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THE IMPACT OF CONFINEMENT SCALING ON ITER PARAMETERS

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FUSION ENGINEERING DESIGN CENTER

OAK RIDGE NATIONAL LABORATORY

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THE IMPACT OF CONFINEMENT SCALING ON ITER PARAMETERS

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ABSTRACT

Energy confinement scaling is a major concern in the design of the International Thermonuclear Experimental Reactor (ITER). The existing database for tokamaks can be fitted with a number of different confinement scaling expressions that have similar degrees of approximation. These scaling laws predict confinement times for ITER that vary by over an order of magnitude. The uncertainties in the form and magnitude of these scaling laws must be substantially reduced before the plasma performance of ITER can be predicted with adequate reliability. The TETRA systems code is used to calculate the dependence of major ITER parameters on the scaling laws currently in use. Design constraints of interest in the present phase of ITER consideration are used, and the minimum-cost devices arising from these constraints are reviewed.

1. INTRODUCTION

Energy confinement scaling is a major concern for the design of the International Thermonuclear Experimental Reactor (ITER). The existing tokamak database can be fitted with a number of different confinement scaling expressions that involve similar degrees of approximation. These scaling laws predict confinement times for ITER that vary by over an order of magnitude. The uncertainties in the form and magnitude of these scaling expressions must be substantially reduced before the plasma performance of ITER can be predicted with adequate reliability.

In our effort to develop the most cost-effective concept for ITER given the uncertainty of the confinement scaling, it is useful to understand the impact of this uncertainty on the design. Such information will help us choose appropriate design margins for ITER. We use the TETRA tokamak systems code¹ to calculate the dependence of major ITER parameters--such as plasma current, aspect ratio, fusion power, neutron wall load, peak magnetic fields, and scaled direct cost--on the various scaling expressions and magnitudes currently in use. We choose design constraints that are of interest to the present phase of ITER and look at the minimum-cost designs permitted by these constraints. The ranges of parameters for these designs indicate the margins that may be needed in these parameters.

In Sects. 2 and 3, we briefly summarize the confinement scalings and design constraints used in this study. Results are presented in Sect. 4 and conclusions in Sect. 5.

2. CONFINEMENT MODELS

The confinement scaling expressions used in this study are given in this section. They are representative of the range of expressions now available.

2.1 NEO-ALCATOR SCALING

Neo-Alcator scaling² is used in conjunction with the other scaling laws considered in this study to provide an upper limit on confinement time in cases for which

the other scalings are more optimistic than neo-Alcator. This scaling is

$$\tau_{NA} = 0.07 (n_{20}) a R^2 q.$$

where

$$q = \frac{5a^2 B_0}{RI} \frac{1 + \kappa^2(1 + 2\delta^2 - 1.2\delta^3)}{2}$$

κ = elongation at the 95% flux surface

δ = triangularity at the 95% flux surface

B_0 = magnetic field on axis, T

a = minor radius, m

R = major radius, m

I = plasma current, MA

n_{20} = the normalized density $n_e/10^{20}$, m⁻³

2.2 KAYE-GOLDSTON SCALING

The Kaye-Goldston scaling³ is

$$\tau_{KG} \approx 0.055 f_L \frac{I^{1.24} R^{1.65} \kappa^{0.26} (n_{20})^{0.26}}{P_{heat}^{0.58} a^{0.49} B_0^{0.09}} \left(\frac{A_i}{1.5} \right)^{0.5},$$

where $f_L = 1.3$ is the L-mode enhancement factor, A_i is the average atomic mass (≈ 2.5 for deuterium-tritium), and $P_{heat} = (P_\alpha + P_{OH} + P_{aux} - P_{rad})$ is the total heating power.

The Kaye-Goldston scaling is combined with neo-Alcator scaling by inverse quadrature to provide the global confinement time,

$$\frac{1}{\tau_E^2} = \frac{1}{\tau_{KG}^2} + \frac{1}{\tau_{NA}^2}$$

2.3 GOLDSTON SCALING

The Goldston scaling⁴ is

$$\tau_G \approx 0.037 f_L \frac{I R^{1.75} \kappa^{0.5}}{P_{heat}^{0.5} a^{0.37}} \left(\frac{A_i}{1.5} \right)^{0.5}$$

Goldston scaling is combined with neo-Alcator scaling by inverse quadrature to provide the global energy confinement time,

$$\frac{1}{\tau_E^2} = \frac{1}{\tau_G^2} + \frac{1}{\tau_{NA}^2}.$$

For Goldston scaling, the recommended L-mode enhancement factor is $f_L = 2$.

