ASSESSING OPTIONS FOR ANTI-SATELITE ARMS CONTROL: THE ANALYTIC HIERARCY PROCESS

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PREFACE

The author, Scott Pace, is a graduate fellow at the Rand Graduate Institute. This paper was prepared for a workshop course on risk and uncertainty in public policy. The course was taught in the fall of 1985 by Dr. Kenneth Solomon and Dr. James Kahan.

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I. INTRODUCTION

In a recent report by the Office of Technology Assessment, "Anti-Satellite Weapons, Countermeasures, and Arms Control," a range of seven Asat policy options was identified. These options packaged possible arms control provisions, Asat postures, and countermeasures in order to examine their interactions. Each package represented a simplified, single policy regime containing options which might reasonably be expected to exist in the same proposal. There are many possible packages, and some limitation on the number of possible combinations was necessary for purposes of discussion. According to the OTA, "Consideration of these regimes is intended to facilitate assessment of the effectiveness and desirability of different combinations of Asat and BMD technology development, satellite survivability, and arms control."[1]

With the starting points drawn by the OTA, the primary objectives of this study were to:

- Evaluate the desirability of each of the OTA regimes from the viewpoint of U.S. interests.
- Identify primary risk areas and uncertainties for further analysis of Asat policies.
- Demonstrate the applicability of a structured quantitative evaluation technique, the Analytic Hierarchy Process (AHP), to a current policy issue.

The result of this study is a quantitative, auditable ranking of the OTA policy regimes by persons familiar with Asat/BMD issues at Rand. As is often the case with the AHP, the process of producing the rankings and feeding that information back to the evaluators is just as interesting as the particular "scores" for each option.

Study Methodology

The methodology for this study was a simple, five-step process. The first step of identifying and summarizing the various Asat policy regimes was accomplished by the OTA in its report. The second step was to develop evaluation criteria. This was done informally in discussions with Rand personnel experienced in national security studies. These criteria were very broad and kept to a small number relevant for "top-level" considerations. Part of the AHP process involves evaluators differing over the relative importance of these criteria.

The third step was the evaluation of the policy options with the AHP technique. This required evaluators to fill out structured questionnaires on the relative importance of the evaluation criteria and the relative desirability of each policy option. The subjective evaluations were used as raw data inputs to a separately developed AHP program which produced a single figure of merit for each option utilizing the weighted evaluation criteria. In addition, the AHP program generated a measure of consistency for the individual evaluators and the overall judgment. This "consistency ratio" is the subject of some discussion on its validity, and this issue is addressed in a separate section.

The fourth and fifth steps involve iterating the questionnaire and AHP evaluation process until a consensus ranking of the alternative options is achieved. Sometimes this consensus is achieved on the first pass, sometimes several feedback rounds are required. The feedback is based on the results of the fifth step. This is the reporting of the figures of merit (individual and group) for each option, reasons for the relative differences in evaluation, and identified areas of contention and/or inconsistency. Individual evaluators may choose to change their subjective judgments on both criteria weights and option preferences. At this point, areas of uncertainty and disagreement can be targeted for more detailed study, thus focusing efforts in the areas of greatest need.

II. ASAT POLICY REGIMES

The seven regimes options created by the OTA were reduced to five for actual evaluation. This was done to make the evaluation easier in that fewer options would have to be considered and because the regimes eliminated were, in one case, redundant and, in the other, unrealistic. The five regimes considered in this study are still identical to those in the OTA study, except that some of the characteristics of the eliminated regimes were incorporated into those remaining. The five regimes then actually evaluated in this study were:

1. *Existing Constraints.* The first regime is defined by the treaties and agreements presently in force. This is a status quo situation with the ABM Treaty, SALT I Agreement, Test Ban Treaty, and Outer Space Treaty especially applicable.

2. *Asat Space Test Ban and a Space-Based Weapon Deployment Ban.* This regime would be created by adhering to treaties and agreements presently in force and, in addition, agreeing to forego testing in an "Asat mode" and the deployment of any weapon in space. This regime differs from proposals for a comprehensive Asat ban in that it does not ban the possession of deliberate Asat weapons on Earth. The OTA regime of a comprehensive Asat ban on Earth and in space is probably unverifiable and was eliminated from consideration in favor of this option.

