worth (in-core) increases 34% upon water-flooding the 211-element core, compared to a 26% increase in the 349-element core and a 20% increase in the infinite cell array. A \$10.00 Gd-155 loading therefore becomes worth \$13.40 upon water-flooding and -reflection of the 211-element reactor core.

No hot calculations were performed for the 211-element reactor. Results would be expected to agree, in general, with the 349-element reactor results; i. e., a reduction in Gd-155 worth of about 10% upon heating to 1293°F should occur.

The reactor calculations illustrate that the in-core worth of Gd is significantly greater than the worth in an infinite cell array. Water-flooding results

TABLE 12
EFFECTIVE MULTIPLICATION FACTORS FOR
211-ELEMENT REACTOR WITH
GADOLINIUM-155

Σ_{at} of Gadolinium-155		K_{eff} for 211-Element Reactor With Gadolinium-155	
Fuel Element	Vessel	Operational	Water-Flooded and -Reflected
0.0	0.0	1.0896	1.0820
0.0	5.0	1.0585	1.0155
0.146	0.0	0.9975	0.9637
0.146	5.0	0.9725	0.9117

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Figure 6. Comparative Worth of Gadolinium-155 in 211- and 349-Element SNAP Reactors

in a larger Gd worth change in the finite reactor due to the increased importance of thermal neutrons in the reactors. The generalization can be made: the greater the leakage from the SNAP core, the greater the Gd worth increase upon water-flooding and -reflection.

It was calculated that a \$3 to \$4 reactivity reduction was possible through use of Gd-155 on the fuel elements of the SNAP reactors studied using the largest Gd-155 loadings which would permit startup of the reactor. Since the cold poisoned excess reactivity of these reactors is usually \$4 to \$6, it is apparent that the use of Gd-155 in-core alone may not be sufficient to provide intrinsic subcriticality. The use of Gd-155 in the core/reflector interface region has therefore been studied to determine the additional reactivity reduction available through these means. These results are presented in the next section.

2. Effect of Placing Gadolinium in Core/Reflector Interface Region

The high neutron leakage which is characteristic of SNAP reactors makes possible reactor control through use of control drums and reactivity adjustments by changing the Be reflector thickness. About 30% of the neutrons born in fission leak from the core, about 80% in the radial direction. Be is superior to

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H₂O as a reflector for SNAP reactor because of its n, 2n reaction in the Mev energy range and superior fast-neutron scattering capability (more than 90% of SNAP reactor leakage is above 100 kev). H₂O scattering results in a large energy loss with each scattering event due its larger slowing-down power ($\xi \Sigma_s = 1.5$ for water vs 0.16 for Be).

Neutron captures in structural materials tend to reduce the effectiveness of the H₂O reflector. A significant number of near-thermal neutrons do, however, return to the water-reflected core. The use of Gd (in natural or isotopic form) permits increasing the thermal-neutron absorption probability to nearly 100% (black). The elimination of thermal reflection does not result in a severe reactivity penalty during normal operation because Be scattering does not result in primarily a thermal-reflected flux. Only Gd-155 was analyzed as an interface absorber, but natural Gd or Gd-157 might be used if burnout during operation were not objectionable.

The worth of black ($\Sigma_a t = 5.0$) Gd-155 on the vessel of the 349-element reactor is shown in Table 13. The worth was not significantly affected by slight changes in core spectrum since the effect is primarily related to the reflected flux spectrum, i.e. neutrons returning from the reflector. The worth of Gd-155 increased markedly when the Be reflector was replaced with H₂O, because of softer reflected neutron spectrum and hence greater parasitic absorption. An average Gd-155 worth increase of 57% was calculated (due to H₂O reflection) for Gd-155 in the 349-element reactor interface.

TABLE 13
REACTIVITY WORTH OF BLACK GADOLINIUM-155 IN CORE/REFLECTOR
INTERFACE REGION OF 349-ELEMENT SNAP REACTOR

Σ_{at} of Gadolinium-155 on Fuel Elements	Worth of $\Sigma_a t = 5.0$ of Gadolinium-155 in Interface Region (\$)		
	Cold Operational	Hot-Spectrum Operational	Water-Flooded and -Reflected
0.000	-2.57	-2.36	-3.69
0.146	-2.20	-2.41	-3.82

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A $\Sigma_a t$ of 5.0 corresponds to an absorption probability of 99% for 2200 m/sec neutrons.* The calculated worths are therefore nearly the maximum for Gd-155 and are probably near the maximum which can be obtained with Gd. The Gd-155 worth change due to water reflection averaged -\$1.35 for the interface Gd on the 349-element core.

