COMPLIANCE DETERMINATION STRATEGY
RRT 3.2.3.3 FAVORABLE CONDITION: MINERAL ASSEMBLAGES

APPLICABLE REGULATORY REQUIREMENTS:

60.21(c)(1)(ii)(B)
60.21(c)(1)(ii)(F)
60.122(b)(4)

TYPES OF REVIEW:

Acceptance Review (Type 1)
Safety Review (Type 3)
Detailed Safety Review Supported by Analyses (Type 4)

RATIONALE FOR TYPES OF REVIEW:

Acceptance Review (Type 1) Rationale:

This regulatory requirement topic is license application-related because, as specified in 10 CFR 60.31(a)(1)(i), it is information that the Commission shall consider in determining if there is reasonable assurance that the types and amounts of radioactive materials described in the application can be received, possessed, and disposed of in a geologic repository operations area without unreasonable risk to the health and safety of the public. As presented in the license application content requirements of 10 CFR 60.21(c) references above and Section 3.2.2.8 of regulatory guide "Format and Content for the License Application for the High-Level Waste Repository (FCRG)," it must be addressed by the U.S. Department of Energy (DOE) in its license application. Therefore, the staff will conduct an Acceptance Review of the license application for this regulatory requirement topic.

Safety Review (Type 3) Rationale:

This regulatory requirement topic is related to containment and waste isolation. It is a requirement for which compliance is necessary to make a safety determination for construction authorization as defined in 10 CFR 60.31 (i.e., regulatory requirements in Subparts E, G, H, and I). It concerns a favorable condition and focuses on the possibility that mineral assemblages, when subjected to thermal loading, will remain unaltered or alter to mineral assemblages having equal or increased capacity to inhibit radionuclide migration. Therefore, the staff will conduct a Safety Review of the license application to determine compliance with this regulatory requirement topic.

Two basic technical issues are engendered by the favorable condition on mineral assemblages. The first comprises the effects of repository thermal loading on mineral assemblages. The second issue is the capacity of the altered mineral assemblages to provide equal or increased inhibition of radionuclide migration. There is significant technical uncertainty associated with both of these issues.

Detailed technical knowledge currently exists on the compositions and distributions of mineral assemblages from several bore holes at Yucca Mountain (Bish and Chipera, 1989). These data provide a generally good basis for characterizing present mineral assemblages. The devitrified rocks are dominantly alkali feldspar and the silica polymorphs cristobalite, quartz, and tridymite. Undevitrified and altered rocks are dominated variably by glass, clinoptilolite, mordenite, and analcime. Clay minerals occur mostly in small concentrations, but over widespread areas. Calcite occurs dominantly in the soil zone and in sparse to moderate abundances in fractures and voids. Site characterization data, particularly from the experimental studies facilities, will augment mineralogical information considerably, and it is assumed that a detailed characterization of the natural mineralogical assemblages at Yucca Mountain will be available to reviewers of the license application.

Current thermal-hydrologic modeling of Yucca Mountain (e.g., Buscheck and Nitao, 1993; Pruess and Tsang, 1993) provide estimates of temperature excursions and moisture distribution within the repository as a function of time. The length of time at elevated temperatures will affect the amount and quality of mineral alteration. Mass transfer and the water distribution in the repository are also important factors in the type and extent of mineral alteration that may occur. Lack of water could result in dehydration of minerals or inhibit water-rock interactions, and the presence of water could promote water-rock interactions. Considerable uncertainty is associated with the details of heat and thermally induced fluid flow. For example, the generation of heat pipes as a heat and fluid transport mechanism has many important implications, but current modeling is inconclusive with regard to the significance of heat pipes in a Yucca Mountain repository. Nevertheless, for the purposes of compliance determination for the mineral assemblages favorable condition, it is assumed that thermal-hydrologic modeling, either by DOE or NRC, will provide ranges of temperatures and fluid distributions that are adequate as a basis for evaluation of their effects on mineral assemblages and radionuclide migration.