3. *A "One Each/No New Types" regime.* This regime includes arms limitation provisions which would permit the U.S. and the Soviet Union to test and deploy their current Asats but would prohibit testing of more advanced systems. Advanced systems prohibited would include those capable of operating or attacking targets at higher altitudes and those deployed in space. The U.S. MHV would be the only deliberate "current" U.S. Asat.

4. *Rules of the Road.* This regime is different from the regime of Existing Constraints in that it establishes declared "keep-out zones" around individual satellites. These zones may be established by international agreement or unilateral declaration. Procedural rules for spacecraft approaching or crossing these zones would be established.

Testing and deployment of weapons beyond a certain altitude may be forbidden. Keep-out zones are not actively defended and serve primarily to prevent accidents and increase warning times. These provisions are vulnerable to directed energy threats, however. This option includes the provisions of the OTA "Space Sanctuaries" regime where satellites could operate at high altitudes but weapons deployment and testing would be forbidden. In effect, the "Space Sanctuary" regime has been absorbed here.

5. *A Space-Based BMD Regime.* This regime results from a U.S. or Soviet withdrawal from the ABM Treaty followed by deployment of space-based BMD systems. This regime is particularly different from the Rules of the Road regime in that keep-out zones may be actively defended. The regimes can be characterized by the extent to which they rely on negotiated arms controls and the extent they allow or encourage Asat development.

	Restrict with arms control	Develop Asat weapons
Existing Constraints	no	yes
Test Ban and Space-Based Weapon Ban	yes	no
One Each/No New Types	yes	yes/no(*)
Rules of the Road	yes	yes (**)
Space-Based BMD Regime	no	yes

(*) Testing and deployment allowed on Earth but not in space.

(**) All Asat weapons other than "current types" could not be tested or deployed in space.

The five regimes listed above are the ones we wish to rank in order of their desirability. Before we can do this, however, we need to specify our evaluation criteria.

III. EVALUATION CRITERIA

The goal of evaluating Asat policy regimes is to select the one regime or set of regimes in the best interests of the United States. To this end, discussions with Rand personnel focused on selecting criteria which were broad and represented crucial national interests affected by Asat policies. In addition, it is desirable to limit the criteria considered to a small number to make the evaluator's job less tedious. Since it is not possible to anticipate all long-run technical and political changes, the selection of policy regimes was assumed to be temporary, 10-20 years in duration, and subject to reevaluation.

The overall figure of merit, the policy's "Desirability," is a composite of several underlying criteria. The four factors contributing to an Asat policy's desirability for the 1985 to 1995/2005 period are its implication for 1) Deterrence Stability, 2) Crisis Stability, 3) Arms Race Stability, and 4) Fiscal Costs. For purposes of this evaluation, it is assumed that negotiability and verifiability are equally feasible for the five regimes considered. These are obviously complex issues which need to be separately examined for their impact on the prior criteria.

Deterrence Stability

Deterrence is the ability to dissuade or discourage an opponent from taking certain actions based on the opponent's fear of the costs or consequences. Deterrence operates by influencing the opponent's behavior, and not being able to prevent it per se. Deterrence stability is greater if opponents are mutually deterred from military actions at a high level. Deterrence stability is lower if one opponent is less deterred than the other or if both opponents are deterred from military action at only a low level. A high degree of deterrence stability is generally assumed to be supportive of U.S. interests.

Crisis Stability

Crisis stability refers to first strike incentives against an opponent's offensive or defensive forces during a crisis. We do not consider accidental or third party actions. During a crisis, the decision to act militarily is based less on an assessment of whether peace is preferable to war (as in deterrence stability above) but more on whether one is better off striking first rather than second. Crisis stability is higher when neither opponent has a first strike incentive. Some commentators have seen crisis stability as the most stressing form of deterrence stability. A high degree of crisis stability is assumed to be in the U.S. interest.

Arms Race Stability

Arms race stability refers to pressures to proliferate offensive and defensive forces in response to an opponent's force deployment. The rationale for such pressures is to maintain or enhance deterrence, crisis stability and/or relative military advantages. The nature of any response is one of competition, not conflict. Its exact form is determined largely by the cost-effectiveness of the response options and political requirements for the military forces. Arms race stability is higher when neither side has incentives to modify or expand its force structure. This stability lessens as one or the other opponent experiences pressures to expand its force structure. A high level of arms race stability is generally thought to be supportive of U.S. interests. Some analysts, however, have argued that it is desirable and possible to influence the force structure of potential opponents in the direction of other U.S. interests.