Results calculated for placing black Gd-155 in the core/reflector interface of the 211-element reactor are shown in Table 14. Since reflected neutrons are more important in the smaller diameter core, the increase in Gd-155 worth shown in the table was anticipated. The average increase in interface Gd worth upon water-flooding and -reflection was 127%. Smaller core diameters would be expected to result in an even larger percentage increase in worth resulting from H₂O reflecting the interface Gd.

TABLE 14
REACTIVITY WORTH OF BLACK GADOLINIUM-155
IN CORE/REFLECTOR INTERFACE REGION
OF 211-ELEMENT SNAP REACTOR

$\Sigma_a t$ of Gadolinium-155 on Fuel Elements	Worth of $\Sigma_a t = 5.0$ of Gadolinium-155 in Interface Region (\$)	
	Cold Operational	Water-Flooded and -Reflected
0.0	-3.37	-7.58
0.146	-3.24	-7.42

The calculations for interface Gd worth in the operational configuration assumed use of a 3-in.-thick Be reflector. Use of a thicker Be reflector would result in greater neutron thermalization and hence, a greater operational poison worth. Worth in the water-reflected configuration would remain unchanged. The \$1.35 and \$4.20 Gd-155 worth changes calculated for interface Gd on the 349- and 211-element cores, respectively (Tables 13 and 14), may be added directly to the reactivity changes calculated for the in-core Gd-155 in the

*The 2200 m/sec cross-section of Gd-155 (60,000 barns) was used to evaluate $\Sigma_a t$ for this study.

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previous section. There does not appear to be any significant interaction effect between core and interface Gd. A reactivity reduction due to water flooding of about \$5.50 can therefore be obtained for the 349-element core if both in-core Gd-155 (about \$15 worth) and black interface Gd (about \$2.40 worth) are used (Figure 5 and Table 13). This reactor would therefore be intrinsically subcritical if the cold poisoned excess reactivity were adjusted to less than \$5.50.

The 211-element reactor exhibits a reactivity reduction of about -\$8.60 when water-flooded and -reflected with \$10.60 worth of Gd-155 in-core and black Gd (about \$3.30 worth) in the interface (Figure 6 and Table 14). Intrinsic subcriticality is therefore attainable with a cold poisoned excess reactivity of up to \$8.50 in the 211-element reactor. If the cold poisoned excess reactivity were adjusted to, e. g., \$5.00 (a more reasonable value), the in-core Gd-155 loading could be reduced to only \$3.00. The 211-element reactor would still be intrinsically subcritical with black interface Gd. Larger reactivity reductions are possible for both reactors through use of larger in-core Gd-155 loadings. The poison loadings used in the above illustrations were chosen to approximate the burnable poison loadings currently being considered for these cores.

The use of Gd-155 on fuel elements and in the core/reflector interface region has been shown capable of providing intrinsic subcriticality for two reactor designs of current interest.

The reactivity penalty associated with use of Gd is discussed in Section IV of this report.

B. EFFECT OF CORE AND REFLECTOR GEOMETRY CHANGES

Variations in SNAP reactor core length or core diameter have a direct effect on the reactivity. This is true for both the operational and the water-flooded configurations. If the core length is reduced, the reactivity is reduced because of the removal of fissionable material and increased axial leakage. The same effect results from a reduction in core diameter. Conversely, an increase in length or diameter of the core will result in a reactivity increase. Both core length and diameter may be varied simultaneously in such a manner that no change in reactivity occurs.

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In the water-immersed and flooded condition a family of SNAP reactor configurations exists which are all just subcritical. These intrinsically subcritical core geometries all have different excess reactivities (operational capabilities) when in the operational condition with some fixed thickness of Be reflector. The operational excess reactivity may be adjusted by varying the Be thickness (up to about 7 in. maximum).

A preliminary calculation of geometry change effects has been completed for SNAP 10A and SNAP 8 type reactors. It was assumed that core volume changes could be accomplished without changing fuel, cladding, or coolant volume fractions in the core region, and that the interface region composition and thickness remained constant.