Several lines of evidence suggest the types of mineral alteration that may result from thermal loading. Four zones of alteration have been well documented at Yucca Mountain (Broxton et al., 1987). With increasing depth from the ground surface (and increasing temperature) these zones are characterized by unaltered glass, glass replacement by clinoptilolite, analcime, and authigenic albite. Although temperature is unlikely to control this sequence uniquely, it probably plays a role. North of Yucca Mountain in drill hole USW G-2, a transition in clay mineralogy from smectite to illite has been observed at depths greater than one kilometer (Bish, 1989). This transition was attributed to a period of elevated temperatures 10 million years ago. Literature on the dehydration and stability of smectite at elevated temperatures, reporting mainly experimental data, has been reviewed in the context of elevated temperatures at a Yucca Mountain repository (Bish, 1988). The reviewer concluded that the data suggest that the smectite to illite transition would be insignificant above the water table in a Yucca Mountain repository given the anticipated thermal regime. Experimental studies of hydrothermal alteration of Yucca Mountain tuffs under pressurized, saturated conditions at 250 °C have shown glass alteration and clinoptilolite formation (Knauss, 1987). Reaction-path modeling of geochemical alteration under unsaturated, nonisothermal conditions specific to a Yucca Mountain repository have shown clinoptilolite, smectite, and calcite formation from primary glass or feldspars (Murphy, 1993). However, these modeling results depend strongly on many incompletely supported assumptions.

Mineral assemblages can inhibit radionuclide migration by acting as sorbers of the radionuclides, by providing surfaces upon which radionuclide-bearing phases can precipitate, by plugging paths for water flow or increasing tortuosity along flow paths, by filtering radionuclide-bearing colloids or particulates, or by controlling water chemistry affecting radionuclide-rock interaction.

Near-field mineral and material assemblages are likely to be strongly affected by exotic materials including grout, metallic rock bolts or other structural materials, container materials or other shields, zircaloy cladding, spent nuclear fuel, and vitrified waste forms. These exotic materials and any others (e.g., garbage) will be considered generally in this CDS as near-field materials. Most of these materials will be highly unstable in the repository environment (relative to natural mineral assemblages) and would generate alteration assemblages. Altered waste forms and containers are unlikely, in general, to provide equal or enhanced inhibition to migration. However, grout and other structural materials that are not designed or intended to inhibit radionuclide migration are likely to alter to assemblages that contribute favorably to radionuclide isolation. A narrow semantic interpretation could exclude consideration of these materials in this regulatory requirement, because "minerals" are narrowly defined as natural crystalline materials. However, the language of 10 CFR 60.122(b)(4) makes no explicit restriction of mineral assemblages to natural materials. Furthermore, volcanic glass must certainly be considered in the context of mineral assemblages at Yucca Mountain, although it fails the strict semantic test because it is not crystalline. Statements of consideration tend to support the interpretation that alteration of exotic materials should be considered in evaluating this favorable condition. To a question of terminology in the precursor of 10 CFR 60.122(b)(4), NRC staff responded "The paragraph is concerned primarily with the behavior of mineral assemblages which form coatings along the fracture paths along which radionuclides are anticipated to migrate; it would be incorrect, when referring to this surface zone, to adopt a commenter's suggestion that the Commission refers instead to 'rock' or 'geologic media'" (NRC, 1983, p. 58). Alteration products of near-field materials are likely to form coatings along fracture paths along which radionuclides are anticipated to migrate. It will be assumed therefore that mineral assemblages are not interpreted according to a narrow semantic definition, and that mineral assemblages resulting from alteration of near-field materials are to be evaluated in the context of this favorable condition for their effects on radionuclide isolation.

Changes in mineral assemblages may also affect water chemistry resulting in a secondary effect on the performance of the engineered barrier and/or the waste form, which in turn could inhibit radionuclide migration. It is assumed, however, that these secondary effects will be addressed in other CDSs relating specifically to the performance of the engineered barrier system.

In summary, thermal loading at Yucca Mountain is likely to result in alterations of mineral assemblages. Some changed assemblages are likely to have an equal or greater capacity to inhibit radionuclide migration. These effects would have a favorable effect on repository performance. Changes in mineralogy that result in a reduced capacity to inhibit radionuclide migration will be considered as "potentially adverse conditions" (10 CFR 60.122 (c)) and will be addressed in the following sections of the License Application Review Plan: 3.2.3.9, Changes in Hydrologic Conditions; 3.2.3.2, Geochemical Processes; 3.2.3.7 Gaseous Radionuclide Movement.