2.4 T-10 SCALING

The T-10 scaling² is

$$\tau_{T-10} \simeq 0.09 a R B_0 \kappa^{0.5} \frac{1}{P_{\text{heat}}^{0.4}} \left(\frac{Z_{\text{eff}}^2 I^4}{a R q^3 \kappa^{1.5}} \right)^{0.08},$$

where Z_{eff} is the effective charge.

The global energy confinement time is taken to be the minimum of T-10 scaling and neo-Alcator scaling,

$$\tau_E \simeq \min(\tau_{T-10}, \tau_{NA})$$

2.5 JAERI SCALING

The Japan Atomic Energy Research Institute (JAERI) scaling⁵ is

$$\tau_J = f_L \left(0.085 \kappa a^2 A_i^{0.5} + 0.069 (n_{20})^{0.6} \frac{I B^{0.2} \kappa^{0.2} a^{0.4} R^{1.6}}{P_{\text{heat}}} G A_i^{0.5} \right),$$

where the recommended value of f_L is 1.5 and

$$\begin{aligned} G &= G(Z_{\text{eff}}, q) = g(Z_{\text{eff}})g(q) \\ &\simeq Z_{\text{eff}}^{0.4} \left(\frac{15 - Z_{\text{eff}}}{20} \right)^{0.6} \left[\frac{3q \cdot (q + 5)}{(q + 2)(q + 7)} \right]^{0.6}, \end{aligned}$$

with G a number of order unity.

The global energy confinement time is taken to be the minimum of JAERI scaling and neo-Alcator scaling,

$$\tau_E = \min(\tau_J, \tau_{NA})$$

2.6 REBUT SCALING

The algorithm used here for Rebut scaling was taken from ref. 6. A revised version of this scaling, given in ref. 7, predicts more optimistic values of confinement time for ITER. This portion of the study will be repeated in the near future to assess the impact of the revised scaling algorithm. The algorithm used here is

$$\tau_{\text{Rebut}} = \frac{0.023 \sqrt{3} \sqrt{n_{19}} A_i^{0.25} \sqrt{\ell^2}}{P_{\text{heat}}^{0.5}}$$

where n_{19} is $n/10^{19}$ (in m^{-3}) and $\ell = (a^2 R_0 \kappa)^{0.333}$.

The global energy confinement time is taken to be equal to Rebut scaling,

$$\tau_E = \tau_{\text{Rebut}}$$

3. DESIGN LIMITS

The TETRA code was used to select candidate ITER designs for minimum direct cost as a function of ignition margin for the various scalings. Both aggressive and conservative limits were placed on the design parameters, in addition to a set of limits used for all cases. The limits, or constraints, placed on the design parameters for all cases included the following:

1. A minimum neutron wall loading of 1.0 MW/m^2 .
2. A maximum value of beta consistent with the Troyon limit, with a Troyon coefficient of 2.8.
3. A maximum value of plasma density consistent with the Greenwald limit.
4. A minimum plasma temperature of 7.5 keV.
5. A maximum value of toroidal field (TF) or ohmic heating (OH) coil current consistent with magnetic field, heat transfer effects, strain effect, protection effects, and quench pressure effects.^a
6. An in-plane stress limit imposed on the TF and OH coil conduits consistent with the structural material and operating scenario.
7. A fixed number of TF coils, $N = 16$.

The aggressive limits were the following:

1. A poloidal field (PF) system with a minimum flux capability of 160% that required for plasma current induction.
2. Inboard (tungsten) shield thickness of 0.55 m and outboard (stainless steel) shield thickness of 1.10 m.
3. A maximum magnetic field ripple at the plasma edge of 1.5%, which in most cases determined the location of the TF coil outer leg.
4. Power for plasma heating (and/or current drive) of 40 MW (for costing purposes only).
5. Engineering design constraints similar to those for the Tokamak Ignition/Burn Engineering Reactor (TIBER) studies.⁹
6. Inboard plasma scrapeoff distance of 10 cm.
7. Gap between the first wall and shield of 6 cm.
8. $Z_{eff} = 1.5$.
9. No requirement for removal of divertor as a single piece.