The SNAP 10A reactor was water-immersed in a critical assembly and the excess reactivity was determined to be $+\$11.60$. A set of calculations was performed to determine equivalent geometries which would all have the same water-immersed excess reactivity. The solid curve in Figure 7 labelled " $+\$11.60$ Water-Immersed Family" represents a family of water-flooded and -reflected SNAP 10A type reactors which all have an excess reactivity of $+\$11.60$. The curve labelled, "Intrinsically Subcritical Family" illustrates a family of reactors which have an excess reactivity which is $\$12.00$ less than the other family, i. e., the excess reactivity of all reactors on the curve is $-\$0.40$.

Figure 7. SNAP 10A Type Reactor Isoreactivity Geometries for Operational and Intrinsically Subcritical Cores

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32

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The dashed curves in Figure 7 are lines of constant reflector thickness. The intersection of the solid and dashed lines represents a reactor which has an operational excess reactivity of +\$5.50. For example, the intersection of the 3.5-in. Be reflector curve with the intrinsically subcritical reactor family curve, at 6.38-in. diam, 15.25-in. long, defines one of the reactor designs which exhibit an excess reactivity of \$5.50 in the operational configuration and an excess reactivity of -\$0.40 in the water-flooded and -reflected configuration.

A similar analysis for a SNAP 8 reactor is shown in Figure 8. The reference SNAP 8 reactor has an operational excess reactivity of about +\$12.00 and a water-flooded and immersed excess reactivity of +\$10.00. The primary differences between the SNAP 8 and SNAP 10A reactor cores are a smaller fuel volume fraction and larger cladding and coolant volume fractions in the SNAP 8 reactor.

The families of SNAP 8 type reactors which have +\$10.00 and -\$0.50 excess reactivities when water-flooded and -reflected are shown by solid curves in Figure 8. Curves of constant reflector thickness are dashed and their intersections with solid curves, again, are specific reactor/reflector examples which exhibit an operational excess reactivity of +\$12.00.

Figures 7 and 8 illustrate families of reactors of SNAP 10A and SNAP 8 types which are intrinsically subcritical while retaining the reference design

Figure 8. SNAP 8 Type Reactor
Isoreactivity Geometries for
Operational and Intrinsically
Subcritical Cores

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excess reactivity. These figures demonstrate the feasibility of the concept. There are, however, disadvantages resulting from the geometry changes.

Figure 8 shows that all the reactors in the intrinsically subcritical family have the characteristic of being longer and smaller in diameter than the reference SNAP 8 core. A specific example is the 7.3-in. diam 19.25-in. long reactor which requires a 6-in.-thick Be reflector to meet the +\$12.00 operational excess reactivity requirement. This characteristic results in several operational penalties which are described in Section IV of this report.

C. COMBINED EFFECTS OF GEOMETRY CHANGES AND GADOLINIUM

The effects of reducing the water-immersed reactivity of a SNAP reactor by making core geometry changes was discussed in the previous section. The general method employed was to reduce the core diameter and to increase core length. Operational excess reactivity was obtained by increasing the reflector thickness. This method of achieving intrinsic subcriticality results in weight penalties due to the effect of increased reactor envelope on shield size and to the decreased flow-area effect on pumping power requirements. In addition, performance capabilities of the reactor are generally reduced by the geometry changes.

Although the penalties associated with changing the core/reflector geometry are not desirable, it may be necessary to change the geometry to attain intrinsic subcriticality with some reactors. Reactors which are somewhat larger in diameter than the 349-element reactor may not retain sufficient operational excess reactivity when loaded with sufficient Gd on the fuel and in the interface region to be subcritical when water-flooded and -reflected. A reduction in core diameter might permit intrinsic subcriticality with use of Gd. An increase in core length and, if necessary, reflector thickness would restore the required operational excess reactivity.

It is concluded that combining the Gd effects with geometry changes may be required in order to permit extension of the intrinsic subcriticality concept to very high power level SNAP systems.