Detailed Safety Review Supported by Analyses (Type 4) Rationale:

The staff considers that there may be high potential risk of failure to achieve a compliance determination with regard to applicable regulatory requirements because, for the Yucca Mountain site, there exist Key Technical Uncertainties concerning the effects of thermal loading on mineral assemblages and the equal or increased capacity of altered mineral assemblages to inhibit radionuclide migration. Therefore, the staff will conduct a Detailed Safety Review Supported by Analysis of the license application to determine compliance with this regulatory requirement topic.

Any finding made under this regulatory requirement topic may be considered highly uncertain due to the Key Technical Uncertainties, discussed below, related to uncertainties in the effects of thermal loading on mineral assemblages and the equal or increased capacity of altered mineral assemblages to inhibit radionuclide migration. If credit is being taken for this favorable condition, Key Technical Uncertainties associated with the effects of thermal loading on mineral assemblages and the equal or increased capacity of altered mineral assemblages to inhibit radionuclide migration are considered to require a Type 4 review because there is a high potential risk of failure to achieve a compliance determination with regard to the performance objectives of 10 CFR 60.112. If this favorable condition is being relied on to meet performance objectives, this concern about high risk of non-compliance will necessitate analyses above and beyond those required for a Type 3 review to assure that the uncertainty, and the associated effects on performance assessment, have been minimized to a reasonable extent. The staff will conduct a "Detailed Safety Review Supported by Analysis" of the license application to determine compliance with the regulatory requirement.

Key Technical Uncertainty Topic: Determining the alteration of mineral assemblages due to thermal loading.

Description of Uncertainty: Although various data and analyses (noted in the Safety Review Rationale) indicate that mineral assemblages are likely to be altered due to thermal loading, the type and extent of alteration and the properties of the minerals in the alteration assemblage are uncertain.

Performance Objective at Risk: 10 CFR 60.112

Explanation of Nature of Risk: The geologic setting can provide a barrier to release of radionuclide to the accessible environment through its capacity to inhibit radionuclide migration. Inhibition of migration depends on mineral assemblages that have a favorable impact on processes contributing to waste isolation. Uncertainties in mineral assemblages that result from thermal loading contribute to uncertainty in the ability of the geologic setting to isolate radionuclides, and therefore pose a high potential risk of failure if this favorable condition is being relied on to achieve a compliance determination with regard to the total system performance objective.

Description of Resolution Difficulty: Possible effects of thermal loading on mineralogy include: dehydration of hydrated minerals such as clays, precipitation of secondary phases such as clays, zeolites, calcite, and silica phase(s), recrystallization of clay minerals or devitrification of glass, volume changes or phase transitions, or reaction to form more stable secondary minerals such as quartz growth at the expense of cristobalite, zeolite replacement of glass, clay mineral alteration of feldspars, and a host of alterations of near-field materials including oxidation, hydration, and calcination sorptive. Clay minerals, zeolites, and iron oxy-hydroxides are likely to be particularly important minerals in the altered assemblages. Fundamental thermodynamic and kinetic properties of minerals and associated fluids generally provide the best means to predict the characteristics of mineral alteration. However, these properties for clay minerals, zeolites, and iron oxy-hydroxides are highly uncertain. The minerals are difficult to characterize because of their wide compositional variations, common nonstoichiometry and variable crystallinity, heterogeneity in nature, and metastability of a variety of polymorphs and phases of differing hydration state. Additional difficulty stems from the transience of the thermal loading. Rates of alteration reactions are unlikely to be sufficient to achieve or maintain equilibrium, limiting the utility of thermodynamic theory to provide predictions of alterations. Rate limiting mechanisms are likely to involve combinations of dissolution rates, diffusion rates in altering solids, fluid flow and moisture distribution rates, and nucleation rates, all of which are highly uncertain and difficult technical problems. Uncertainty associated with the variably saturated conditions creates difficulties in resolving the properties of the altered assemblages because water plays a critical role in mineral alteration. Also, most field and laboratory data on mineral alteration at elevated temperatures are relevant to saturated hydrologic conditions. Few experimental studies have focused on mineral alteration in hydrologically unsaturated conditions at elevated temperatures. It is therefore difficult to rely on existing experimental data to resolve uncertainties in the properties of altered mineral assemblages. Geochemical modeling of mineral alterations supported by thermodynamic and kinetic data and extensive analysis of site characterization data, data from natural analog sites, and laboratory analyses of thermal alteration of mineral assemblages under variably saturated conditions are likely to be required to determine the properties of the alteration mineral assemblages. DOE is expected to address this difficulty through an ongoing program involving laboratory experiments and modeling activities. The NRC staff and Center for Nuclear Waste Regulatory Analysis personnel, while doing IPA, are independently addressing this issue through geochemical modeling. This modeling is expected to be used in evaluating the needs for specific research. Although there is ongoing work with regard to *in-situ* mineral assemblages, additional work will be needed to in characterize the mineral assemblages that may result from thermal alteration of near-field materials and from the interactions of near-field and natural materials.