The following conservative limits were used:

1. A PF system with a minimum flux capability of that needed for plasma current induction plus a 300-s burn plus 30 V·s for resistive startup.
2. A maximum magnetic field ripple at the plasma edge of 1.0%.
3. Power for plasma heating (and/or current drive) of 60 MW (for costing purposes only).
4. Inboard plasma scrapeoff distance of 20 cm.
5. Gap between the first wall and shield of 9 cm.
6. $Z_{eff} = 1.8$.
7. Removal of divertor as a single piece required (in most instances, this set the TF coil outer leg location).

4. RESULTS

Design parameters for an ITER with minimum direct cost were obtained as a function of ignition margin for the five confinement scaling laws given in Sect. 2. The confinement times for these five scalings are either limited to the maximum value consistent with neo-Alcator scaling or else combined with neo-Alcator scaling

by inverse quadrature. This confinement study was done with the aggressive limits imposed on the design parameters and then repeated with the conservative limits (for Kaye-Goldston scaling only) to assess the impact of the choice of parameter limits.

The dependence of major ITER parameters on the five selected scaling laws is presented in this section for minimum-cost designs. In addition, the sensitivity to the choice of parameter limits, or constraints, is presented for Kaye-Goldston confinement scaling.

4.1 PLASMA CURRENT

Figure 1 shows the required plasma current as a function of ignition margin for minimum direct cost. Ignition is seen to be possible in ITER for all scalings except

Fig. 1. Plasma current vs ignition margin for minimum-cost designs.

Rebut, if the plasma current is in the range from 10 to 21 MA. For the Rebut scaling used here, the plasma current required for ignition is significantly above 50 MA. As noted in Sect. 2.6, the Rebut scaling portion of this study will be repeated using a revised, more optimistic algorithm⁷ in the near future.

4.2 MAJOR RADIUS

Figure 2 shows the required major radius as a function of ignition margin for minimum direct cost. The Kaye-Goldston, Goldston, and JAERI scalings are similar; for marginal ignition, the required major radius is between 4.2 and 4.5 m for these three scalings if TIBER-like engineering design is used. The T-10 and Rebut scalings are more pessimistic. For T-10, a major radius of approximately 10 m is required for marginal ignition. If a more reasonable maximum value of major radius—for example, 6 m—is specified, then an ITER with an ignition margin of 0.75 (T-10 scaling) or 0.45 (Rebut scaling) can be attained.

Fig. 2. Major radius vs ignition margin for minimum-cost designs.

4.3 DIRECT COST

Figure 3 shows the minimum direct cost for ITER configurations as a function of ignition margin. The capital cost lies between \$1300 million and \$2000 million for configurations designed for marginal ignition with Goldston, Kaye-Goldston, and JAERI scaling. Again, the T-10 and Rebut scalings result in configurations requiring very high capital cost at ignition conditions. For a competitive direct cost of \$2000 million, we can buy an ITER configuration that achieves an ignition margin of 0.35 with Rebut scaling, 0.65 with T-10 scaling, and 1.0 to 1.3 with the JAERI, Kaye-Goldston, and Goldston scalings.

The capital costs for Kaye-Goldston scaling, shown in Fig. 3, are listed by system in Table 1 to provide insight into the major cost drivers. All of the variable costs increase as the ignition margin is increased, with the greatest percentage of the cost increase being in the PF magnet system, the heat transport system, the TF magnet system, and the power conditioning system.

Fig. 3. Minimum direct cost vs ignition margin.

Table 1. Cost breakdown as a function of ignition margin for a case with Kaye-Goldston scaling (in millions of dollars)

	Ignition margin			
	1.0	1.15	1.3	1.4
Buildings	169	186	214	245
Reactor systems	384	508	719	989
TF magnets	231	394	715	1089
PF magnets	168	244	534	1051
Cryostat	12	15	19	25
Vacuum system	84	145	250	357
Power conditioning	92	150	291	483
Heat transport system	92	129	178	219
Fuel handling system	88	96	109	123
Electrical plant	19	22	26	31
Heat rejection system	23	32	44	53
Fixed cost ^a	305	305	305	305
Total direct cost	1667	2226	3404	4970

^aIncludes \$120 million for power injection, \$100 million for instrumentation and controls, \$60 million for maintenance equipment, and \$25 million for miscellaneous expenses.