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IV. EFFECT OF INTRINSIC SUBCRITICALITY ON OPERATIONAL CABILITIES

Perturbations to the basic SNAP reactor designs will, generally, result in a reactivity, weight, or performance penalty. The basic designs were chosen to provide a minimum weight system for a particular power level. Any design change which permanently reduces the operational excess reactivity or changes the length or diameter of the reactor results in penalties. The two methods for achieving intrinsic subcriticality discussed in this report were analyzed to determine the penalties which they impose on operation of SNAP reactors.

A. PENALTIES ASSOCIATED WITH USE OF GADOLINIUM

The penalties associated with use of Gd to provide intrinsic subcriticality result from reactivity lost at end-of-life due to residual (unburned) Gd. The penalties vary over a wide range depending upon the mission requirements for each specific SNAP reactor. For example, a SNAP 8 (211-element) reactor with black interface poison, natural Gd, and \$5.00 worth of Gd-155 in core would be intrinsically subcritical. Operation at 600 kw for 3 yr would result in virtually complete burnout of the in-core Gd and the Gd-157 contained in the interface poison. The end-of-life penalty would therefore be only that associated with the residual Gd-155 in the interface region. The reactivity penalty would be less than \$0.68 for this particular case, assuming no burnout of Gd-155 in the interface region. This reactivity penalty may be converted to weight penalty by increasing the initial excess reactivity to account for the residual poison at end-of-life. The reflector could be increased less than 1/4 in. to add the required end-of-life reactivity. The weight penalty would be that associated with a 1/2-in. increase in shielding envelope diameter, equivalent to a 3.5% increase in shadow shield weight or about 65 lb for an unmanned mission. There would be no power/temperature/lifetime performance penalties because no changes were made to core geometry. If the same reactor were operated for only a 1-yr mission the in-core Gd would not be completely burned out and would result in a larger end-of-life reactivity penalty. The penalty, then, is dependent upon the degree to which Gd isotopes meet the burnable poison requirements for each specific mission.

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B. PENALTIES ASSOCIATED WITH CORE/REFLECTOR GEOMETRY CHANGES

Changes in core geometry may be made which will render the SNAP core subcritical in water. The reflector thickness may be increased to provide the required operational excess reactivity. These changes result in significant system weight and performance penalties as described below.

1. Envelope Change Weight Penalty

The reactor shield envelope is a conical volume with its base at the payload and enclosing the reactor (including an additional 4 in. on the reactor diameter for outward rotation of control drums). Changes in the core and reflector geometry result in changes in the diameter of the shielding envelope, hence, changing the shield weight. The model and method used to calculate reactor shield weights are shown in Appendix B. Figure 9 shows the weights of the reference SNAP 8 reactor (and equal reactivity reactors from Figure 8) and the family of intrinsically subcritical SNAP 8 type reactors (from Figure 7). Figure 9 shows that a 343-lb weight penalty exists between the minimum weight designs from each family (about 15%).

Figure 9. SNAP 8 Reactor and Shield Weights for Operational and Intrinsically Subcritical Core Geometry Designs

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The analysis of the SNAP 8 type reactors could be performed for other SNAP reactor designs, but the results would be generally the same in each case. The shield design assumed here was a typical shadow shield for an unmanned mission. Weight penalties for 4π shields would be considerably larger than for the shadow shield used in the above illustration.

2. Pressure Drop Weight Penalty

The geometry change approach to intrinsic subcriticality requires reducing the core diameter to make the core subcritical in water. The coolant pressure drop in the core region varies approximately as the inverse flow area squared. An analysis for the SNAP 8 reference and subcritical reactors showed that the reactor pressure drop increased from 1.39 to 3.04 psi as the core diameter was reduced. For typical operating conditions (600 kw, 200°F temperature rise through core, 48,800 lb of NaK/hr flowrate) the weight of direct radiating thermoelectric pumps required was increased from 225 to 547 lb, a 322-lb weight penalty. The weight penalty due to changing the core pressure drop would have to be determined separately for each reactor design and set of operating conditions.

The total weight penalty is the sum of the envelope change penalty (343 lb) and the pressure-drop penalty (322 lb), or 665 lb. This represents a 29% increase in total system weight for the 2266-lb reference system used as a typical design.