Key Technical Uncertainty Topic: Equal or increased capacity of alteration mineral assemblages to inhibit radionuclide migration.

Description of Uncertainty: There is significant technical uncertainty associated with the determination of whether or not altered mineral assemblages will have an equal or increased capacity to inhibit radionuclide migration.

Performance Objective at Risk: 10 CFR 60.112

Explanation of Nature of Risk: The geologic setting can provide a barrier to release of radionuclides to the accessible environment through its capacity to inhibit radionuclide migration. Inhibition of migration depends on mineral assemblages that have a favorable impact on processes contributing to waste isolation. Uncertainties in the capacity of altered mineral assemblages to inhibit radionuclide migration contribute to uncertainty in the ability of the geologic setting to isolate radionuclides, and therefore pose a high potential risk of failure if this FAC is being relied on to make a compliance determination with regard to the total system performance objective.

Description of Resolution Difficulty: Quantitative characterization of the capacity of mineral assemblages to retard radionuclide migration is a difficult problem, which is further complicated when applied to mineral assemblages that are only postulated to form as a result of future alteration. Altered mineral assemblages could have an equal or enhanced capacity to inhibit radionuclide migration through a variety of complex processes. For example, alteration minerals could have a greater surface area, potential for surface sorption, or ion exchange potential. Alteration mineral assemblages could control water chemistry in a pH range that results in increased (or decreased) sorption. Alteration, during periods of either increasing or decreasing temperature could lead to precipitation of minerals in which radionuclides may be coprecipitated. Thermally-induced precipitation of mineral cements such as calcite could alter fluid flow paths, sealing fluid pathways increasing tortuosity, or filtering of radionuclide-bearing colloids or particulates, processes which could lead to an increased capacity of the altered assemblage to inhibit radionuclide migration. Thermal expansion of minerals could increase groundwater travel times (Manteufel et al., 1993; Daily et al., 1987), and therefore affect radionuclide migration. Numerous difficulties are associated with these complex and coupled geochemical, hydrological, thermal, and mechanical processes in determining if altered mineral assemblages will have an equal or enhanced capacity to inhibit radionuclide migration. These difficulties are compounded by the interactions of exotic materials from the near field in the genesis of altered mineral assemblages. Much work is currently being conducted by the NRC staff, Center for Nuclear Waste Regulatory analysis personnel, and DOE on radionuclide sorption on a variety of mineral and rock substrates under a variety of conditions.

Nevertheless, the problem proves to be complex and multifaceted. Empirical data exist on the physical distribution of alteration minerals and their effects on fluid flow in a limited range of systems (e.g., Moore et al., 1986; Daily et al., 1987). However, prediction of these effects remains a very difficult problem. The cumulative effects of thermal loading on a given mineral assemblage are likely to affect radionuclide isolation in ways that lead to potentially adverse as well as favorable conditions. Therefore, difficulty will arise in the determination in many cases that particular cumulative effects are favorable with regard to radionuclide isolation.

Summary: The following assumptions have been made in assigning a Type 4 level of review to this CDS:

(1) DOE will take credit for this FAC to demonstrate compliance with the performance objectives.

(2) The thermal load for the repository is expected to be high relative to the ambient temperatures.

(3) Mineral assemblages at the repository will be altered by the thermal loading. Some altered mineral assemblages will have an equal or greater capacity to inhibit radionuclide migration than the precursor assemblage.

(4) Due to the introduction of man-made materials to the repository environment, additional alteration phases, beyond those expected from alteration of *in-situ* materials, can be expected.