Fiscal Costs

This criterion refers to the implications of each policy regime for the U.S. budget. Costs may be incurred not only in the requirements for each Asat regime, but in the implications of each regime for other elements of the U.S. force structure. Costs may also be reduced for the overall force structure under different policy regimes. In general, lower fiscal costs are in the interest of the U.S. As we are looking at a 10 to 20 year period, potential costs past that horizon are heavily discounted. Increased costs may be justified and desirable if other criteria, such as those above, can be enhanced.

IV. ANALYTIC HIERARCHY PROCESS

The Analytic Hierarchy Process was developed by Thomas L. Saaty, and is described in his book of the same name.[2] AHP is a decision support system for the evaluation of alternative options with explicit criteria and expert judgment. It relies on the subjective judgments of evaluators and structures those judgments in a quantitative and auditable way. While the subject is too large for treatment here, a brief overview of the AHP technique is given below, along with modifications favored by recent Rand work on handling subjective judgments.

The central technique of AHP is the pairwise comparison of alternatives to elicit the relative preferences of experts. Comparison of more than two alternatives at a time is often difficult to perform consistently. Therefore, AHP only requires the evaluator to state his relative preference for one choice over another at any particular time. For example, suppose we have four criteria and four evaluators (there is no restriction on the number of evaluators):

Step 1

Each evaluator states his relative preference for each possible pairing of the criteria:

	Preferred a lot	Preferred a little	Equal	Preferred a little	Preferred a lot	
Criterion A						Criterion B

9 8 7 6 5 4 3 2 1 1/2 1/3 1/4 1/5 1/6 1/7 1/8 1/9

Depending on the direction and magnitude of the preference for A or B, a number is assigned via a hidden scale (shown above).

Step 2

The numbers assigned in Step 1 form a matrix with the different evaluators constituting the rows:

	A	B	C	D
Evaluator 1	1	1/3	7	1
Evaluator 2	3	1	9	7
Evaluator 3	1/7	1/9	1	1/9
Evaluator 4	1	1/7	9	1

The geometric mean is taken for each column and the results summed and normalized to get the weights for each criterion. In this example we have

$$W_a = .12 \quad W_b = .04 \quad W_c = .71 \quad W_d = .14 \qquad \text{Sum} = 1.0$$

for the relative criteria weights.

Step 3

This process of performing pairwise comparisons is repeated for all possible paired combinations of options. These pairwise comparisons are done by considering each criterion alone. That is, if Criterion A was the only consideration, what is the relative preference between the ith and jth options? We, again, get a matrix and a series of values for each option under each criterion.

Step 4

The values assigned, A through D, for each option are combined with the weights derived in Step 2. This forms a linear equation giving a single figure of merit for each of the options:

$$F(i) = Wa*A(i) + Wb*B(i) + Wc*C(i) + Wd*D(i)$$

Step 5

The options are now quantitatively ranked in an auditable way. We can see how each figure of merit is calculated by looking at the criteria weights and the values assigned to each option when considered alone against each criterion. In addition, we can check for how consistent our results are. This requires a measure of the relative consistency in magnitude and direction of preference rankings by the evaluators. There is some disagreement as to how this should be done, as discussed below.

Measures of Consistency

The original form of AHP by Saaty uses the "dominant" right eigenvector, corresponding to the maximal eigenvalue, of the subjective judgment matrices. This is done to estimate the underlying scale of preferences. The argument is that the dominant eigenvector is a continuous function of the matrix elements, and if the matrix is consistent, the eigenvector gives the unique (within a scaler multiplication) scale. Thus, if the elements of the matrix are perturbed in the process of being subjectively quantified by an evaluator, the dominant eigenvector will return a scale only slightly different from the scale of an underlying consistent judgment matrix. In the computer program developed in prior work, this form of AHP was used. Computation of the eigenvector was based on the theorem that the normalized row sums of the limiting power of a primative matrix gives the desired eigenvector. Thus, we can raise the judgment matrix to powers that are successively squared each time. The row sums are calculated and normalized. The program is instructed to stop when the difference between these sums in two consecutive calculations is smaller than a prescribed value. Convergence typically takes 4-9 iterations, or over 20, if the evaluator's responses are very inconsistent. Based on Saaty's book[3] we have a crude estimate of the consistency of the judgments:

> "The closer the principal eigenvalue (L) is to n (the number of activities in the matrix), the more consistent the result...deviation from consistency may be represented by (L-n)/(n-1) which we call the consistency index, C.I."