3. Performance Penalties

Changing the core diameter and length and the reflector thickness also results in changes in the power distribution in the core. The LOAFER computer code⁽¹⁷⁾ was used to determine the effect of the changes on the temperature/power/time performance of the SNAP 8 type reactors. End-of-life was defined as occurring when one of three events occurred; (1) Excess reactivity reached zero, (2) fuel swelled and touched cladding, or (3) Zr-H_x phase changed from delta to beta plus delta at any point in the core. Power/life curves for the reference and intrinsically subcritical reactors (at 1300°F outlet coolant temperature) are shown in Figures 10 and 11. These figures show that the 1300°F, 600 kw lifetime capability is reduced from 21 to 14 months when the core geometry is modified to achieve intrinsic subcriticality.*

*Improvements have been made in the LOAFER computation of hydrogen leakage and fuel swelling since the completion of these calculations.

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Figure 10. Power/Lifetime Capability Limits
for Reference SNAP 8 Reactor with Outlet
Coolant Temperature = 1300°F

Figure 11. Power/Lifetime Capability Limits
for Intrinsically Subcritical SNAP 8 Type
Reactor with Outlet Coolant
Temperature = 1300°F

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While the end-of-life definitions are admittedly quite severe (the reactor could continue to operate at a lower power or higher reactivity loss-rate for some time after reaching the defined end points), the percentage reduction in capability should be reasonably accurate, i. e., 33% at 600 kw.

It may be concluded that the performance and weight penalties associated with attaining intrinsic subcriticality by changing the core geometry are quite severe for the SNAP 8 reactor design. The penalties for other SNAP reactor designs have not yet been determined.

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V. CONCLUSIONS

Safety of SNAP reactors during all phases of operation has been studied at Atomics International. Specific areas of potential hazard have been identified which occur during reactor fabrication, prelaunch testing, transportation and handling, launch abort, and end-of-mission disposal. As a result of these analyses, nuclear safeguards (both procedural and mechanical) have been developed to prevent a nuclear accident.

The problem of end-of-mission disposal is discussed elsewhere;^(3, 4) only the prevention of accidental criticality was studied in this report. Water-immersion (core flooding and reflection) is the most reactive situation conceived for accidental criticality due to the high neutron leakage and undermoderation which are characteristic of SNAP reactors.

Two isotopes of Gd (-155 and -157) were found to be useful in preventing water-immersion accidents because of the large absorption resonances which they exhibit at low neutron energies. This characteristic results in a significant increase in Gd worth when water-flooding softens the SNAP spectrum. Use of Gd-155 isotope in SNAP 8 (211-element) and 349-element SNAP reactors was analyzed in some detail with Gd-155 both on the fuel elements and in the core/reflector interface region. It was concluded that both of the reactors which were studied could be made intrinsically subcritical by use of Gd-155.

The effective absorption cross-section for Gd-157 is very large, but it may be useful as a burnable poison in a 40 to 60 kw SNAP reactor. Gd-155 appears to be a good burnable poison for reactors operating in the 250- to 1000-kw range. Applying the Gd as a burnable poison resulted in a very small weight penalty associated with the attainment of water-immersion subcriticality.

Core geometry changes required to achieve intrinsic subcriticality were analyzed for SNAP 10A and SNAP 8 type reactors. In this concept the core diameter was decreased until the reactor was subcritical in water. Operational excess reactivity was obtained by increasing the core length and the radial Be reflector thickness. Core geometry changes were effective in achieving intrinsic subcriticality in the reactors which were analyzed. This technique offers the advantage of permanent water-immersion safety, i.e., the reactor is always

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subcritical in water whether clean or having been operated. Gd, however, burns out during operation so that the shutdown margin decreases in time. Core geometry changes have two main operational disadvantages. The overall reactor envelope is increased due to replacing fuel elements with (less effective) Be. This results in a weight penalty due to increased shadow-shield weight. An additional weight penalty is incurred because the smaller core diameter results in increased system pressure drop (larger coolant pumps). The weight penalties totalled 665 lb for one SNAP 8 type reactor which was studied. The weight penalties may not be as significant a disadvantage as the reduction in power/lifetime capabilities which results from the core geometry changes. Changes in power density peak fuel and cladding temperature, etc. which result from the core geometry changes can result in a 33% reduction in 600-kw reactor lifetime capability. Core geometry changes may be combined with use of Gd in higher power reactors if they are too large to be made intrinsically subcritical through use of Gd alone.