4.4 NEUTRON WALL LOADING

Figure 4 shows neutron wall loading as a function of ignition margin for minimum direct cost. The design based on Goldston scaling is bounded by the minimum value of 1.0 MW/m². The general trend for the other scalings is for the neutron wall loading to increase with increasing values of ignition margin until a maximum value is achieved and then decrease as the ignition margin is further increased. At an ignition margin of 1.0, the JAERI scaling results in a value of 1.8 MW/m², which is the highest value for all of the scalings considered at the marginal ignition condition.

4.5 ASPECT RATIO

Figure 5 shows aspect ratio as a function of ignition margin, at minimum direct cost. The T-10 scaling requires the highest aspect ratio (greater than 4.0), followed

Fig. 4. Neutron wall loading vs ignition margin for minimum-cost designs.

Fig. 5. Aspect ratio vs ignition margin for minimum-cost designs.

in descending order by the Goldston, Kaye-Goldston, and JAERI scalings. The aspect ratio is a weak function of ignition margin, generally decreasing as the ignition margin increases.

The indicated variation of aspect ratio with ignition margin for T-10 scaling, and to a lesser degree for Goldston scaling, is large because the minimum direct cost, at a given value of ignition margin, was essentially independent of the aspect ratio for these two scalings. This is shown in Fig. 6, which shows the variation of minimum direct cost with the aspect ratio for the T-10 scaling, at a fixed ignition value of 0.65. The direct cost is nearly flat for aspect ratios from 3.0 to 5.5, even though the major radius increases by about 0.5 m. The plasma current and minor radius decrease rather substantially as the aspect ratio is increased over this range, as shown in Fig. 7.

4.6 TOROIDAL FIELD

Figure 8 shows that the field on axis varies between 4.0 and 7.5 T for an ignition margin between 0.25 and 1.50. The highest value (7.5 T) is associated with the high-aspect-ratio designs obtained with the T-10 scaling. Figure 9 shows that the

Fig. 6. Major radius and minimum direct cost vs aspect ratio for T-10 scaling at an ignition margin of 0.65.

Fig. 7. Plasma current and minor radius for T-10 scaling at an ignition margin of 0.65.

Fig. 8. Field on axis vs ignition margin for minimum-cost designs.

Fig. 9. Maximum toroidal field vs ignition margin for minimum-cost designs.

maximum field at the TF coil winding lies between 10 and 12.5 T; the T-10 and Kaye-Goldston scalings require the highest values and the JAERI scaling the lowest.

4.7 BETA LIMIT

Figure 10 shows the beta, given as a fraction of the Troyon beta limit, f_β , as a function of ignition margin. The Troyon limit scales directly with the plasma current and inversely with the minor radius and field on axis. For the Goldston, Kaye-Goldston, T-10, and Rebut scalings, f_β decreases with increasing ignition margin. This is attributed to the unfavorable scaling of confinement time with plasma heating (alpha) power. The JAERI scaling is composed of two terms, only one of which degrades with plasma heating power; thus beta is at the Troyon limit for ignition margins greater than 0.8 with the JAERI scaling.

Fig. 10. Fraction of beta limit vs ignition margin for minimum-cost designs.

The numerical optimizer in the TETRA code finds an optimum value of beta (as a fraction of the Troyon limit). It is of interest to determine the consequences of forcing beta to be greater than this optimum value. This was done for the design obtained with Kaye-Goldston scaling at marginal ignition. This design, the parameters for which are shown in the first column of Table 2, has a fractional beta limit of 0.68. The parameters shown in columns 2 and 3 of Table 2 are for designs with f_β of 0.85 and 0.99, respectively. The table shows that the numerical optimizer did indeed find the minimum-cost point. As f_β increases from 0.68 to 0.99, the major radius decreases slightly (15 cm), the fusion power and neutron wall loading increase substantially (77 and 81%, respectively), and the global energy confinement time decreases from 2.31 s to 1.58 s. The net effect of these changes is an increase of \$137 million in the direct cost.