The consistency index of a randomly generated reciprocal matrix with the 1-9 scale used in typical AHP applications, reciprocals forced, is the random index, R.I. Based on statistical work at the Oak Ridge National Laboratory, the order of the matrix (first row) and the average R.I. (second row) is[4]:

1	2	3	4	5	6	7	8	9	10	11
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

The ratio of C.I. to the average R.I. for the same order matrix is called the consistency ratio. The lower the consistency ratio, the more consistent the matrix. The problem is that there are no obvious criteria for determining what an acceptable C.R. is. In practice, C.R.'s above 0.5 are a flag to have the evaluator redo his input and try for greater consistency. C.R.'s above 0.1 are still noted, but only as areas of uncertainty and/or confusion. Values below 0.1 are noted as areas of consensus. Saaty himself offers no other justification for the C.R. than it seems to be useful and people like this simple figure for feedback.

Crawford and Williams (1985)[5] at Rand have focused on a much more basic issue of the eigenvector approach. The eigenvector is not the only continuous vector-valued function of judgment matrices that yields the correct scale when the matrix is consistent. They argue that the geometric mean vector is a preferable metric which, in their words: "satisfies the continuity and consistency criteria Saaty uses to defend the dominant eigenvector, (and) has several other desirable traits: In certain circumstances, it is statistically optimal and gives rise to an estimate of scales and a measure of consistency that have known statistical distributions...it seems to do as well as, or better than, the eigenvector in preserving rank order."

Certainly the geometric mean is computationally easier to calculate and explain than a dominant eigenvector. In most normal cases, there is little difference between the two approaches in their computed figures of merit, and rank preservation abilities are similar. In the case of the Asat policy options examined here, the eigenvector program and geometric mean approaches yielded the same results. If the distribution of errors is unusual (e.g., bimodal) then the eigenvector method is slightly better at preserving rank order. The major noticeable difference between the two approaches is in their measures of consistency. The geometric mean approach uses the Sum of Squared Log Errors (see Table 1). The lower the SSLE, the more consistent the judgment matrix. There are no rules of thumb to tell us when we should become concerned with a "large" SSLE as with the C.R. Finding what those levels of concern should be is a problem that needs study. While the consistency ratio may have a shaky justification, it has the advantage of being easily explainable and in current use. In this study, we have used Saaty's eigenvector technique and consistency ratios while checking the results with the geometric mean approach for rank preservation. Given the uncertain utility of the SSLE measure of consistency, it was not calculated.

Table 1

RATIO SCALES PERTURBED BY LOGNORMAL ERRORS, SUM OF SQUARED ERRORS OF LOGARITHMS, MONTE CARLO COMPARISON OF GEOMETRIC MEAN VECTOR AND EIGENVECTOR

Dimension, Variance, (L-n)/(n-1), Number of Trials	Sum of Squared Error of Logs, Geometric Mean	Sum of Squared Error of Logs, Eigenvector	Percentage of Trials in Which Geometric Mean is Better in Squared Error of Logs
5/.01/.003/5000	42.4	42.5	51
5/.04/.012/5000	170.8	171.7	52
5/.09/.028/5000	377.6	382.1	53
5/.16/.051/1000	135.2	138.4	57
5/.25/.080/1000	210.4	218.8	60
5/.49/.165/1000	427.0	448.6	56
5/1.0/.349/1000	863.3	947.7	61
7/.01/.005/5000	45.2	45.3	53
7/.04/.015/5000	178.9	180.6	55
7/.09/.033/5000	403.5	410.9	55
7/.16/.059/1000	150.9	154.5	56
7/.25/.095/1000	222.7	235.1	59
7/.49/.203/1000	440.6	485.2	61
7/1.0/.445/1000	928.2	1102	67
10/.01/.040/5000	46.4	46.5	53
10/.04/.016/5000	185.4	187.6	56
10/.09/.036/5000	421.9	433.4	60
10/.16/.067/1000	147.7	156.2	66
10/.25/.108/1000	234.2	251.6	65
10/.49/.223/1000	456.2	524.2	69
10/1.0/.516/1000	946.1	1268	78