The general conclusion of this report is that SNAP reactors can be made intrinsically subcritical through use of either the Gd-155 and -157 isotopes or the core geometry changes. Since Gd may also be used as a burnable poison, and core geometry changes result in considerable operational penalties, it is recommended that Gd isotopes be employed to attain intrinsic subcriticality when required for SNAP reactor safety.

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APPENDIX A

INFLUENCE OF INTRINSIC SUBCRITICALITY ON SNAP REACTOR SAFETY

The potential radiological problems associated with the use of nuclear reactors in space must be carefully and completely evaluated and suitable controls provided. The purpose of this Appendix is to review the more significant safety problems which have been identified and to show how the "design for intrinsic subcriticality in water" safeguard feature alters the total safety picture. This feature is not the solution for all SNAP reactor safety problems, but it is an effective control for many. While various missions and several types of reactor power-conversion systems must be considered, the sequence of ground handling and operational events will be much the same in each case.

SNAP reactor safety problems may be conveniently divided into the following chronological phases:

- 1) Fabrication and assembly
- 2) Transport to launch base
- 3) Ground handling and prelaunch checkout
- 4) Vehicle fueling and launch
- 5) Orbital operation
- 6) Post-mission disposal

FABRICATION AND ASSEMBLY OPERATIONS

During these operations a criticality accident could occur. This problem is amenable to control by standard procedural techniques⁽¹⁸⁾ and it is not unique for space-reactor systems. Further, because these operations are performed in special experimental facilities, the potential hazard to the public is slight.

TRANSPORTATION OF FISSILE MATERIALS

This transportation on the public thoroughfares is regulated by standards. Since a SNAP reactor core is more reactive than normal fissile material shipping units, many of the normal safety measures for fissile material shipments are impractical for SNAP reactor shipments. For example, a major consideration in the SNAP 10A shipping problem was the possibility of accidental core reflection from such causes as vehicle upset in water or fire fighting activities.

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Figure A-1. SNAP 10A Reactor Shipping Sleeve

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Figure A-2. SNAP 10A Reflector Safety Devices

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Thus, to preclude this possibility, a unique safety device (Figure A-1) was necessary for the SNAP 10A flight test.⁽¹¹⁾ While the SNAP 10A shipping experience showed the general feasibility of shipment of intact SNAP cores, other factors such as greater distances, core size, and the possible desirability of air shipment may alter the already complex shipping problem. Intrinsic subcriticality would significantly simplify and provide economies in SNAP core shipment.

GROUND HANDLING AND PRELAUNCH CHECKOUT OPERATIONS

These are essentially conventional nuclear operations. The possibility of accidental criticality can be positively precluded by the use of appropriate safety devices. For the SNAP 10A flight test "void filler blocks" (Figure A-2) eliminated the criticality hazard by preventing control drum rotation and by limiting the worth of inadvertent reflection, such as by water-immersion or the human body.⁽¹⁹⁾ These potential problems must be controlled for any flight reactor, but their control appears to provide no intractable problems. The intrinsic subcriticality feature would be of value, however, in the event of loss of the reflector system and immersion in hydrogenous media such as the launch pad deluge water or fuel.

LAUNCH PHASE

The most important application of the intrinsic subcriticality features is during the launch phase. A launch abort could involve temperature, pressure, shock, and other conditions capable of reducing the effectiveness of most safety devices. A failure during the preorbital stage could involve aerodynamic heating, and could produce a nuclear accident in a completely uncontrolled area. It is during this phase in which a significant hazard of uncontrolled criticality exists and for which no other effective safeguards have been developed that the intrinsic subcriticality feature can be of greatest value. As the reactor contains no fission products at this stage, the only radiological safety requirement is that postimpact criticality be prevented.

OPERATIONAL PHASE

During the operational phase there are no public safety problems, hence, the intrinsic subcriticality feature will be of limited value.