Table 3 shows the elements of the cost for the designs of Table 2. The costs of the reactor systems (primarily shielding) and the TF magnet decrease by \$10 million

Table 2. Effect of varying minimum fractional Troyon beta limit for a case with Kaye-Goldston scaling and an ignition margin of 1.0

	Fraction of beta limit f_β		
	0.68	0.85	0.99
R_0 , m	4.38	4.33	4.23
a , m	1.43	1.43	1.45
A	3.06	3.02	2.93
I_p , MA	16.2	16.2	16.7
B_t , T	5.41	5.27	5.14
T_e , keV	7.28	8.5	9.6
Power, MW	670	929	1187
τ , s	2.31	1.83	1.58
Cost, millions of dollars	1666	1709	1803
L_w , MW/m ²	1.15	1.61	2.08
B_{max} , T	11.8	11.6	11.8
$f_{n.}$	0.995	1.0	1.0

Table 3. Cost breakdown for designs in Table 2 (in millions of dollars)

	Fraction of beta limit f_β		
	0.68	0.85	0.99
Buildings	169	169	170
Reactor	382	378	372
TF magnets	233	209	203
PF magnets	170	172	195
Cryostat	12	12	12
Power injection	120	120	120
Vacuum systems	83	121	163
Power conditioning	93	91	100
Heat transport	90	114	137
Fuel handling	88	89	91
Instrumentation and controls, maintenance, miscellaneous	185	185	185
Electrical plant	19	20	21
Heat rejection	22	29	34
Total	1666	1709	1803

and \$30 million, respectively (primarily because of the smaller major radius), while the PF magnet costs increase by \$25 million, the vacuum system costs increase by \$80 million (because of the increased pumping required by the degraded plasma confinement), and the heat transport system costs increase by \$47 million (because of the higher fusion power) as f_β is increased from its optimum value of 0.68 to 0.99.

4.8 PLASMA TEMPERATURE

Figure 11 shows the variation of plasma volume-averaged temperature as a function of ignition margin. The temperature generally increases as the ignition margin is increased. A lower limit of 7.5 keV was imposed; the upper value of plasma temperature is about 13 keV.

Fig. 11. Plasma temperature vs ignition margin for minimum-cost designs.

4.9 DENSITY LIMIT

Figure 12 shows the variation in the density as a fraction of the Greenwald density limit f_n , as a function of ignition margin for minimum direct cost. The Greenwald limit varies directly with the plasma current and inversely with the plasma cross-sectional area. The fraction of the Greenwald plasma density generally increases with increasing ignition margin up to the density limit and then remains constant for further increases in ignition margin. However, for Goldston scaling, the fraction of the density limit decreases as the ignition margin increases.

4.10 SCALING FACTOR

It has been proposed² that $Tn\tau$, a measure of confinement capability, should scale as a function of IA^a/R^x , where I is the plasma current, A is the aspect ratio, R is the major radius, and a and x depend upon the confinement scaling and

Fig. 12. Fraction of density limit vs ignition margin for minimum-cost designs.

operational density and beta limits. The proposed specific forms of these scalings, at the Murakami density limit with fixed plasma temperature, are

$$[(f_L(I A^{1.37})/R^{0.12})^2]$$

for Goldston scaling,

$$[(f_L^{0.8}(I A^{1.32})/R^{0.55})^3]$$

for Kaye-Goldston scaling, and

$$[(f_L^{0.5}(I A^{0.5})/R^{0.25})^2]$$

for Rebut-Lallia scaling. These proposed scaling factors are computed as functions of $Tn\tau$ and are plotted in Fig. 13. Normalizing factors are applied at values of $Tn\tau$ consistent with an ignition margin of 1.0 for the Goldston and Kaye-Goldston scaling and an ignition margin of 0.40 for Rebut scaling. It is seen that these scaling factors increase monotonically with $Tn\tau$, so a higher scaling factor indicates a higher confinement capability. However, the scaling factors deviate from $Tn\tau$ significantly in slope in all cases. The difference in the scaling factor and $Tn\tau$ can be seen from

Fig. 13. Ignition scaling factor vs $Tn\tau$ for minimum-cost designs.