(From Crawford and Williams, R-2572-1-AF)

V. RESULTS

Based on questionnaires from five evaluators in the Rand Engineering and Applied Science Department, the AHP technique produced the output shown in Table 2. The first block shows how the criteria were weighted:

Crisis Stability	=	40.1%
Deterrence Stability	=	34.5%
Fiscal Costs	=	15.8%
Arms Race Stability	=	9.6%

Crises and deterrence stability were closely linked and, as might be expected, their relative weights are close. Fiscal costs are about half as important to these evaluators, with arms race stability being in last place. This is reasonable as the evaluators saw costs as a partial measure of arms race stability (i.e., more stability, less cost). As long as crisis and deterrence stability goals were being met, actual costs and force structures were secondary concerns.

Each of the Asat policy regimes were evaluated against each of the evaluation criteria. In the case of crisis stability, the relative preferences were:

Asat & Space Weapons Ban	=	56.0%
One Each/No New Types	=	16.2%
Rules of the Road	=	15.4%
Existing Constraints	=	8.2%
BMD Regime	=	4.2%

For deterrence stability, the ranking was:

Asat & Space Weapons Ban	= 55.7%
One Each/No New Types	= 20.5%
Rules of the Road	= 11.4%
Existing Constraints	= 8.0%
BMD Regime	= 4.4%

For fiscal costs, the ranking was:

Asat & Space Weapons Ban	= 51.4%
One Each/No New Types	= 23.7%
Existing Constraints	= 12.2%
Rules of the Road	= 10.0%
BMD Regime	= 2.7%

For arms race stability, the ranking was:

Asat & Space Weapons Ban	= 53.4%
One Each/No New Types	= 23.7%
Rules of the Road	= 10.4%
Existing Constraints	= 9.4%
BMD Regime	= 3.2%

In these cases, rank order was preserved among the options for each of the criteria, with only minor exceptions. This is not generally the case, as the criterion which favors one option usually works against another. The consistency ratios for the judgment matrices were satisfactory (subject to the caveats of the previous section). There was a consensus on the importance of crisis and deterrence stability as witnessed by the C.R.'s of 0.08 each. There was some inconsistency in the area of arms race stability, with a C.R. of 0.1. The greatest area of inconsistency was in the area of fiscal costs, as might be expected given the uncertain nature of future strategic systems affected by Asat policies. The role of new technology was a hidden factor as the evaluators assumed there would be no dramatic cost-effectiveness breakthroughs.

Table 2

OUTPUT OF AHP EVALUATIONS

AHP weights, highest to lowest for all

criteria: important

1	2 crises	0.401
2	1 deter	0.345
3	4 costs	0.158
4	3 arms	0.096
		1.000

consistency index (ci) = 0.018
random index (ri) = 0.900
CONSISTENCY RATIO (CR) = 0.020

criteria: crises

1	2 ban	0.560
2	3 one each	0.162
3	4 rules	0.154
4	1 existing	0.082
5	5 bmd	0.042
		1.000

consistency index (ci) = 0.093
random index (ri) = 1.120
CONSISTENCY RATIO (CR) = 0.083

criteria: arms

1	2 ban	0.534
2	3 one each	0.237
3	4 rules	0.104
4	1 existing	0.094
5	5 bmd	0.032
		1.000

consistency index (ci) = 0.130
random index (ri) = 1.120
CONSISTENCY RATIO (CR) = 0.116

criteria: deter

1	2 ban	0.557
2	3 one each	0.205
3	4 rules	0.114
4	1 existing	0.080
5	5 bmd	0.044
		1.000

consistency index (ci) = 0.089
random index (ri) = 1.120
CONSISTENCY RATIO (CR) = 0.080

criteria: costs

1	2 ban	0.514
2	3 one each	0.237
3	1 existing	0.122
4	4 rules	0.100
5	5 bmd	0.027
		1.000

consistency index (ci) = 0.136
random index (ri) = 1.120
CONSISTENCY RATIO (CR) = 0.121

It should be noted that some evaluators had higher consistency ratios than the final results. The AHP eigenvector method derives a more consistent underlying matrix from the varied subjective judgments. The Sum of the Squared Log Errors measure performs in an analogous way for the geometric mean AHP method. The effect is obviously dependent on the size and distribution of the error, or inconsistency in the judgment matrices. It is not yet clear, however, how large a "drive for consistency" can be expected with either method.