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TABLE A-1
SUMMARY OF APPLICABILITY OF INTRINSIC SUBCRITICALITY

Phase	Safety Considerations	Value of Intrinsic Subcriticality	Remarks
Fabrication and Assembly	Avoidance of accidental criticality	Minor	Through the reduction in initial excess reactivity, would provide simplification of procedures used during core loading and final closure of core vessel.
Core Shipment	Transportation mishap resulting in core reflection and criticality	Major	Would provide essentially total reduction of inadvertent criticality during shipment. Would make air transportation readily feasible.
Prelaunch Ground Handling	Inadvertent criticality	Minor	
System Launch	Water-immersion criticality resulting from launch abort or preorbital vehicle failure causing impact in an uncontrolled area	Major	Would provide essentially total elimination of uncontrolled criticality.
Orbital Operation		Not significant	
Postmission Disposal, Low Earth Orbit	Water-immersion criticality	Significant	Even though the major safety problem results from fission product inventory, the hazard of recovery of an intact core would be significantly reduced. Possibility of prolonged and low-level criticality after impact is eliminated.
Disposal, High Earth Orbit	Water-immersion criticality	Major	Long-term decay of radioactivity provided by a high-altitude orbit makes water-immersion criticality one of the significant remaining safety problems. Intrinsic subcriticality would eliminate this problem. Again, recovery of an intact core would be simplified.

NAA-SR-11361

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POSTMISSION DISPOSAL CONSIDERATIONS

The significance of these is determined by mission and orbit characteristics as well as by characteristics of the reactor. Disposal problems represent dominant safety considerations for missions in short-lived earth orbits. In such missions, a large fission product inventory is accumulated and this inventory can constitute a public hazard in a variety of ways because there is little time for fission product decay in orbit. For low-orbit missions, intrinsic subcriticality reduces disposal hazards, but other safeguards are needed.

Postmission disposal problems for long-lived (~ 400 -yr) orbits are less severe than the corresponding problems with short-lived orbits. There is time for fission product decay before reentry. Radiological safety objectives are achieved if (1) the reactor is made subcritical after a few years operation and (2) postimpact criticality is prevented. Techniques have been developed for ensuring intrinsic end-of-life shutdown.^(5,6) Intrinsic subcriticality combined with the end-of-life shutdown device can completely eliminate postmission disposal hazards for long-duration orbits.

In summary, intrinsic subcriticality can completely eliminate the potential nuclear hazards in the shipment and launch phases. It is also of some value during ground handling and checkout but of little value during orbital operations. Intrinsic subcriticality reduces the number and variety of safety problems for disposal from low orbits. For high long-duration orbits, disposal phase safety problems can be controlled by the end-of-life shutdown device combined with intrinsic subcriticality. A summary of the application of intrinsic subcriticality during the various phases is presented in Table A-1.

In conclusion, the overall safety of SNAP reactors is greatly enhanced by intrinsic subcriticality.

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APPENDIX B

COMPUTATION OF REACTOR-SHIELD SYSTEM WEIGHT

The model used to estimate the variation of the reactor-shield system weight as a function of reactor geometry is shown in Figure B-1. The terminology and equations used, together with the assumed values of certain parameters, are listed below.

S = separation distance, core midplane to dose plane, = 40 ft

D_p = payload diameter, = 20 ft

a = distance from bottom of core to top of gamma shield, = 10 in. + end reflector thickness

T_1 = gamma shield thickness, = 0.75 in.

$T_2 + M$ = LiH neutron shield thickness, T_2 = 28 in., M = 4.75 in.

D_c = core diameter

D_e = envelope diameter (includes 4 in. for extension of control drums during operation)

H = active fuel height

$$\tan \phi = \frac{D_p - D_e}{2S + H} \quad ; \quad \tan \theta = \frac{D_p - D_c}{2S + H}$$

$$D_1 = D_c + 2(H + a) \tan \theta$$

$$D_2 = D_1 + 2T_1 \tan \theta$$

$$D_3 = D_e + 2(H + a) \tan \phi$$

$$D_4 = D_3 + 2T_2 \tan \phi$$

$$V = \text{volume of gamma shield, } = (\pi/12) T_1 [D_1^2 + D_1 D_2 + D_2^2]$$

$$V_n = \text{volume of neutron shield, } = (\pi/12) T_2 [D_4^2 + D_4 D_3 + D_3^2] \\ + (\pi/6) M [(3/4) D_4^2 + M^2]$$

The gamma shield was assumed to be tungsten with a density of 19.2 gm/cm³.

The density used for lithium hydride was 0.74 gm/cm³. An allowance of 30.4% was added to the shield weight to account for structural materials.

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Figure B-1. SNAP Reactor Shield Model

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