Figs. 10 and 11, which show that the minimum-cost designs may not occur at the density limit or at a fixed value of plasma temperature. In addition, the Greenwald density limit, not the Murakami limit, was used in this study. However, the scaling factors would approximately fit if they have different exponents:

$$[(f_L(I A^{1.37})/R^{0.12})^{0.96}]$$

for Goldston scaling,

$$[(f_L^{0.8}(I A^{1.32})/R^{0.55})^{1.17}]$$

for Kaye-Goldston scaling, and

$$[(f_L^{0.5}(I A^{0.5})/R^{0.25})^{0.67}]$$

for Rebut-Lallia scaling.

4.11 CHOICE OF DESIGN LIMITS

Major ITER parameters, at marginal ignition for Kaye-Goldston confinement scaling, are shown in Table 4 for aggressive and conservative design limits (or constraints). The conservative limits produce increases of about 1 m in major radius,

Table 4. ITER parameters for marginal ignition with Kaye-Goldston scaling and aggressive or conservative design limits

	Design limits	
	Aggressive	Conservative
Major radius, m	4.40	5.33
Minor radius, m	1.43	1.93
Aspect ratio, A	3.07	2.76
Plasma current, MA	16.2	20.8
Field on axis, T	5.41	5.05
Plasma temperature, keV	7.5	8.3
Maximum toroidal field, T	11.8	12.5
Fusion power, MW	680	925
Fraction of beta limit f_β	0.69	0.63
Fraction of density limit	0.97	1.0
Single-piece divertor removal	No	Yes
Direct cost, millions of dollars	1667	2134

4 MA in plasma current, 250 MW in fusion power, and \$470 million in direct cost above the values with aggressive limits. The effect of the ignition margin on major radius, plasma current, cost, aspect ratio, fusion power, neutron wall loading, and other parameters is shown in Figs. 14-18 for conservative design limits. The variation in major parameters as a function of ignition margin is similar to that observed when the aggressive design limits are imposed (see Figs. 1-13).

5. CONCLUSIONS

1. Rebut scaling is the most pessimistic scaling considered. It was not possible to define an ITER configuration that achieved ignition for plasma currents up to 35 MA when optimizing for minimum capital cost with this scaling. A revised, more optimistic algorithm⁷ for Rebut scaling has been received. The required plasma current will be determined using the revised algorithm in the near future.
2. The plasma current necessary for ignition lies between 10 and 21 MA for all other scaling laws considered when optimizing for minimum capital cost.

Fig. 14. Major radius and minimum direct cost as functions of ignition margin for a minimum-cost design with Kaye-Goldston scaling and conservative limits.

Fig. 15. Plasma current and aspect ratio as functions of ignition margin for a minimum-cost design with Kaye-Goldston scaling and conservative limits.

Fig. 16. Fusion power and neutron wall loading as functions of ignition margin for a minimum-cost design with Kaye-Goldston scaling and conservative limits.

Fig. 17. Beta as fraction of the Troyon limit f_β and plasma temperature as functions of ignition margin for a minimum-cost design with Kaye-Goldston scaling and conservative limits.

Fig. 18. Maximum toroidal field and field on axis as functions of ignition margin for a minimum-cost design with Kaye-Goldston scaling and conservative limits.

3. The required major radius lies between 4.2 and 4.5 m with a corresponding direct cost of \$1400 million to \$2000 million for the Goldston, Kaye-Goldston, and JAERI scalings.
4. T-10 scaling results in a configuration outside the region of interest (major radius of 10 m, cost of \$7400 million) when optimizing for minimum capital cost. If either the T-10 or the pessimistic Rebut scaling proves valid in the ITER region of parameter space, then compromises or innovations will be required to achieve an acceptable ignited ITER design.
5. The required aspect ratio is not a strong function of ignition margin for minimum capital cost and for the scaling laws considered.
6. Maximum toroidal fields at the TF coil winding range from 10 to 12.5 T for ITER designs based on minimum direct cost for the confinement scalings considered.
7. The variation in major physics and engineering parameters as a function of ignition margin for ITER is essentially independent of the choice of design limits investigated in this study (aggressive or conservative). The conservative limits, of course, result in a larger, more expensive version of ITER.

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