The Bottom Line Evaluation

The summary result for all evaluators is shown in Figure 1:

Criteria	Alternatives
C1 = deterrence stability	A1 = existing constraints
C2 = crisis stability	A2 = Asat & space weapons ban
C3 = arms race stability	A3 = one each/no new types
C4 = fiscal costs	A4 = rules of the road
	A5 = BMD regime

	C1	C2	C3	C4	Score	
A1	3	3	1	2	9	
A2	19	22	5	8	55	Most Preferred
A3	7	6	2	4	20	
A4	4	6	1	2	13	
A5	2	2	0	0	4	Least Preferred

We can see directly that the Asat & space weapons ban option is the most preferred, in this exercise, due in large part to a strong contribution in the areas of deterrence and crisis stability. The BMD regime is the least preferred by the evaluators in that it showed only weak preference in the highly weighted areas of crisis and deterrence stability and no preference in arms race stability or fiscal costs.

VI. CONCLUSIONS

The evaluators strongly preferred a restrictive Asat regime for the near future. The order of preferences is also striking:

1. Asat Test Ban & Space-Based Weapons Deployment Ban
2. One Each/No New Types
3. Rules of the Road
4. Existing Constraints
5. BMD Regime

Some sort of Asat restriction is preferred over the status quo, and a BMD regime, at least for the near term, is less preferred than the status quo. Of the more restrictive options, the most restrictive is preferred, followed by a "freeze" at the current level of development, and then followed by agreements on satellite keep-out zones. It should be emphasized that this ordering is for the specific group of evaluators, and cannot be considered a general policy recommendation.

The criteria of crisis stability and deterrence stability were closely linked and dominated the secondary criteria of fiscal cost and arms race stability. In noting the consistency ratios for the evaluators, only one of them had a "serious" problem with a consistency ratio above 1. This was a matrix that was worse than random in consistency. Even so, the AHP process proved to be robust in handling these "outlier" judgments. It took merely 22 iterations to get a convergence using the eigenvector method, as compared to the normal 4 to 5. Of the other consistency ratios, three of the five evaluators were a C.R. of 0.2 in evaluating fiscal costs. This tells us that the cost implications of the Asat policy options need to be more carefully examined and explained in order to achieve a closer consensus.

The AHP process was able to quickly display areas of agreement and differences among different evaluators. While this was useful, it is only a decision support system. It cannot create new options or combinations of options to be evaluated. This remains the preserve of the analyst and strategist. As one evaluator pointed out, the regimes considered here could be considered as "building blocks" rather than self-contained proposals. The real challenge is to assemble an overall package that not only meets national goals, but is feasible as well. For example, it was suggested that a more realistic package would combine several elements:

1) Adhere to existing constraints
2) Ban the deployment of any space weapons
3) Allow only earth-based Asats, with testing only up to medium earth orbit (e.g., 5000 nmi.)
4) Establish Rules of the Road and high-orbit space sanctuaries

The AHP process can clarify and structure policy debates among analysts by showing what areas are important or uncertain. It is limited, however, to the criteria and alternatives provided to it.

FOOTNOTES

1. U.S. Congress, Office of Technology Assessment, *Anti-Satellite Weapons, Countermeasures, and Arms Control,* OTA-ISC-281 (Washington, D.C.: U.S. Government Printing Office, September 1985).

2. T. L. Saaty, *The Analytic Hierarchy Process* (McGraw-Hill, Inc., 1980).

3. Op. cit. p. 21

4. Op. cit.

5. Gordon Crawford, Cindy Williams, *Analysis of Subjective Judgment Matrices,* R-2572-1-AF (Rand Corporation, May 1985).

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