REVIEW STRATEGY:

Acceptance Review:

In conducting the Acceptance Review of this Favorable Condition, the reviewer should determine if the content of the license application is complete in technical depth and breadth with respect to the information requested by Section 3.2.3.3 of regulatory guide "Format and Content of the License Application for the High-Level Waste Repository (FCRG)." The reviewer should determine whether the license application contains all appropriate information with respect to this Favorable Condition that the staff needs to support the Safety Review (described below) and the total system and subsystem performance assessments.

The information presented in the license application should be presented in such a manner that the assumptions, data, and logic lead to a clear demonstration of compliance with the requirement. The reviewer should not be required to conduct extensive analyses or literature searches. The reviewer should also determine whether an appropriate range of alternative interpretations and models has been described.

Finally, the reviewer should determine if the U.S. Department of Energy (DOE) has either resolved all the NRC staff objections that apply to the applicable regulatory requirement or provided all the information requested in Section 1.6.2 of the FCRG, for unresolved objections. The reviewer will evaluate the effects of any unresolved objections, both individually and in combination with others, on: (1) the reviewer's ability to conduct a meaningful and timely review; and (2) the Commission's ability to make a decision regarding construction authorization within the three-year statutory period.

Safety Review:

This regulatory requirement topic is limited to the consideration of thermal alteration of *in-situ* mineral assemblages to mineral assemblages having equal or increased capacity to inhibit radionuclide migration. This regulatory requirement topic is not concerned with potentially adverse conditions resulting from thermal alteration of mineral assemblages to mineral assemblages with decreased capacity to inhibit radionuclide migration. These subjects will be covered under Sections 3.2.3.4 (Potentially Adverse Conditions: Groundwater Conditions and the Engineered Barrier System), 3.2.3.5 (Potentially Adverse Conditions: Geochemical Processes), and 3.2.3.7 (Potentially Adverse Conditions: Gaseous Radionuclide Movement) of the license application and its attendant review plans.

Following the Acceptance Review, the first step will be to evaluate DOE's analyses to determine if the following basic assumptions have been met:

(1) DOE will take credit for this FAC to demonstrate compliance with the performance objectives.

(2) The thermal load design basis to the repository is expected to be high relative to ambient temperatures.

(3) Mineral assemblages at the repository will be altered by the thermal loading. Some altered mineral assemblages will have an equal or greater capacity to inhibit radionuclide migration than the precursor assemblage.

(4) Due to the introduction of man-made materials to the repository environment, additional alteration phases, beyond those expected from alteration of *in-situ* materials, can be expected.

If the above assumptions are met, the staff review will follow the review strategy described here. If these assumptions are not met, the staff review may require a different review strategy for evaluation DOE's demonstration of compliance with the applicable regulatory requirements. It is expected, however, that any deviation from these assumptions will be known well in advance of the time of license application submittal, and this strategy shall be reviewed in accordance with such new information as it becomes available to the staff.

In conducting the Safety Review, the reviewer will, at a minimum, determine the adequacy of the data and analyses to support DOE's demonstrations regarding 10 CFR 60.122(b)(4). Specifically, DOE will need to (1) provide information to determine whether, and to what degree, this favorable condition is present; (2) assure the sufficiency of the lateral and vertical extent of the field data collection; and (3) evaluate the information presented under item (1) above, using assumptions and analysis methods that adequately describe the presence of the favorable condition and ranges of relevant parameters. The specific aspects of the license application on which the reviewer will focus are discussed below, and the Acceptance Criteria are identified in Section 3.0 of this Review Plan.

In conducting the Safety Review, the staff should also confirm that DOE has submitted information regarding mineral assemblages that, when subjected to anticipated thermal loading, will remain unaltered or alter to mineral assemblages having equal or increased capacity to inhibit radionuclide migration. This information is expected to include adequate data concerning mineralogy, geochemistry, hydrology, and structural geology to allow assessment of relevant geochemical processes.

DOE will also need to explain how models that are used to assess the presence or absence of the favorable condition are supported. Analyses and models that will be used to predict future conditions and changes in the geologic setting shall be supported by an appropriate combination of methods such as field tests, laboratory tests that are representative of field conditions, monitoring data, and natural analog studies. For purposes of determining the presence or absence of this favorable condition, investigations should extend from the ground surface to a depth sufficient to determine critical pathways for radionuclide migration from the underground facility. Investigations should be sufficient to demonstrate a suitable understanding of potential effects of mineral assemblage alteration that reasonable bounds can be placed on the different conceptual models.

In conducting the aforementioned evaluations, the reviewer should determine that DOE uses: (1) analyses that are sensitive to evidence of the favorable condition; and (2) assumptions which are not likely to overestimate its effects. In general, the reviewer will assess the adequacy of DOE's investigations regarding the likelihood of this favorable condition, both within the controlled area and outside the controlled area, as necessary, in the manner defined in 10 CFR 60.21(c)(1)(ii)(B).

Reviewers will rely on staff expertise and independently-acquired knowledge, information, and data such as the results of research activities being conducted by the NRC Office of Regulatory Research, in addition to that provided by the DOE in its license application. The reviewer should focus on additional data which can refine knowledge of the favorable condition, and should perform, as necessary, additional analyses to confirm the resolution capabilities of the methods. The reviewer must have acquired a body of knowledge regarding these and other critical considerations in anticipation of conducting the review to assure that site characterization has been sufficient in scope and depth to provide the information needed to resolve the concerns. For example, research undertaken in the Center for Nuclear Waste Regulatory Analyses Geochemistry, Sorption, and Geochemical Natural Analogs research projects are expected to provide data relevant to the assessment of information regarding thermal alteration of mineral assemblages to mineral assemblages having equal or increased capacity to inhibit radionuclide migration.

Detailed Safety Review Supported by Analysis:

A Detailed Safety Review will be needed to evaluate the Key Technical Uncertainty regarding alteration of mineral assemblages by thermal loading and equal or increased capacity of alteration mineral assemblages to inhibit radionuclide migration. This will ensure that DOE has adequately demonstrated Items (1)-(3) listed above in the previous section (see Section 2.2.1, "Safety Review," second paragraph). Activities performed in this Detailed Safety Review will help to assure that DOE has adequately addressed and resolved these Key Technical Uncertainties so that they do not lead to a failure to achieve a determination of compliance with regard to the overall system performance objectives.

Specifically, this review will require analysis of geologic, mineralogic, chemical, and hydrologic data developed by DOE. These analyses will be accomplished through detailed thermal-chemical-hydrologic-mechanical calculations using models and parameters developed from theoretical considerations and observations of natural and laboratory mineral alteration observed under conditions comparable to those anticipated in the proposed repository host rock. There are a number of numerical modeling codes available for calculating the transformation of minerals with increasing temperature (e.g., EQ3/6; Wolery, 1992; MINTEQA2; Allison et al., 1991; MPATH, Lichtner, 1992). The effects of thermal alteration of mineral assemblages on hydrologic pathways will require relating chemical reactions to spatial orientation and textures of the mineral assemblages.

Examples of specific review activities that will be required include: (1) review and analysis of mineralogical data from the site for adequacy to support detailed interpretation and modeling; (2) review and analysis of assumptions and data supporting the interpretation of the results of thermal alteration of mineral assemblages; and (3) review and analysis of information describing changes or the absence of changes in the capacity to inhibit the migration of radionuclides by the mineral assemblages; and (4) review and analysis of calculations and modeling of the thermal response of the mineral assemblages and the associated parameters.

RATIONALE FOR REVIEW STRATEGY:

In view of the complexity of the key technical uncertainty addressed above, it is appropriate that the NRC conduct the independent activities described in order to (1) develop the licensing tools and technical basis necessary to judge the adequacy of DOE's license application, (2) assure sufficient independent understanding of the basic physical processes taking place at the geologic repository, and (3) maintain an independent but limited confirmatory research capability under NRC auspices.

Contributing Analysts:

CNWRA: William M. Murphy, E.C. Pearcy, R.T. Pabalan, R.D. Manteufel

NRC: V.A. Colten-Bradley

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APPLICABLE REGULATORY REQUIREMENTS FOR EACH TYPE OR REVIEW:

<u>Type 1:</u>

60.21(c)(1)(ii)(B)
60.21(c)(1)(ii)(F)
60.122(b)(4)

<u>Type 3:</u>

60.122(b)(4)

<u>Type 4:</u>

(60.122(b)(4)

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